Small sizes that matter:

Opportunities and risks of Nanotechnologies

Report in co-operation with the OECD International Futures Programme

OECD

Allianz

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1. Executive Summary

Nanotechnologies are being spoken of as the driving force behind a new industrial revolution. Both private- and public-sector spending are constantly increasing. Spending on public research has reached levels of well over EUR 3 billion world-wide, but private sector spending is even faster—it is expected to exceed government spending in 2005. Nanotechnologies will be a major technological force for change in shaping Allianz's business environment across all industrial sectors in the foreseeable future and are likely to deliver substantial growth opportunities. The size of the market for nanotechnology products is already comparable to the biotechnology sector, while the expected growth rates over the next few years are far higher. At the same time, scientists have raised concerns that the basic building blocks of nanotechnologies—particles smaller than one billionth of a meter—pose a potential new class of risk to health and the environment. Allianz calls for a precautionary approach based on risk research and good risk management to minimize the likelihood of nanoparticles bringing a new dimension to personal injury and property damage losses or posing third party liability and product-recall risks.

The Allianz Center for Technology and Allianz Global Risks, in co-operation with the OECD International Futures Programme, has reviewed the likely economic impact, investment possibilities, and potential risks of nanotechnologies. This report analyses the opportunities and risks from the perspective of the Allianz Group. The opinions expressed in this report are those of the Allianz Group and do not engage the OECD or its Member governments.

1.1. Nanotechnology and the market place

The term nanotechnology describes a range of technologies performed on a nanometer scale with widespread applications as an enabling technology in various industries. Nanotechnology encompasses the production and application of physical, chemical, and biological systems at scales ranging from individual atoms or molecules to around 100 nanometers, as well as the integration of the resulting nanostructures into larger systems. The area of the dot of this ”i” alone can encompass 1 million nanoparticles.

What is different about materials on a nanoscale compared to the same materials in larger form is that, because of their relatively larger surface-area-to-mass ratio, they can become more chemically reactive and change their strength or other properties. Moreover, below 50 nm, the laws of classical physics give way to quantum effects, provoking different optical, electrical and magnetic behaviours.

Nanoscale materials have been used for decades in applications ranging from window glass and sunglasses to car bumpers and paints. Now, however, the convergence of scientific disciplines (chemistry, biology, electronics, physics, engineering etc.) is leading to a multiplication of applications in materials manufacturing, computer chips, medical diagnosis and health care, energy, biotechnology, space exploration, security and so on. Hence, nanotechnology is expected to have a significant impact on our economy and society within the next 10 to 15 years, growing in importance over the longer term as further scientific and technology breakthroughs are achieved.

It is this convergence of science on the one hand and growing diversity of applications on the other that is driving the potential of nanotechnologies. Indeed, their biggest impacts may arise from unexpected combinations of previously separate aspects, just as the internet and its myriad applications came about through the convergence of telephony and computing.

Sales of emerging nanotechnology products have been estimated by private research to rise from less than 0.1 % of global manufacturing output today to 15 % in 2014. These figures refer however to products ”incorporating nanotechnology” or ”manufactured using nanotechnology”. In many cases nanotechnology might only be a minor – but sometimes decisive -- contribution to the final product.

The first winners in the nanotechnology industry are likely to be the manufacturers of instruments allowing work on a nanoscale. According to market researchers, the nanotechnology tools industry ($245 million in the US alone) will grow by 30 % annually over the next few years.

The following projected three-phase growth path seems credible:

- In the present phase, nanotechnology is incorporated selectively into high-end products, especially in automotive and aerospace applications.
- Through 2009, commercial breakthroughs unlock markets for nanotechnology innovations. Electronics and IT applications dominate as microprocessors and memory chips built using new nanoscale processes come on to the market.

- From 2010 onwards, nanotechnology becomes commonplace in manufactured goods. Health care and life sciences applications finally become significant as nano-enabled pharmaceuticals and medical devices emerge from lengthy human trials.

1.2. Investments in nanotechnology

The financial sector will have a key role in transferring technology knowledge from the research centres to the industry and the markets. For the development of new products and processes and also for the penetration of new markets, sizeable investments are needed, especially in the seed phase. A closer co-operation between the financial community and nanotechnology companies can help to overcome these barriers.

By the end of 2004 venture capitalists had already invested $1 billion in nano companies, nearly half of that alone in 2003 and 2004. It is expected that most of these nanotechnology companies will be sold through trade sales.

For successful investments two aspects will be of critical importance: timing and target selection. Applying the process of ”technical due diligence” will be essential in making acquisitions.

The difficulty and expense involved in building up nanotechnology companies suggests that future winners in the sector will be well-funded companies and institutes that can attract and nurture the scientific and technical expertise needed to understand the problems and challenges. Moreover, the long lead times involved in moving from concept to commercialisation necessitate considerable long-term commitment to projects.

1.3. The environmental, health and safety discussion related to nanoparticles

Along with the discussion of their enormous technological and economic potential, a debate about new and specific risks related to nanotechnologies has started.
The catch-all term ”nanotechnology” is so broad as to be ineffective as a guide to tackling issues of risk management, risk governance and insurance.
A more differentiated approach is needed regarding all the relevant risk management aspects.

With respect to health, environmental and safety risks, almost all concerns that have been raised are related to free, rather than fixed manufactured nanoparticles. The risk and safety discussion related to free nanoparticles will be relevant only for a certain portion of the widespread applications of nanotechnologies.

Epidemiological studies on ambient fine and ultrafine particles incidentally produced in industrial processes and from traffic show a correlation between ambient air concentration and mortality rates. The health effects of ultrafine particles on respiratory and cardiovascular endpoints highlight the need for research also on manufactured nanoparticles that are intentionally produced.

In initial studies, manufactured nanoparticles have shown toxic properties. They can enter the human body in various ways, reach vital organs via the blood stream, and possibly damage tissue. Due to their small size, the properties of nanoparticles not only differ from bulk material of the same composition but also show different interaction patterns with the human body.
A risk assessment for bulk materials is therefore not sufficient to characterise the same material in nanoparticulate form.

The implications of the special properties of nanoparticles with respect to health and safety have not yet been taken into account by regulators. Size effects are not addressed in the framework of the new European chemicals policy REACH. Nanoparticles raise a number of safety and regulatory issues that governments are now starting to tackle. From Allianz’s perspective, a review of current legislation and continuous monitoring by the authorities is needed.

At present, the exposure of the general population to nanoparticles originating from dedicated industrial processes is marginal in relation to those produced and released unintentionally e.g. via combustion processes. The exposure to manufactured nanoparticles is mainly concentrated on workers in nanotechnology research and nanotechnology companies. Over the next few years, more and more consumers will be exposed to manufactured nanoparticles. Labelling requirements for nanoparticles do not exist. It is inevitable that in future manufactured nanoparticles will be released gradually and accidentally into the environment. Studies on biopersistence, bioaccumulation and ecotoxicity have only just started.

From Allianz’s perspective more funding for independent research on risk issues is necessary and we propose a dedicated research center at European level.

1.4. Allianz's position on industrial insurance cover

From an insurance perspective, several basic points define possible risk scenarios from nanoparticles:

- an increasingly high number of persons will be exposed,
- potential harmful effects are expected to evolve over longer periods of many years,
- in individual cases it will be difficult to establish a causal relationship between actions of a company and the resulting injury or damage,
- occupational exposure is a main concern,
- a certain closeness to major liability losses from the past will be evident.

In the absence of more basic evidence, all parties involved should take interim steps to manage risk.

The mechanisms that could lead to liability cases involve not only the development of our scientific understanding of the effects of nanoparticles, but also include legal and socio-economic developments that are difficult to foresee. More and more we realise that long-term illnesses are caused by a complex interaction of different risk factors. It is likely that nanoparticles will be not be so much a single cause or central origin of an illness but more of a contribution to a general health condition. In the traditional regime of liability and compensation, a causal relationship based on a one-to-one assignment of damaging agent and injury needs to be established. In the European legal framework, that causal relationship has to be proven – at least from today's perspective.

For Allianz it seems neither feasible nor appropriate to start a debate about a *general* exclusion of nanotechnologies from the commercial and industrial insurance cover today.

From the available evidence, we believe that the question is not whether or not nanotechnology risks can be controlled – and insured – but rather how they can best be managed and insured in a responsible way.

For a successful risk management of nanotechnologies from our perspective, the following framework is needed:

- sufficient funding of independent research on nanotechnology related risks with active steering by governments,
- transparency about and open access to the results of research activities,
- ongoing dialogue between insurers and commercial and industrial clients,
- international standards and nomenclature,
- adequate regulation of risk issues,
- a global risk governance approach.

Allianz's role is to meet client's demands while, at the same time, prudently protecting its balance sheet. We have started monitoring scientific, legal, social and economic trends in this field. We will constantly adapt our policy towards nanotechnologies as new evidence appears and, possibly, as claims in this field are made.

Given the fact that nanotechnologies have an enabling character and will penetrate almost every industry over the coming years, we expect that nanotechnology risks will be part of the industrial insurance portfolio. However, we will closely watch changes in the field. Where doubts arise, we would, where appropriate, talk with clients. We would also actively steer our portfolio. This might range from assessing the risk appetite for certain classes of business to posing questions about trigger of coverage and making detailed individual risk assessments.

Allianz wants to contribute to a dialogue-oriented approach using sustainability as both a vision and a yardstick of success.

2. What is nanotechnology and what makes it different?

2.1. Introduction

A nanometer (nm) is one thousand millionth of a meter. A single human hair is about 80,000 nm wide, a red blood cell is approximately 7,000 nm wide, a DNA molecule 2 to 2.5 nm, and a water molecule almost 0.3 nm. The term *”nanotechnology”* was created by Norio Taniguchi of Tokyo University in 1974 to describe the precision manufacture of materials with nanometer tolerances[1], but its origins date back to Richard Feynman’s 1959 talk ”There’s Plenty of Room at the Bottom”[2] in which he proposed the direct manipulation of individual atoms as a more powerful form of synthetic chemistry. Eric Drexler of MIT expanded Taniguchi’s definition and popularised nanotechnology in his 1986 book ”Engines of Creation: The Coming Era of Nanotechnology”[3]. On a nanoscale, i.e. from around 100nm down to the size of atoms (approximately 0.2 nm) the properties of materials can be very different from those on a larger scale. Nanoscience is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, in order to understand and exploit properties that differ significantly from those on a larger scale. Nanotechnologies are the design, characterisation, production and application of structures, devices and systems by controlling shape and size on ananometer scale.

Modern industrial nanotechnology had its origins in the 1930s, in processes used to create silver coatings for photographic film; and chemists have been making polymers, which are large molecules made up of nanoscale subunits, for many decades. However, the earliest known use of nanoparticles is in the ninth century during the Abbasid dynasty. Arab potters used nanoparticles in their glazes so that objects would change colour depending on the viewing angle (the so-called polychrome lustre)[4]. Today’s nanotechnology, i.e. the planned manipulation of materials and properties on a nanoscale, exploits the interaction of three technological streams[5]:

1. new and improved control of the size and manipulation of nanoscale building blocks
2. new and improved characterisation of materials on a nanoscale (e.g., spatial resolution, chemical sensitivity)
3. new and improved understanding of the relationships between nanostructure and properties and how these can be engineered.

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[1] ”Nano-technology' mainly consists of the processing of separation, consolidation, and deformation of materials by one atom or one molecule.
” N. Taniguchi, "On the Basic Concept of 'Nano-Technology'," Proc. Intl. Conf. Prod. Eng. Tokyo, Part II, Japan Society of Precision Engineering, 1974.

[2] A transcript of the classic talk that Richard Feynman gave on December 29th 1959 at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech) was first published in the February 1960 issue of Caltech's Engineering and Science which owns the copyright. It has been made available on the web at http://www.zyvex.com/nanotech/feynman.html with their kind permission.

[3] Engines of Creation was originally published in hardcover by Anchor Books in 1986, and in paperback in 1987. The web version published here http://www.foresight.org/EOC/ was reprinted and adapted by Russell Whitaker with permission of the copyright holder.

[4] ”The oldest known nanotechnology dates back to the ninth century” New Materials International, March 2004 http://www.newmaterials.com/news/680.asp

[5] US National Science and Technology Council, Committee on Technology, Interagency Working Group on NanoScience, Engineering and Technology: ”Nanostructure Science and Technology, A Worldwide Study”. September 1999. http://www.wtec.org/loyola/nano/

The properties of materials can be different on a nanoscale for two main reasons. First, nanomaterials have, relatively, a larger surface area than the same mass of material produced in a larger form. This can make materials more chemically reactive (in some cases materials that are inert in their larger form are reactive when produced in their nanoscale form), and affect their strength or electrical properties. Second, below 50 nm, the laws of classical physics give way to quantum effects, provoking optical, electrical and magnetic behaviours different from those of the same material at a larger scale. These effects can give materials very useful physical properties such as exceptional electrical conduction or resistance, or a high capacity for storing or transferring heat, and can even modify biological properties, with silver for example becoming a bactericide on a nanoscale. These properties, however, can be very difficult to control. For example, if nanoparticles touch each other, they can fuse, losing both their shape and those special properties—such as the magnetism—that scientists hope to exploit for a new generation of microelectronic devices and sensors.

On a nanoscale, chemistry, biology, electronics, physics, materials science, and engineering start to converge and the distinctions as to which property a particular discipline measures no longer apply. All these disciplines contribute to understanding and exploiting the possibilities offered by nanotechnology, but if the basic science is converging, the potential applications are infinitely varied, encompassing everything from tennis rackets to medicines to entirely new energy systems. This twin dynamic of convergent science and multiplying applications means that nanotechnology's biggest impacts may arise from unexpected combinations of previously separate aspects, just as the internet came about through the convergence of telephony and computing.

2.2. Nanomaterials: basic building blocks

This section outlines the properties of three of the most talked-about nanotechnologies: carbon nanotubes, nanoparticles, and quantum dots[6].

Carbon Nanotubes

Carbon nanotubes, long thin cylinders of atomic layers of graphite, may be the most significant new material since plastics and are the most significant of today's nanomaterials. They come in a range of different structures, allowing a wide variety of properties. They are generally classified as single-walled (SWNT), consisting of a single cylindrical wall, or multiwalled nanotubes (MWNT), which have cylinders within the cylinders. When the press mentions the amazing properties of nanotubes, it is generally SWNT they are referring to. The following table summarises the main properties of SWNT:

Size	0.6 to 1.8 nanometer in diameter	Electron beam lithography can create lines 50 nm wide, a few nm thick
Density	1.33 to 1.40 grams per cubic centimeter	Aluminium has a density of 2.7g/cm^3
Tensile Strength	45 billion pascals	High-strength steel alloys break at about 2 billion Pa
Resilience	Can be bent at large angles and restraightened without damage	Metals and carbon fibers fracture at grain boundaries
Current Carrying Capacity	Estimated at 1 billion amps per square centimeter	Copper wires burn out at about 1 million A/cm^2
Field Emission	Can activate phosphors at 1 to 3 volts if electrodes are spaced 1 micron apart	Molybdenum tips require fields of 50 to 100 V/µm and have very limited lifetimes
Heat Transmission	Predicted to be as high as 6,000 watts per meter per kelvin at room temperature	Nearly pure diamond transmits 3,320 W/m·K
Temperature Stability	Stable up to 2,800 degrees Celsius in vacuum, 750 degrees C in air	Metalwires in microchips melt at 600 to 1,000 degrees C

© Scientific American December 2000[7]

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[6] Nanotechnology white papers published by Cientifica at http://www.cientifica.com/html/Whitepapers/whitepapers.htm were particularly useful for this section. Registration (free) is required to consult the documents.

[7] Philip G. Collins and Phaedon Avouris "Nanotubes for electronics" Scientific American, December 2000, page 69

However, SWNT are more difficult to make than MWNT, and confusion arises about the quantities of nanotubes actually being manufactured. Carbon Nanotechnologies of Houston, one of the world's leading producers, only makes up to 500g per day. One problem is that economies of scale are practically impossible with today's production technologies – the machines used to manufacture the tubes cannot be scaled up, so producing bigger quantities means using more machines.

Another drawback is that it is difficult to make nanotubes interact with other materials. For example, to fully exploit their strength in composite materials, nanotubes need to be "attached" to a polymer. They are chemically modified to facilitate this (a process known as "functionalization"), but this process reduces the very properties the nanotubes are being used for. In the long-term, the ideal solution would be to use pure nanomaterials, e.g. nanotubes spun into fibers of any desired length, but such a development is unlikely in the next couple of decades unless a radically more efficient production process is developed.

The most promising applications of nanotubes may be in electronics and optoelectronics[8]. Today, the electronics industry is producing the vital components known as MOSFETs (metal oxide semiconductor field-effect transistors) with critical dimensions of just under 100 nm, with half that size projected by 2009 and 22 nm by 2016. However, the industry will then encounter technological barriers and fundamental physical limitations to size reduction. At the same time, there are strong financial incentives to continue the process of scaling, which has been central in the effort to increase the performance of computing systems in the past. A new microchip manufacturing plant costs around $1.5 billion, so extending the technology's life beyond 2010 is important. One approach to overcoming the impending barriers while preserving most of the existing technology, is to use new materials.

With carbon nanotubes, it is possible to get higher performance without having to use ultra thin silicon dioxide gate insulating films. In addition, semiconducting SWNTs, unlike silicon, directly absorb and emit light, thus possibly enabling a future optoelectronics technology. The SWNT devices would still pose manufacturing problems due to quantum effects at the nanoscale, so the most likely advantage in the foreseeable future is that carbon nanotubes will allow a simpler fabrication of devices with superior performance at about the same length as their scaled silicon counterparts.

Other proposed uses for nanotubes:

Chemical and Genetic Probes A nanotube-tipped atomic force microscope can trace a strand of DNA and identify chemical markers that reveal which of several possible variants of a gene is present in the strand. This is the only method yet invented for imaging the chemistry of a surface, but it is not yet used widely. So far it has been used only on relatively short pieces of DNA.

Mechanical memory (nonvolatile RAM). A screen of nanotubes laid on support blocks has been tested as a binary memory device, with voltages forcing some tubes to contact (the "on" state) and others to separate ("off"). The switching speed of the device was not measured, but the speed limit for a mechanical memory is probably around one megahertz, which is much slower than conventional memory chips.

Field Emission Based Devices. Carbon Nanotubes have been demonstrated to be efficient field emitters and are currently being incorporated in several applications including flat-panel display for television sets or computers or any devices requiring an electron producing cathode such as X-ray sources (e.g. for medical applications).

Nanotweezers. Two nanotubes, attached to electrodes on a glass rod, can be opened and closed by changing voltage. Such tweezers have been used to pick up and move objects that are 500 nm in size. Although the tweezers can pick up objects that are large compared with their width, nanotubes are so sticky that most objects can't be released. And there are simpler ways to move such tiny objects.

Supersensitive Sensors. Semiconducting nanotubes change their electrical resistance dramatically when exposed to alkalis, halogens and other gases at room temperature, raising hopes for better chemical sensors. The sensitivity of these devices is 1,000 times that of standard solid state devices.

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[8] Phaedon Avouris and Joerg Appenzeller: "Electronics and optoelectronics with carbon nanotubes: New discoveries brighten the outlook for innovative technologies" The Industrial Physicist, June/July 2004, American Institute of Physics

Hydrogen and Ion Storage. Nanotubes might store hydrogen in their hollow centers and release it gradually in efficient and inexpensive fuel cells. They can also hold lithium ions, which could lead to longer-lived batteries. So far the best reports indicate 6.5 percent hydrogen uptake, which is not quite dense enough to make fuel cells economical. The work with lithium ions is still preliminary.

Sharper Scanning Microscope. Attached to the tip of a scanning probe microscope, nanotubes can boost the instruments' lateral resolution by a factor of 10 or more, allowing clearer views of proteins and other large molecules. Although commercially available, each tip is still made individually. The nanotube tips don't improve vertical resolution, but they do allow imaging deep pits in nanostructures that were previously hidden.

Superstrong Materials. Embedded into a composite, nanotubes have enormous resilience and tensile strength and could be used to make materials with better safety features, such as cars with panels that absorb significantly more of the force of a collision than traditional materials, or girders that bend rather than rupture in an earthquake. Nanotubes still cost 10 to 1,000 times more than the carbon fibers currently used in composites. And nanotubes are so smooth that they slip out of the matrix, allowing it to fracture easily.

There are still many technical obstacles to overcome before carbon nanotubes can be used on an industrial scale, but their enormous potential in a wide variety of applications has made them the "star" of the nanoworld[9] and encouraged many companies to commit the resources needed to ensure that the problems will be solved. Fujitsu, for example, expects to use carbon nanotubes in 45 nm chips by 2010 and in 32 nm devices in 2013[10].

Nanoparticles

Nanoparticles have been used since antiquity by ceramists in China and the West, while 1.5 million tons of carbon black, the most abundant nanoparticulate material, are produced every year. But, as mentioned earlier, nanotechnology is defined as knowingly exploiting the nanoscale nature of materials, thereby excluding these examples. Although metal oxide ceramic, metal, and silicate nanoparticles constitute the most common of the new generation of nanoparticles, there are others too. A substance called chitosan for example, used in hair conditioners and skin creams, has been made in nanoparticle form to improve absorption.

Moving to nanoscale changes the physical properties of particles, notably by increasing the ratio of surface area to volume, and the emergence of quantum effects. High surface area is a critical factor in the performance of catalysis and structures such as electrodes, allowing improvement in performance of such technologies as fuel cells and batteries. The large surface area also results in useful interactions between the materials in nanocomposites, leading to special properties such as increased strength and/or increased chemical/heat resistance. The fact that nanoparticles have dimensions below the critical wavelength of light renders them transparent, an effect exploited in packaging, cosmetics and coatings.

Quantum dots

Just as carbon nanotubes are often described as the new plastics, so quantum dots are defined as the ball bearings of the nano-age[11]. Quantum dots are like "artificial atoms". They are 1 nm structures made of materials such as silicon, capable of confining a single electron, or a few thousand, whose energy states can be controlled by applying a given voltage. In theory, this could be used to fulfil the alchemist's dream of changing the chemical nature of a material, making lead emulate gold, for example.

One more likely set of possible applications exploits the fact that quantum dots can be made to emit light at different wavelengths, with the smaller the dot the bluer the light. The dots emit over a narrow spectrum making them well suited to imaging, particularly for biological samples. Currently, biological molecules are imaged using naturally fluorescent molecules, such as organic dyes, with a different dye attached to each kind of molecule in a sample. But the dyes emit light over a broad range of wavelengths, which means that their spectra overlap and only about three different

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[9] "Nanotubes 2003" http://www.researchandmarkets.com/reports/220255/220255.htm

[10] Paul Kallender "Fujitsu touts carbon nanotubes for chip wiring" IDG News Service, March 2005 http://www.infoworld.com/article/05/03/01/HNfujinanotubes_1.html

[11] Paul O'Brien Physics World, December 2003. A summary is available here: http://www.nanotechweb.org/articles/feature/2/12/1/1

dyes emit light over a broad range of wavelengths, which means that their spectra overlap and only about three different dyes can be used at the same time. With quantum dots, full-colour imaging is possible because large numbers of dots of different sizes can be excited by a light source with a single wavelength.

The wide range of colors that can be produced by quantum dots also means they have great potential in security. They could, for example, be hidden in bank notes or credit cards, producing a unique visible image when exposed to ultraviolet light.

It is possible to make light-emitting diodes (LEDs) from quantum dots which could produce white light e.g. for buildings or cars. By controlling the amount of blue in the emission-control the "flavor" or "tone" of the white light can be tuned.

Quantum dots are also possible materials for making ultrafast, all-optical switches and logic gates that work faster than 15 terabits a second. For comparison, the Ethernet generally can handle only 10 megabits per second. Other possible applications are all-optical demultiplexers (for separating various multiplexed signals in an optical fiber), all-optical computing, and encryption, whereby the spin of an electron in a quantum dot represent a quantum bit or qubit of information.

Biologists are experimenting with composites of living cells and quantum dots. These could possibly be used to repair damaged neural pathways or to deliver drugs by activating the dots with light.

Once again, significant advances in manufacturing will be needed to realise the potential of quantum dots. For example, the quantum state needed to make a quantum computer is relatively easily to create, but its behavior is still unpredictable.

2.3. Nano tools and fabrication techniques

Legend has it that the people who profited most from the Klondike gold rush at the end of the 19th century were the sellers of picks and shovels. The same may hold true for nanotechnology, at least in the coming decade before production techniques are improved. According to market researchers Freedonia, the $245 million nanotech tools industry will grow by 30 % annually over the next few years[12]. Microscopes and related tools dominate now, but measurement, fabrication / production and simulation / modelling tools will grow the fastest. Electronics and life sciences markets will emerge first; industrial, construction, energy generation and other applications will arise later.

Microscopy

Nanotechnology uses two main kinds of microscopy. The first involves a stationary sample in line with a high-speed electron gun. Both the scanning electron microscope (SEM) and transmission electron microscope (TEM) are based on this technique. The second class of microscopy involves a stationary scanner and a moving sample. The two microscopes in this class are the atomic force microscope (AFM) and the scanning tunnelling microscope (STM).

Microscopy plays a paradoxical role in nanotechnology because, although it is the key to understanding materials and processes, on a nanoscale samples can be damaged by the high-energy electrons fired at them. This is not a problem with STM, but a further drawback is that most microscopes require very stringent sample preparation. The SEM, TEM, and STM need well prepared samples that are also electrically conductive. There are ways to get around this, but the fact remains that it can take hours to prepare and mount a sample correctly (and hours to actually synthesise the sample).

Top-down and bottom-up synthesis techniques

There are two approaches to building nanostructures, both having their origins in the semiconductor industry[13]. In the traditional ”top-down” approach a

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[12] ”Nanotech Tools to 2008” August 2004 http://freedonia.ecnext.com/coms2/summary_0285-21108_ITM

[13] Materials Research Society Bulletin, July 2001, special focus on Emerging Methods of Micro- and Nanofabrication

larger material such as a silicon wafer is processed by removing matter until only the nanoscale features remain. Unfortunately, these techniques require the use of lithography, which requires a mask that selectively protects portions of the wafer from light. The distance from the mask to the wafer, and the size of the slit define the minimum feature size possible for a given frequency of light, e.g. extreme ultraviolet light yields feature sizes of 90 nm across, but this scale is near the fundamental limit of lithography. Nonetheless lithography can be used for patterning substrates used to produce nanomaterials, e.g. guiding the growth of quantum dots and nanowires.

The ”bottom-up” approach starts with constituent materials (often gases or liquids) and uses chemical, electrical, or physical forces to build a nanomaterial atom-by-atom or molecule-by-molecule[14]. The simplest bottom up synthesis route is electroplating to create a material layer-by-layer, atom-by-atom. By inducing an electric field with an applied voltage, charged particles are attracted to the surface of a substrate where bonding will occur. Most nanostructured metals with high hardness values are created with this approach.

Chemical vapour deposition (CVD) uses a mix of volatile gases and takes advantage of thermodynamic principles to have the source material migrate to the substrate and then bond to the surface. This is the one proven method for creating nanowires and carbon nanotubes, and is a method of choice for creating quantum dots.

Molecular self-assembly promises to be a revolutionary new way of creating materials from the bottom up. One way to achieve self-assembly is to use attractive forces like static electricity, Van der Waals forces, and a variety of other short-range forces to orient constituent molecules in a regular array. This has proven very effective in creating large grids of quantum dots.

The bottom up approach promises an unheard-of level of customisability in materials synthesis, but controlling the process is not easy and can only produce simple structures, in time-consuming processes with extremely low yields. It is not yet possible to produce integrated devices from the bottom up, and any overall order aside from repeating grids cannot be done without some sort of top-down influence like lithographic patterning. Nanotechnology synthesis is thus mainly academic, with only a few companies in the world that can claim to be nanotechnology manufacturers. And until understanding of synthesis is complete, it will be impossible to reach a point of mass production.

2.4. Present and future areas of application

What is nanotechnology already used for[15]?

Nanoscale materials, as mentioned above, have been used for many decades in several applications, are already present in a wide range of products, including mass-market consumer products. Among the most well-known are a glass for windows which is coated with titanium oxide nanoparticles that react to sunlight to break down dirt. When water hits the glass, it spreads evenly over the surface, instead of forming droplets, and runs off rapidly, taking the dirt with it.

Nanotechnologies are used by the car industry to reinforce certain properties of car bumpers and to improve the adhesive properties of paints. Other uses of nanotechnologies in consumer products include:

Sunglasses using protective and antireflective ultrathin polymer coatings. Nanotechnology also offers scratch-resistant coatings based on nanocomposites that are transparent, ultra-thin, simple to care for, well-suited for daily use and reasonably priced.

Textiles can incorporate nanotechnology to make practical improvements to such properties as windproofing and waterproofing, preventing wrinkling or staining, and guarding against electrostatic discharges. The windproof and waterproof properties of one ski jacket, for example, are obtained not by a surface coating of the jacket but by the use of nanofibers. Given that low-cost countries are capturing an ever-increasing share of clothes manufacturing, high-cost regions are likely to focus on high-tech clothes with the additional benefits for users that nanotech can help implement. Future projects include clothes with additional electronic functionalities, so-called ”smart clothes” or ”wearable electronics”. These could include sensors to monitor body functions or release

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[14] A layperson’s guide to fabrication techniques can be found here, in the section called ”Synthesis” http://www.ringsurf.com/info/Technology_/Nanotechnology/

[15] ”Current Consumer Products using Nanotechnology” http://www.azonano.com/details.asp?ArticleID=1001

drugs in the required amounts, self-repairing mechanisms or access to the Internet.

Sports equipment manufacturers are also turning to nanotech. A high-performance ski wax, which produces a hard and fast-gliding surface, is already in use. The ultra-thin coating lasts longer than conventional waxing systems. Tennis rackets with carbon nanotubes have increased torsion and flex resistance. The rackets are more rigid than current carbon rackets and pack more power. Long-lasting tennis-balls are made by coating the inner core with clay polymer nanocomposites and have twice the lifetime of conventional balls.

Sunscreens and cosmetics based on nanotech are already widely used. Customers like products that are translucent because they suggest purity and cleanliness, and L'Oréal discovered that when lotions are ground down to 50 or 60 nms, they let light through. For sunscreens, mineral nanoparticles such as titanium dioxide offer several advantages. Traditional chemical UV protection suffers from its poor long-term stability. Titanium dioxide nanoparticles have a comparable UV protection property as the bulk material, but lose the cosmetically undesirable whitening as the particle size is decreased. For anti-wrinkle creams, a polymer capsule is used to transport active agents like vitamins.

Televisions using carbon nanotubes could be in use by late 2006 according to Samsung[16]. Manufacturers expect these "field effect displays," (FED) to consume less energy than plasma or liquid crystal display (LCD) sets and combine the thinness of LCD and the image quality of traditional cathode ray tubes (CRT). The electrons in an FED are fired through a vacuum at a layer of phosphorescent glass covered with pixels. But unlike CRT, the electron source, the carbon, is only 1 to 2 mm from the target glass instead of 60cm with CRT, and, instead of one electron source, the electron gun, there are thousands. FED contain less electronics than LCD and can be produced in a wide range of sizes. Toshiba, for example, will offer screen sizes of at least 50 inches, around 130 cm.

What applications are foreseen in the medium term[17]?

The following list gives a quick overview of the many domains where nanotechnology is expected to fundamentally change products and how they are produced over the next two decades. Some of these uses will be examined in more detail in the section entitled "Sectoral examples".

Electronics and communications: recording using nanolayers and dots, flat-panel displays, wireless technology, new devices and processes across the entire range of communication and information technologies, factors of thousands to millions improvements in both data storage capacity and processing speeds and at lower cost and improved power efficiency compared to present electronic circuits

Chemicals and materials: catalysts that increase the energy efficiency of chemical plants and improve the combustion efficiency (thus lowering pollution emission) of motor vehicles, super-hard and tough (i.e., not brittle) drill bits and cutting tools, "smart" magnetic fluids for vacuum seals and lubricants

Pharmaceuticals, healthcare, and life sciences: nanostructured drugs, gene and drug delivery systems targeted to specific sites in the body, bio-compatible replacements for body parts and fluids, self-diagnostics for use in the home, sensors for labs-on-a-chip, material for bone and tissue regeneration

Manufacturing: precision engineering based on new generations of microscopes and measuring techniques, new processes and tools to manipulate matter at an atomic level, nanopowders that are sintered into bulk materials with special properties that may include sensors to detect incipient failures and actuators to repair problems, chemical-mechanical polishing with nanoparticles, self-assembling of structures from molecules, bio-inspired materials and biostructures

Energy technologies: new types of batteries, artificial photosynthesis for clean energy, quantum well

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[16] Michael Kanellos, "Carbon TVs to edge out liquid crystal, plasma?" ZDNET News, January 56th, 2005 http://news.zdnet.com/2100-9596_22-5512225.html

[17] « Nanosciences et nanotechnologies » Ministère délégué, recherches et nouvelles technologies, Paris, 2003. English site here : English site here: http://www.nanomicro.recherche.gouv.fr/uk_index.html

solar cells, safe storage of hydrogen for use as a clean fuel, energy savings from using lighter materials and smaller circuits

Space exploration: lightweight space vehicles, economic energy generation and management, ultra-small and capable robotic systems

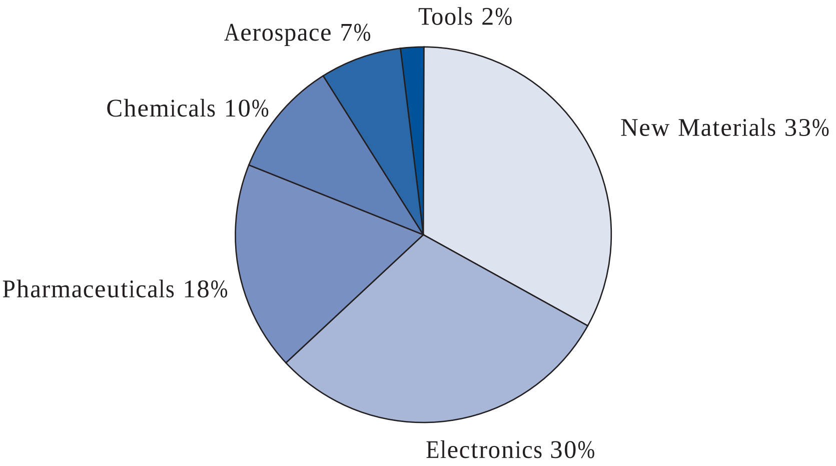
Environment: selective membranes that can filter contaminants or even salt from water, nanostructured traps for removing pollutants from industrial effluents, characterisation of the effects of nanostructures in the environment, maintenance of industrial sustainability by significant reductions in materials and energy use, reduced sources of pollution, increased opportunities for recycling

National security: detectors and detoxifiers of chemical and biological agents, dramatically more capable electronic circuits, hard nanostructured coatings and materials, camouflage materials, light and self-repairing textiles, blood replacement, miniaturised surveillance systems.

3. Market prospects and opportunities

As an OECD survey emphasises[18], most statistical offices do not collect data on nanotechnology R&D, human resources or industrial development, in part because nanotechnology remains a relatively new field of science and technology (and even more so of government policy) and also because of its interdisciplinary and cross-sectoral character. Given this, estimates of potential nanotech markets tend to come from private sources such as specialised consultancy firms who survey a wide number of actors in the field. Lux Research, for example, states that: ”Sales of products incorporating emerging nanotechnology will rise from less than 0.1% of global manufacturing output today to 15% in 2014, totalling $2.6 trillion. This value will approach the size of the information technology and telecom industries combined and will be 10 times larger than biotechnology revenues”[19]. Insurers SwissRe echo this: ”Sales revenues from products manufactured using nanotechnology have already reached eleven-digit figures and are projected to generate twelve-digit sums by 2010, even thirteen-digit sums by 2015”[20]. The chart below shows a projection for the US economy from the National Science Foundation.

Projected contribution of nanotechnology to the US economy, 2015



Source: US National Science Foundation, 2003[21]

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[18] OECD, Working Party on Innovation and Technology Policy ”Results of OECD Mini-Survey on Nanotechnology R&D Programmes” 7-8 June 2004

[19] Lux Research, October 25, 2004: ”Revenue from nanotechnology-enabled products to equal IT and telecom by 2014, exceed biotech by 10 times.” http://www.luxresearchinc.com/press/RELEASE_SizingReport.pdf

[20] Swiss Re, 2004 ”Nanotechnology : Small matter, many unknowns” http://www.swissre.com/INTERNET/pwswpspr.nsf/fmBookMarkFrameSet?ReadForm&BM=../vwAllbyIDKeyLu/yhan-5yucvt?OpenDocument

[21] OECD Information Technology Outlook 2004, ch. 7, page 264, from M.C. Roco "The Future of National Nanotechnology Initiative" NSF, November 7, 2003

These estimates should be treated with caution, because, as their authors point out, they refer to products ”incorporating nanotechnology” or ”manufactured using nanotechnology”, not to nanotechnology products as such. (It’s as if the value textile industry were calculated by including everything ”incorporating” textiles, be it clothes, aircraft or automobiles.) Lux actually evaluates sales of basic nanomaterials like carbon nanotubes at $13 billion in 2014, a considerable sum, but far from $2.6 trillion. Although the accountancy may be contested, the projected three-phase growth path seems credible:

1. In the present phase, nanotechnology is incorporated selectively into high-end products, especially in automotive and aerospace applications.
2. Through 2009, commercial breakthroughs unlock markets for nanotechnology innovations. Electronics and IT applications dominate as microprocessors and memory chips built using new nanoscale processes come to market.
3. From 2010 onwards, nanotechnology becomes commonplace in manufactured goods. Health- care and life sciences applications finally become significant as nano-enabled pharmaceuticals and medical devices emerge from lengthy human trials.

Following the dotcom fiasco, potential investors are justifiably wary of treating nanotech (or anything else) as ”the next big thing”. While the excitement and hype generated by nanotech’s apostles may be reminiscent of how internet was going to change the world and make everybody rich, there are two crucial differences that counteract the likelihood of a nanobubble: nanotechnology is extremely difficult and extremely expensive, which is why it is concentrated in well-funded companies and institutes that can attract and nurture the scarce scientific and technical expertise needed to understand the problems and challenges. Moreover, the long lead times involved in moving from concept to commercialisation make nanotech particularly unsuitable for making money fast.

3.1. Sectoral example: Medicine[22]

Medical and life-cience applications may prove to be the most lucrative markets for nanotechnologies, with ”lab-on-a-chip” devices already being manufactured and animal testing and early clinical trials starting on nanotechniques for drug delivery. However, the long product approval processes typical of the domain may mean that the health benefits to users and economic benefits to companies will take longer to realise than in other domains. Nanotech’s promise comes from the fact that nanoscale devices are a hundred to ten thousand times smaller than human cells and are similar in size to large biological molecules ("biomolecules") such as enzymes and receptors. For example, haemoglobin, the molecule that carries oxygen in red blood cells, is approximately 5 nm in diameter, DNA 2.5, while a quantum dot is about the same size as a small protein (<10 nm) and some viruses measure less than 100 nm. Devices smaller than 50 nm can easily enter most cells, while those smaller than 20 nm can move out of blood vessels as they circulate through the body.

Because of their small size, nanoscale devices can readily interact with biomolecules on both the surface of cells and inside of cells. By gaining access to so many areas of the body, they have the potential to detect disease and deliver treatment in new ways. Nanotechnology offers the opportunity to study and interact with cells at the molecular and cellular scales in real time, and during the earliest stages of the development of a disease. And since nanocomponents can be made to share some of the same properties as natural nanoscale structures, it is hoped to develop artificial nanostructures that sense and repair damage to the organism, just as naturally-occurring biological nanostructures such as white blood cells do.

Cancer research illustrates many of the medical potentials of nanotechnologies in the longer term. It is hoped that nanoscale devices and processes will help to develop[23]:

- Imaging agents and diagnostics that will allow clinicians to detect cancer in its earliest stages,
- Systems that will provide real-time assessments of therapeutic and surgical efficacy for accelerating

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[22] Medicine Canadian Institute of Neurosciences, Mental Health and Addiction ”Nanomedicine Taxonomy”, February 2003
http://www.regenerativemedicine.ca/nanomed/Nanomedicine%20Taxonomy%20(Feb%202003).PDF

[23] US Dept. of Health and Human Services: ”Going Small for Big Advances Using Nanotechnology to Advance Cancer Diagnosis, Prevention and Treatment” January 2004
http://nano.cancer.gov/resource_brochure_cancer_nanotechnology.pdf

clinical translation,

- Multifunctional, targeted devices capable of bypassing biological barriers to deliver multiple therapeutic agents directly to cancer cells and those tissues in the microenvironment that play a critical role in the growth and metastasis of cancer,
- Agents that can monitor predictive molecular changes and prevent precancerous cells from becoming malignant,
- Novel methods to manage the symptoms of cancer that adversely impact quality of life,
- Research tools that will enable rapid identification of new targets for clinical development and predict drug resistance.

Drug delivery

This may be the most profitable application of nanotechnology in medicine, and even generally, over the next two decades. Drugs need to be protected during their transit through the body to the target, to maintain their biological and chemicals properties or to stop them damaging the parts of the body they travel through. Once a drug arrives at its destination, it needs to be released at an appropriate rate for it to be effective. This process is called encapsulation, and nanotechnology can improve both the diffusion and degradation characteristics of the encapsulation material, allowing the drug to travel efficiently to the target and be released in an optimal way. Nanoparticle encapsulation is also being investigated for the treatment of neurological disorders to deliver therapeutic molecules directly to the central nervous system beyond the blood-brain barrier, and to the eye beyond the blood-retina barrier. Applications could include Parkinson’s, Huntington’s chorea, Alzheimer’s, ALS and diseases of the eye.

Repair and replacement

Damaged tissues and organs are often replaced by artificial substitutes, and nanotechnology offers a range of new biocompatible coatings for the implants that improves their adhesion, durability and lifespan. New types of nanomaterials are being evaluated as implant coatings to improve interface properties. For example, nanopolymers can be used to coat devices in contact with blood (e.g. artificial hearts, catheters) to disperse clots or prevent their formation. Nanomaterials and nanotechnology fabrication techniques are being investigated as tissue regeneration scaffolds. The ultimate goal is to grow large complex organs. Examples include nanoscale polymers moulded into heart valves, and polymer nanocomposites for bone scaffolds. Commercially viable solutions are thought to be 5 to 10 years away, given the scientific challenges related to a better understanding of molecular / cell biology and fabrication methods for producing large three-dimensional scaffolds.

Nanostructures are promising for temporary implants, e.g. that biodegrade and do not have to be removed in a subsequent operation. Research is also being done on a flexible nanofiber membrane mesh that can be applied to heart tissue in open-heart surgery. The mesh can be infused with antibiotics, painkillers and medicines in small quantities and directly applied to internal tissues.

Subcutaneous chips are already being developed to continuously monitor key body parameters including pulse, temperature and blood glucose. Another application uses optical microsensors implanted into subdermal or deep tissue to monitor tissue circulation after surgery, while a third type of sensor uses MEMS (microelectromechanical system) devices and accelerometers to measure strain, acceleration, angular rate and related parameters for monitoring and treating paralysed limbs, and to improve the design of artificial limbs. Implantable sensors can also work with devices that administer treatment automatically if required, e.g. fluid injection systems to dispense drugs. Initial applications may include chemotherapy that directly targets tumors in the colon and are programmed to dispense precise amounts of medication at convenient times, such as after a patient has fallen asleep. Sensors that monitor the heart’s activity level can also work with an implantable defibrillator to regulate heartbeats.

Hearing and vision

Nano and related micro technologies are being used to develop a new generation of smaller and potentially more powerful devices to restore lost vision and hearing. One approach uses a miniature video camera attached to a blind person’s glasses to capture visual signals processed by a microcomputer worn on the belt and transmitted to an array of electrodes placed in the eye. Another approach uses of a subretinal implant designed to replace photoreceptors in the retina. The implant uses a microelectrode array powered by up to 3500 microscopic solar cells.

For hearing, an implanted transducer is pressure-fitted onto a bone in the inner ear, causing the bones to vibrate and move the fluid in the inner ear, which stimulates the auditory nerve. An array at the tip of the device uses up to 128 electrodes, five times higher than current devices, to simulate a fuller range of sounds. The implant is connected to a small microprocessor and a microphone in a wearable device that clips behind the ear. This captures and translates sounds into electric pulses transmitted by wire through a tiny hole made in the middle ear.

3.2. Sectoral example: Food and agriculture

Nanotechnology is rapidly converging with biotech and information technology to radically change food and agricultural systems. Over the next two decades, the impacts of nano-scale convergence on farmers and food could even exceed that of farm mechanisation or of the Green Revolution according to some sources such as the ETC group[24]. Food and nutrition products containing nano-scale additives are already commercially available. Likewise, a number of pesticides formulated at the nano-scale are on the market and have been released in the environment. According to Helmut Kaiser Consultancy, some 200 transnational food companies are currently investing in nanotech and are on their way to commercialising products[25]. The US leads, followed by Japan and China. HKC expects the nanofood market to surge from $2.6 billion in 2003 to $7.0 billion in 2006 and to $20.4 billion in 2010.

Companies not associated with food production in the public mind are already supplying nano-enabled ingredients to the industry. BASF, for example, exploits the fact that many vitamins and other substances such as carotinoids are insoluble in water, but can easily be mixed with cold water when formulated as nanoparticles. Many lemonades and fruit juices contain these specially formulated additives, which can also be used to provide an ”attractive” color[26].

Expected breakthroughs in crop DNA decoding and analysis could enable agrifirms to predict, control and improve agricultural production. And with technology for manipulating the molecules and atoms of food, the food industry would have a powerful method to design food with much greater capability and precision, lower costs and improved sustainability. The combination of DNA and nanotechnology research could also generate new nutrition delivery systems, to bring active agents more precisely and efficiently to the desired parts of the human body.

Nanotechnology will not only change how every step of the food chain operates but also who is involved. At stake is the world’s $3 trillion food retail market, agricultural export markets valued at $544 billion, the livelihoods of farmers and the well-being of the rest of us. Converging technologies could reinvigorate the battered agrochemical and agbiotech industries, possibly igniting a still more intense debate – this time over "atomically-modified" foods.

The most cited nano-agricultural developments are:

Nanoseeds: In Thailand, scientists at Chiang Mai University's nuclear physics laboratory have rearranged the DNA of rice by drilling a nano-sized hole through the rice cell's wall and membrane and inserting a nitrogen atom. So far, they've been able to change the colour of the grain, from purple to green.

Nanoparticle pesticides: Monsanto, Syngenta and BASF are developing pesticides enclosed in nanocapsules or made up of nanoparticles. The pesticides can be more easily taken up by plants if they're in nanoparticle form; they can also be programmed to be ”time-released.”

Nanofeed for Chickens: With funding from the US Department of Agriculture (USDA), Clemson University researchers are feeding bioactive polystyrene nanoparticles that bind with bacteria to chickens as an alternative to chemical antibiotics in industrial chicken production.

Nano Ponds: One of the USA’s biggest farmed fish

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[24] ETC Group ”Down on the Farm: The Impact of Nano-scale Technologies on Food and Agriculture” November 2004 2004 http://www.etcgroup.org/documents/ETC_DOTFarm2004.pdf

[25] HKC ”Nanotechnology in Food and Food Processing Industry Worldwide 2003-2006-2010-2015” 2003 . http://www.hkc22.com/nanofood.html. [The subsequent projections for the world nanofood market may well prove to be underestimates, given the future purchasing power of senior citizens in developed economies and a world-wide functional food market of already $70 billion.]

[26] BASF ”Improved products, more efficient processes, and new properties” http://www.corporate.basf.com/en/innovationen/felder/nanotechnologie/nanotech.htm?printview=on&docid=22321&id=V00-6iy3A6dubbcp-S3

companies, Clear Spring Trout, is adding nanoparticle vaccines to trout ponds, where they are taken up by fish.

”Little Brother”: The USDA is pursuing a project to cover farmers’ fields and herds with small wireless sensors to replace farm labour and expertise with a ubiquitous surveillance system.

Nano foods: Kraft, Nestlé, Unilever and others are employing nanotech to change the structure of food – creating ”interactive” drinks containing nanocapsules that can change colour and flavour (Kraft) and spreads and ice creams with nanoparticle emulsions (Unilever, Nestlé) to improve texture. Others are inventing small nanocapsules that will smuggle nutrients and flavours into the body (what one company calls ”nanoceuticals”).

Nano packaging: BASF, Kraft and others are developing new nanomaterials that extend food shelf life and signal when a food spoils by changing colour.

Food safety: Scientists from the University of Wisconsin have successfully used single bacterial cells to make tiny bio-electronic circuits, which could in the future be used to detect bacteria, toxins and proteins[27].

Nanosensors can work through a variety of methods such as by the use of nanoparticles tailor-made to fluoresce different colors or made from magnetic materials can selectively attach themselves to food pathogens. Handheld sensors employing either infrared light or magnetic materials could then note the presence of even minuscule traces of harmful pathogens. The advantage of such a system is that literally hundreds and potentially thousands of nanoparticles can be placed on a single nanosensor to rapidly, accurately and affordably detect the presence of any number of different bacteria and pathogens. A second advantage of nanosensors is that given their small size they can gain access into the tiny crevices where the pathogens often hide, and nanotechnology may reduce the time it takes to detect the presence of microbial pathogens from two to seven days down to a few hours and, ultimately, minutes or even seconds[28].

3.3. Sectoral example: Semiconductors and computing

The computer industry is already working on a nanoscale. Although the current production range is at 90 nm, 5 nm gates have been proven in labs, although they cannot be manufactured yet. By 2010, world-wide, about $300 billion worth of semiconductor production will be nanotechnology-based (including nanocomponents such as nanolayers, nanoscale treated materials, or other nanostructures) and by 2015, about $500 billion. Because nanotechnology can reduce its basic features, CMOS will continue being used for a decade or more. The intermediate future will have CMOS married to a generation of nanodevices as yet undefined, because there are many alternatives, and it is still too early to tell which will prevail. One solution could be hybrid structures exploiting the advantages of today’s CMOS technology (integration and scaling of transistors and high functionality on a small support) with off-chip optoelectronic interconnects to overcome the throughput bottlenecks[29].

Towards 2015, semiconductor development priorities will change, as the focus shifts from scaling and speed to system architecture and integration, with user-specific applications for bio-nanodevices, the food industry and construction applications. Another trend is the convergence between IT, nanotechnology, biotechnology and cognitive sciences. The higher speeds at which information will be disseminated will change how we work with computers, and also perhaps how we deal with things like damaged nerves, possibly by developing direct interfaces with the nervous system and electronic circuits, so-called neuromorphic engineering, where signals are directly transmitted from a human organism to a machine.

The actual technologies employed are hard to predict. Currently there exist at least four interrelated technical barriers to nanoscale manufacturing:
How to control the assembly of 3-D heterogeneous systems, including alignment, registration and interconnection at 3-D and with multiple functionalities.

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[27] Robert J. Hamers et al. ”Manipulation and Real-Time Electrical Detection of Individual Bacterial Cells at Electrode Junctions: A Model for Assembly of Nanoscale Biosystems” Nano Letters April 2005. First presented at American Chemical Society, March 2005
http://pubs.acs.org/journals/nalefd/

[28] Manuel Marquez ”Nanotechnology to play important and prominent role in food safety” Advantage Magazine, February 2004
http://www.azonano.com/details.asp?ArticleID=858

[29] Alexander E. Braun ”Nanotechnology : genesis of semiconductors future” Semiconductor International, November 2004
http://www.reed-electronics.com/semiconductor/article/CA476295?pubdate=11%2F1%2F2004

How to handle and process nanoscale structures in a high-rate / high-volume manner without compromising beneficial nanoscale properties.
How to test nanocomponents' long-term reliability, and detect, remove or prevent defects and contamination.
Metrology. At present, using an electron microscope, it is possible to get depth of field, sufficient resolution or low energy (important so as not to damage certain components), but not all three at once. Failure analysis is another metrology issue: how to get a real 3-D view of the structure and defects that may develop during processing or use.

At present, technology front runners include spin electronics, molecular electronics (see below), biocomponents, quantum computing, DNA computing, etc. However, the history of technology teaches that sudden upsets that could change everything are to be expected. As recently as 1998, limited use was predicted for giant magnetoresistance introduced by IBM. But within two years it replaced all equivalent hard disk reading technologies and their extensive production facilities. The technique exploits the electron's spin to produce novel interconnect and device structures, giving rise to the name "spintronics"[30]. Spin is present in all electrons, and manipulating spin would use conventional solid-state semiconductor and metal materials, without the problems associated with nanotubes or molecules. Spin packets have a long lifetime and high mobility in semiconductors, making them attractive for transmitting information in the chip, within the silicon, without using a metal. One major problem with spintronics is that when a magnet heats up, it ceases being ferromagnetic, a condition necessary to exploit the electron spin. It is also difficult to control the ferromagnetic force or direction.

Assuming these problems can be solved, promising applications for spintronics include MRAM (magnetic random access memory), a high-speed non-volatile memory architecture; and logic devices like the spin field effect transistor (spin FET), which consumes less power and operates faster than its conventional counterpart.

Chip makers are already working at around 100 nm, but this is essentially a ”shrinking” of conventional technologies to make them smaller, and this is now reaching its limits. Miniaturisation to much smaller scales will run into problems caused by quantum phenomena, such as electrons tunnelling through the barriers between wires, so an alternative to transistor technology must be found, one whose components will exploit quantum effects rather suffer from them. The first generation of nanocomputers will have components that behave according to quantum mechanics, but their algorithms will probably not involve quantum mechanics. If quantum mechanics could be used in the algorithms as well, the computer would be enormously more powerful than any classical scheme, but such developments are unlikely in the foreseeable future[31].

In the meantime, research is in progress to manipulate molecules to carry out calculations. In "chemical computing", a series of chemical reactions, e.g. of DNA, corresponds to a computation, with the final products of the reactions representing the answer. With this technique, many calculations can be carried out in parallel, but each step requires a long time, and can be very expensive because of the cost of the chemicals used.

A second approach is to use molecules as the ”host” for nuclear spins that form the quantum bits (qubits) in a nuclear magnetic resonance-based computer. However, this approach may not be able to scale up to a computationally useful number of qubits.

The most promising approach is thought to be molecular electronics, using a molecule or group of molecules in a circuit. Bit densities for molecular logic and memory components could be on the order of a terabit / cm^2 (6.5 terabits / in2). Switching speeds could get down into the range of a few picoseconds (1000 times faster than current DRAM)[32].

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[30] Albert Fert et al ”The new era of spintronics” Europhysics News (2003) Vol. 34 No. 6 http://www.europhysicsnews.com/full/24/article9/article9.html

[31] Simon Benjamin and Artur Ekart ”Towards Quantum Information Technology” CambridgeCentre for Quantum Computation, 2002 2002 http://cam.qubit.org/articles/intros/nano/nano.php

[32] Cientifica ”Molecular electronics” October 2003 http://nanotechweb.org/dl/wp/molecular_electronics_WP.pdf

3.4. Sectoral example: Textiles

The textile industry could be affected quite significantly by nanotechnology, with some estimates talking of a market impact of hundreds of billions of dollars over the next decade. Nanoscience has already produced stain- and wrinkle-resistant clothing, and future developments will focus on upgrading existing functions and performances of textile materials; and developing ”smart” textiles with unprecedented functions such as:

- sensors and information acquisition and transfer,
- multiple and sophisticated protection and detection,
- health-care and wound-healing functions,
- self-cleaning and repair functions.

This last function illustrates how nanotechnology could impact areas outside its immediate application.

US company Nano-Tex is already marketing its NanoCare stain- and wrinkle-resistant technology, and NanoFresh (to freshen sports clothing) is expected soon. Scientists at the Hong Kong Polytechnic University have built a nano layer of particles of titanium dioxide, a substance that reacts with sunlight to break down dirt and other organic material. This layer can be coated on cotton to keep the fabric clean. Clothes simply need to be exposed to natural or ultraviolet light for the cleaning process to begin. Once triggered by sunlight, clothing made out of the fabric will be able to rid itself of dirt, pollutants and micro-organisms. The whole laundry industry would be affected if the technology proves to be economically viable.

Research involving nanotechnology to improve performances or to create new functions is most advanced in nanostructured composite fibers employing nanosize fillers such as nanoparticles (clay, metal oxides, carbon black), graphite nanofibers (GNF) and carbon nanotubes (CNT). The main function of nanosize fillers is to increase mechanical strength and improve physical properties such as conductivity and antistatic behaviours. Being evenly distributed in polymer matrices, nanoparticles can carry load and increase the toughness and abrasion resistance; nanofibers can transfer stress away from polymer matrices and enhance tensile strength of composite fibers. Additional physical and chemical performances imparted to composite fibers vary with specific properties of the nanofillers used. Although some of the filler particles such as clay, metal oxides, and carbon black have previously been used as microfillers in composite materials for decades, reducing their size into nanometer range have resulted in higher performances and generated new market interest.

Carbon Nanofibers and Carbon Nanoparticles

Carbon nanofibers and carbon black nanoparticles are among the most commonly used nanosize filling materials. Carbon nanofibers can effectively increase the tensile strength of composite fibers due to their high aspect ratio, while carbon black nanoparticles can improve abrasion resistance and toughness. Both have high chemical resistance and electric conductivity.

Clay Nanoparticles

Clay nanoparticles or nanoflakes possess electrical, heat and chemical resistance and an ability to block UV light. Composite fibers reinforced with clay nanoparticles exhibit flame retardant, anti-UV and anti-corrosive behaviours.

Metal Oxide Nanoparticles

Certain metal oxide nanoparticles possess photocatalytic ability, electrical conductivity, UV absorption and photo-oxidising capacity against chemical and biological species. Research involving these nanoparticles focuses on antimicrobial, self-decontaminating and UV blocking functions for both military protection gear and civilian health products.

Carbon Nanotubes

Potential applications of CNTs include conductive and high-strength composite fibers, energy storage and energy conversion devices, sensors, and field emission displays. One CNT fiber already exhibits twice the stiffness and strength, and 20 times the toughness of steel wire of the same weight and length. Moreover, toughness can be four times higher than that of spider silk and 17 times greater than Kevlar fibers used in bullet-proof vests, suggesting applications in safety harnesses, explosion-proof blankets, and electromagnetic shielding.

Nanotechnology in Textile Finishing

Nanoscale emulsification, through which finishes can be applied to textile material in a more thorough, even and precise manner provide an unprecedented level of textile performance regarding stain-resistant, hydrophilic, anti-static, wrinkle resistant and shrink-proof properties.

Nanosize metal oxide and ceramic particles have a larger surface area and hence higher efficiency than larger size particles, are transparent, and do not blur the color and brightness of the textile substrates. Fabric treated with nanoparticles $Ti0_2$ and MgO replaces fabrics with active carbon, previously used as chemical and biological protective materials. The photocatalytic activity of $Ti0_2$ and MgO nanoparticles can break down harmful chemicals and biological agents.

Finishing with nanoparticles can convert fabrics into sensor-based materials. If nanocrystalline piezoceramic particles are incorporated into fabrics, the finished fabric can convert exerted mechanical forces into electrical signals enabling the monitoring of bodily functions such as heart rhythm and pulse if they are worn next to skin.

Self assembled Nanolayers

In the longer-term future, self-assembled nanolayer (SAN) coating may challenge traditional textile coating. Research in this area is still in the very early stages, but the idea is to deposit a coating less than one nanometer thick on the textile, and then to vary the number of successive nanolayers to modulate the desired physical properties of the finished article.

3.5. Sectoral example: Energy

Breakthroughs in nanotechnology could provide technologies that would contribute to world-wide energy security and supply. A report published by Rice University (Texas) in February 2005 identified numerous areas in which nanotechnology could contribute to more efficient, inexpensive, and environmentally sound technologies than are readily available[33]. Although the most significant contributions may be to unglamorous applications such as better materials for exploration equipment used in the oil and gas industry or improved catalysis, nanotechnology is being proposed in numerous energy domains, including solar power; wind; clean coal; fusion reactors; new generation fission reactors; fuel cells; batteries; hydrogen production, storage and transportation; and a new electrical grid that ties all the power sources together. The main challenges where nanotechnology could contribute are:

- Lower the costs of photovoltaic solar energy tenfold,
- Achieve commercial photocatalytic reduction of CO_2 to methanol,
- Create a commercial process for direct photo-conversion of light and water to produce hydrogen,
- Lower the costs of fuel cells between tenfold and a hundredfold and create new, sturdier materials,
- Improve the efficiency and storage capacity of batteries and supercapacitors between tenfold and a hundredfold for automotive and distributed generation applications,
- Create new lightweight materials for hydrogen storage for pressure tanks, liquid hydrogen vessels, and an easily reversible hydrogen chemisorption system,
- Develop power cables, superconductors or quantum conductors made of new nanomaterials to rewire the electricity grid and enable long-distance, continental and even international electrical energy transport, also reducing or eliminating thermal sag failures, eddy current losses and resistive losses by replacing copper and aluminium wires,
- Develop thermochemical processes with catalysts to generate hydrogen from water at temperatures lower than 900C at commercial costs,
- Create superstrong, lightweight materials that can be used to improve energy efficiency in cars, planes and in space travel; the latter, if combined with nanoelectronics based robotics, possibly enabling space solar structures on the moon or in space,
- Create efficient lighting to replace incandescent and fluorescent lights,
- Develop nanomaterials and coatings that will enable deep drilling at lower costs to tap energy resources, including geothermal heat, in deep strata,
- Create CO_2 mineralization methods that can work on a vast scale without waste streams.

Solving these challenges will take many years, but commercial and public research institutes are already exploiting nanotechnology for energy applications. Bell Labs, for example, is exploring the possibility of producing a microbattery that would still work 20 years after purchase by postponing the chemical reactions that degrades traditional batteries. The battery is based on a Bell Labs discovery that liquid droplets of electrolyte will stay in a dormant state atop microscopic structures called "nanograss" until stimulated to flow, thereby triggering a reaction producing electricity[34]. Other researchers hope to

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[33] "Energy and Nanotechnology : Strategy for the Future"
http://www.rice.edu/energy/publications/docs/NanoReport.pdf

[34] "mPhase Technologies and Bell Labs Successfully Demonstrate First Battery Based on 'Nanograss'"
Lucent Technologies, September 28 2004
http://www.lucent.com/press/0904/040928.bla.html

dispense with batteries completely by developing nanotubes-based ”ultra” capacitors powerful enough to propel hybrid-electric cars. Compared with batteries, ultracapacitors can put out much more power for a given weight, can be charged in seconds rather than hours, and can function at more extreme temperatures. They're also more efficient, and they last much longer. The technology is in it earlier stages: the world-wide market was only $38 million in 2002, the most recent year for which figures are available, but researcher firm Frost & Sullivan predicts total 2007 revenues for ultracapacitors of $355 million[35].

Photovoltaics is another area where nanotech is already providing products that could have a significant impact. Three US-based solar cell start-ups (Nanosolar, Nanosys and Konarka Technologies), and corporate players including Matsushita and STMicroelectronics are striving to produce photon-harvesting materials at lower costs and in higher volumes than traditional crystalline silicon photovoltaic cells[36]. Nanosolar has developed a material of metal oxide nanowires that can be sprayed as a liquid onto a plastic substrate where it self-assembles into a photovoltaic film. A roll-to-roll process similar to high-speed printing offers a high-volume approach that does not require high temperatures or vacuum equipment. Nanosys intends its solar coatings to be sprayed onto roofing tiles. And Konarka is developing plastic sheets embedded with titanium dioxide nanocrystals coated with light-absorbing dyes. The company acquired Siemens' organic photovoltaic research activities, and Konarka's recent $18 million third round of funding included the world's first- and fifth-largest energy companies, Electricité de France and ChevronTexaco. If nanotech solar fabrics could be applied to, e.g., buildings and bridges, the energy landscape could change in important ways. Integrated into the roof of a bus or truck, they could split water via electrolysis and generate hydrogen to run a fuel cell. Losers would include current photovoltaic-cell makers and battery manufacturers who failed to react to the new challenge.

Such developments however depend on solving a number of fundamental problems at the nanoscale, but researchers are making fast progress using nanoscale design, include accelerating the kinetics of reactions through catalysis, separating the products at high temperature, and directing products to the next reaction step.

3.6. Nanotechnology and the situation of developing countries

While research and development in nanotechnology is quite limited in most developing countries, there will be increasing opportunities to import nano products and processes. It can be argued of course that nanotechnology could make the situation of developing countries worse by reducing demand for their exports, notably raw materials. Moreover, even in developing countries, few nanotech projects specifically target the needs of the poor, leading to fears of a ”nano divide” similar to the digital divide. The UN’s International Centre for Science and High Technology tackled such issues in February 2005 at a meeting entitled ”North-South dialogue on nanotechnology”[37]. The Centre argued that nanotechnology may offer important benefits to developing countries and it is not correct to assume that it is too difficult or too expensive for them. A similar theme was the subject of a report published in April 2005 by the Canadian Program on Genomics and Global Health (CPGGH) at the University of Toronto Joint Centre for Bioethics (JCB)[38]. The CPGGH asked over 60 international experts to assess the potential impacts of nanotechnologies for developing countries within the framework of the UN Millennium Development Goals. Agreed in 2000 for achievement by 2015, the UN goals are: to halve extreme poverty and hunger; achieve universal primary education; empower women and promote equality between women and men; reduce under-five mortality by two-thirds; reduce maternal mortality by three-quarters; reverse the spread of diseases, especially HIV/AIDS and malaria; ensure environmental sustainability; and create a global partnership for development.

The CPGGH study ranks the 10 nanotechnology applications most likely to have an impact in the areas of water, agriculture, nutrition, health, energy and the environment by 2015. The ranking is markedly different from similar exercises in the more advanced industrial economies, where applications in electronics and computing are generally seen as the most significant,

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[35] Frost&Sullivan ”World Ultracapacitor Markets” October 2003 http://www.frost.com/prod/servlet/research.pag

[36] ”Forbes Category killers: 5 nanotechnologies that could change the world”, September 2004 http://www.forbesinc.com/newsletters/nanotech/public/samples/Nanotech_5technologies.pdf

[37] http://www.ics.trieste.it/Nanotechnology/

[38] CPGGH ”Nanotechnology and the developing world” April 2005 http://www.utoronto.ca/jcb/home/documents/PLoS_nanotech.pdf

with pharmaceuticals and other health sectors featuring strongly. For developing countries, the experts reckon the top 10 nanotechnology applications are:

1. Energy. There was a high degree of unanimity in ranking this area number 1. Nanomaterials are being used to build a new generation of solar cells, hydrogen fuel cells and novel hydrogen storage systems that could deliver clean energy to countries still reliant on traditional, non-renewable contaminating fuels. Advances in the creation of synthetic nanomembranes embedded with proteins are capable of turning light into chemical energy. If successfully developed on an industrial scale, such technologies could help developing countries avoid recurrent shortages and price fluctuations that come with dependence on fossil fuels, as well as the environmental consequences of mining and burning oil and coal.

2. Agriculture. Researchers are developing a range of inexpensive nanotech applications to increase soil fertility and crop production, and help eliminate malnutrition – a contributor to more than half the deaths of children under five in developing countries. Nanotech materials are in development for the slow release and efficient dosage of fertilisers for plants and of nutrients and medicines for livestock. Other agricultural developments include nanosensors to monitor the health of crops and farm animals and magnetic nanoparticles to remove soil contaminants.

3. Water treatment. Nano-membranes and nano-clays are inexpensive, portable and easily cleaned systems that purify, detoxify and desalinate water more efficiently than conventional bacterial and viral filters. Researchers also have developed a method of large-scale production of carbon nano-tube filters for water quality improvement. Other water applications include systems (based on titanium dioxide and on magnetic nanoparticles) that decompose organic pollutants and remove salts and heavy metals from liquids, enabling the use of heavily contaminated and salt water for irrigation and drinking. Several of the contaminating substances retrieved could then be easily recycled.

4. Disease diagnosis and screening. Technologies include the "lab-on-a-chip", which offers all the diagnostic functions of a medical laboratory, and other biosensors based on nanotubes, wires, magnetic particles and semiconductor crystals (quantum dots). These inexpensive, hand-held diagnostic kits detect the presence of several pathogens at once and could be used for wide-range screening in small peripheral clinics. Other nanotechnology applications are in development that would greatly enhance medical imaging.

5. Drug delivery systems. Nano-capsules, dendrimers (tiny bush-like spheres made of branched polymers), and "buckyballs" (soccerball-shaped structures made of 60 carbon atoms) for slow, sustained drug release systems, characteristics valuable for countries without adequate drug storage capabilities and distribution networks. Nanotechnology could also potentially reduce transportation costs and even required dosages by improving shelf-life, thermo-stability and resistance to changes in humidity of existing medications;

6. Food processing and storage. Improved plastic film coatings for food packaging and storage may enable a wider and more efficient distribution of food products to remote areas in less industrialised countries; antimicrobial emulsions made with nano-materials for the decontamination of food equipment, packaging, or food; and nanotech-based sensors to detect and identify contamination;

7. Air pollution remediation. Nanotech-based innovations that destroy air pollutants with light; make catalytic converters more efficient, cheaper and better controlled; detect toxic materials and leaks; reduce fossil fuel emissions; and separate gases.

8. Construction. Nano-molecular structures to make asphalt and concrete more resistant to water; materials to block ultraviolet and infrared radiation; materials for cheaper and durable housing, surfaces, coatings, glues, concrete, and heat and light exclusion; and self-cleaning for windows, mirrors and toilets.

9. Health monitoring. Nano-devices are being developed to keep track of daily changes in physiological variables such as the levels of glucose, of carbon dioxide, and of cholesterol, without the need for drawing blood in a hospital setting. For example, patients suffering from diabetes would know at any given time the concentration of sugar in their blood; similarly, patients with heart diseases would be able to monitor their cholesterol levels constantly.

10. Disease vector and pest detection control. Nanoscale sensors for pest detection, and improved pesticides, insecticides, and insect repellents.

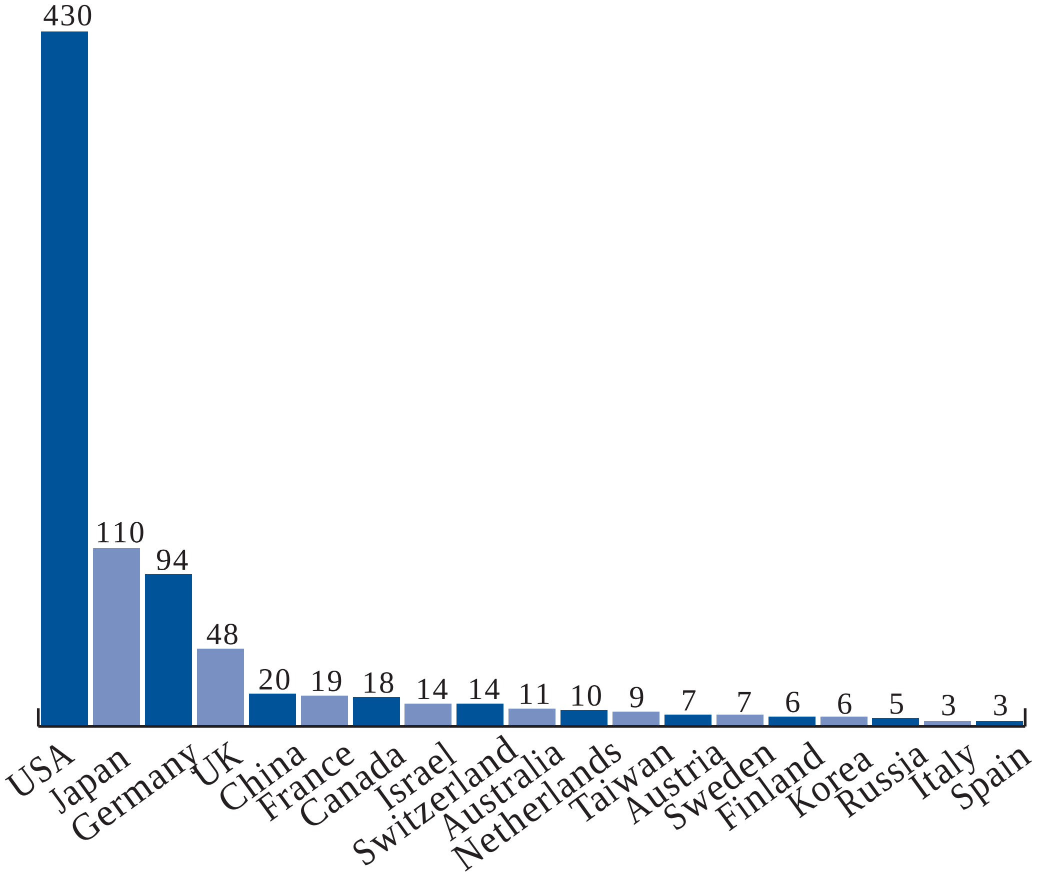
The report also recommends an initiative called Addressing Global Challenges Using Nanotechnology to encourage the development of nanotechnologies targeted at developing nations. It could work along the lines of the Grand Challenges in Global Health initiative launched in 2004 by the Foundation for the National Institutes of Health and the Bill and Melinda Gates Foundation. The authors point out that several developing countries have already launched nanotechnology initiatives. For example, India's Department of Science and Technology will invest $20 million over 2005-2009, and China ranks third in the world behind the United States and Japan in the number of nanotech patent applications. Researchers at China's Tsinghua University have begun clinical tests for a bone scaffold based on nanotechnology which gradually disintegrates as the patient's damaged skeletal tissue heals. This application is especially relevant for developing countries, where the number of skeletal injuries resulting from road traffic accidents is acute.

In Brazil, the projected budget for nanoscience over 2004-2007 is about $25 million, and three institutes, four networks, and approximately 300 scientists are working in nanotechnology. Brazilian researchers are investigating the use of modified magnetic nanoparticles to remove oil from oil spills; both the nanoparticles and the oil could potentially be recycled.

4. Players

As the table below shows, most nanotech companies are in the US, mainly because of the more developed venture capital market (over half the venture capital investors in nanotechnology are from the US). Statistics for universities and research institutes also shows a strong, but less marked, US bias.

These figures should be treated with caution, since new companies are created all the time and some do not remain active very long. Moreover, the lack of any clear nanotech strategy even in companies heavily involved in nanotechnology means that tomorrow’s winners will not necessarily be today’s heavy investors. A survey of executives responsible for nanotech at 33 companies with over $5 billion annual revenue found that they have not converged towards any particular model for organising and governing their nanotechnology initiatives. Forty-two percent of represented companies have centralised nanotechnology programs, but an equal share pursue decentralised



© Cientifica and Jaakko Pöyry Consulting 2003[39]

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[39] Cientifica: "Nanotechnology Opportunity Report, 2nd Edition Executive Summary" June 2003 (unpaginated)

activity with no co-ordination. At 45% of companies, the R&D organisation "owns" nanotech; ownership varies widely across the rest[40].

Barely half of interviewees' firms have a stated nanotech strategy today. When a strategy does exist, it is frequently a platitude like "survey the field and move quickly." Fewer than half of interviewees rate their companies' current approaches to nanotech as "very effective." Pharmaceutical companies are least likely to have an explicit nanotechnology strategy; they also invest the lowest level of people and funding compared with other sectors. (This could however change quite quickly, of course, once critical research thresholds have been crossed.) Asian companies across industries show the highest levels of staffing, funding, and executive sponsorship for nanotech.

These results are all the more surprising given the size of the companies and the sums of money involved. The median corporation had 55 people working on nanotechnology, allocated $33 million in R&D funding in 2004 to nanoscale research, and has partnerships with universities, start-ups, and public sector agencies on multiple nanotech projects. Interviewees expect double-digit increases on each front through 2006.

The roles of the different players in the nanotech sector are no different from those elsewhere[41]:

- large organisations, with the resources to investigate longer-term technologies, seek applications to improve margins, lower costs or increase market share,
- start-ups, seeking to apply technologies in order to capture market share or disrupt existing markets, attract the attention of acquisition-hungry incumbents,
- economic blocs compete for supremacy, mindful of the economic benefits that strength in many of the applications of nanotechnology will bring,
- public agencies attempt to capture the maximum number of links in the value chain.

The long-term outcome is also likely to be similar, with, as happened in microcomputing, one or two new large companies emerging and most of the other viable start-ups being absorbed by large firms. Small companies are likely to target emerging technologies, seeking new generations of products, of which four generations were identified in 2004 by Mihail Roco, Chairman of the Federal Subcommittee on Nanoscale Science Engineering and Technology which oversees the National Nanotechnology Initiative[42]. At the University of Southern California's ”Nano Ethics Conference” in March 2005, Dr Roco revised his estimates for third and fourth generations (making them five years later) and added even a fifth generation[43].

1. 2001. Passive nanostructures. This corresponds to the current state of affairs, with the creation of commercial prototypes and the acquisition of systematic control at the nanoscale for these products using nanostructure polymers, wires, coatings, etc,
2. 2005. "Active" nanostructures, i.e. devices such as actuators that behave like muscles; transistors with active parts created by design; drug delivery within the human body at specific locations and times. Such applications are already in advanced R&D, and some commercial prototypes are expected in the next year or so. Active nanostructure devices will lead to a significant market expansion,
3. 2015-20 (2010 in previous estimate). The third generation will arrive when nanodevices and nanomaterials are integrated into larger nanosystems, and systems of nanosystems with emerging behaviour will be created as commercial prototypes. This includes directed multiscale self-assembling and chemico-mechanical processing. By 2015 nanoscale designed catalysts will expand the use in ”exact” chemical manufacturing to cut and link molecular assemblies, with minimal waste,
4. 2020 (previously 2015). Fourth-generation large nanosystems whose different components will be molecules or macromolecules will emerge over 2005-2020. These will approximate how living systems work (except that living systems are more complex, being integrated on lengthier scales, generally use water, and grow slowly). In detail, this generation includes heterogeneous molecular nanosystems, where each molecule in the nanosystem has a specific structure and plays a different role. Molecules will be used as devices and from their engineered structures and architectures will emerge fundamentally new functions. Research focus will

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[40] Peter Herbert ”Corporate nanotechnology investments are at risk of being wasted” Lux Research, January 2004 http://www.luxresearchinc.com/press/RELEASE_CEOPlaybook.pdf

[41] Cientifica ”Nanotechnology opportunity report” June 2003 (no longer available online)

[42] Mihail C; Roco ”Nanoscale Science and Engineering: Unifying and Transforming Tools” AIChE Journal Vol. 50, Issue 5, published online in April 2004

[43] USC Nano Ethics Conference, 3-5 March 2005 http://nsts.nano.sc.edu/conferences.html

be on atomic manipulation for design of molecules and supramolecular systems, dynamics of single molecule, molecular machines, design of large heterogeneous molecular systems, controlled interaction between light and matter with relevance to energy conversion among others, exploiting quantum control, emerging behaviour of complex macromolecular assemblies, nanosystem biology for healthcare and agricultural systems, human-machine interface at the tissue and nervous system level, and convergence of nano-bio-info-cognitive domains. Examples are creating multifunctional molecules, catalysts for synthesis and controlling of engineered nanostructures, subcellular interventions, and biomimetics for complex system dynamics and control,

5. Starting around 2030, with nanorobotics, guided assembly, and diverging architectures.

5. Nanotechnology programs of governments

An OECD survey published in 2004 indicates that many countries have developed definitions of nanotechnology as a field of science and technology, and explicitly recognise nanotechnology as a multi- or inter-disciplinary field that draws upon work in the physical science, life sciences and engineering[44]. The survey underlines the lack of progress in developing a statistical definition of nanotechnology that can be used for collecting data on R&D expenditures, human resources, firm creation, etc. This should be borne in mind in the evaluating the usefulness of figures quoted elsewhere in this report.

The organisation of government support for nanotechnology reflects its multi-disciplinary nature, with funding for nanotechnology R&D generally channelled through a number of ministries and research councils with responsibility for different fields of application (e.g., environment, industry, health) or fields of science and technology (e.g., physics, life sciences, engineering). Some countries have begun to take steps to centralise management of their R&D programs, even if program implementation remains distributed. In most cases, co-ordination also entails development of a national strategy for nanotechnology development.

The R&D programs vary considerably in size and scope. In many countries, programs are aimed at developing world-class R&D capability in nanotechnology, recognising its importance in a number of industrial fields and in addressing a number of social needs. Japan, for example, has a range of programs aimed at basic research, nano-materials and nano-electronic devices. Canada has established the National Institute of Nanotechnology as an integrated research institute with 150 researchers from various disciplines and a business incubation facility. Denmark has established three new research centres, two of which focus on interdisciplinary approaches to nanoscience, and one of which will address nano systems engineering.

In addition to these broad-based efforts, some countries (including those mentioned above) have established more focused programs as well, linking R&D to specific national needs. For example, the Netherlands is financing three programs dealing respectively with nanotechnology, microsystems, materials science and microelectronics; electronic devices, circuits and systems; and molecular nanotechnologies. Norway is concentrating on sensors and smart materials, microtechnology, energy (e.g., improving value added from oil and gas resources), environment (e.g., improving process efficiency, recycling and reuse), and new process technology. It also has a program aimed at stimulating innovation and growth in the biomedical industry, based on the production of new materials. Poland’s R&D prioritises nanomaterials processing, nano-metals for construction and functional applications, and polymers.

Support for nanotechnology is not limited to R&D. Canada, for example, identifies a number of programs at the federal and provincial levels for major infrastructure support and training. Denmark funds education programs at a number of universities. In Japan, METI supports the Nanotechnology Business Creation Initiative, with 300 corporations, to promote business-matching. MEXT operates a Nanotechnology Support Project which makes specialised facilities available to nanotechnology researchers. Other programs to support international exchanges of young researchers, entrepreneurship, technology licensing and industrial R&D are also expected to support innovation in nanotechnology. Poland has also supported nanotechnology education programs and is creating a virtual institute to strengthen collaboration among nanotechnology researchers in Poland and with

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[44] OECD: 2004 Results of OECD mini-survey on nanotechnology R&D programmes DSTI/STI/TIP(2004)9

researchers in other countries. The UK’s Micro and Nanotechnology Manufacturing Initiative includes funding for a new network of micro and nanotechnology facilities. It is open to public and private companies, research institutes and universities.

Two other programs are worth mentioning in addition to those covered by the OECD survey. In 2003, the United States passed the 21st Century Nanotechnology Research and Development Act, authorising $3.7 billion in federal subsidies for three years beginning in 2005. This is for projects supported by the National Nanotechnology Initiative (NNI), a federal R&D program established in 2001. Government funding for the NNI itself is projected to be $886 million for 2005, roughly 3% of overall US government R&D expenditure[45].

The EU’s Sixth Research Framework Programme (FP6) includes nanotechnologies and nano-sciences, knowledge-based multifunctional materials and new production processes and devices among its priorities, with total Community support of around ¤1 billion over 2002-2006. The program’s main objectives are the development of a successful European nanotechnology industry, and the application of nanotechnologies in existing industrial sectors. Additional nanotechnology research is supported by other parts of FP6. The follow-up, FP7, calls for almost 5 billion to be spent on nanotechnology over 2007-2013[46].

6. What are the risks of Nanotechnology?

6.1. Broad range of technologies, variety of risks

Keeping in mind the broad range of applications of nanotechnologies outlined in the previous chapters and the variety of industrial sectors that are affected, it is self-evident, that the risks associated with nanotechnologies will also form a complex risk landscape rather than a homogenous set of risks. The emphasis on what kind of risks are key to consider will depend on the perspective of the particular organisation involved in nanotechnologies. To name just a few:

- business risks involved with marketing of nanotechnology enabled products,
- risks related to the protection of intellectual property,
- political risks regarding the impact on the economical development of countries and regions,
- risks regarding privacy when miniature sensors become ubiquitous,
- environmental risks from the release of nanoparticles into the environment,
- safety risks from nanoparticles for workers and consumers,
- futuristic risks like human enhancement and self replications of nano machines.

The catch-all term ”nanotechnology” is not sufficiently precise for risk governance and risk management purposes. From a risk-control point of view it will be necessary to systematically identify those critical issues, which should be looked at in more detail. This risk identification process is a task for all parties involved and it should remain a dynamic process which always takes into account new scientific, technological, societal and legal trends.

This report mainly focuses on potential risks that are relevant to property and casualty insurance, rather than try to cover the broad range of topics indicated above.

Almost all safety concerns that have been raised about nanotechnologies are related to ”free” rather than fixed engineered nanoparticles. The state of the discussion on these risks will be discussed.

The risk and safety discussion related to free nanoparticles will concern only a fraction of the applications of nanotechnologies. In most applications nanoparticles will be embedded in the final product and therefore not come into direct contact with workers, consumers or the environment. They are unlikely to raise concerns because of their immobilisation. Exceptions are possible when the products or materials within which nanoparticles are enclosed are discarded, burned or otherwise destroyed (e.g. in an accident).

Looking at the manufacturing processes involved, they are similar to conventional well-established chemical

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[45] www.nano.gov

[46] http://www.cordis.lu/nanotechnology/

and engineering processes. Building on established previous experience can be a guideline for risk assessment purposes, but the approach to health and safety issues needs to be modified to address the special characteristics of nanoparticles.

In the early phase of commercialisation most applications of nanotechnology will improve existing products, rather than generating new products. In themselves, most areas of nanotechnology are not likely to present novel safety risks. As with all new technologies new risks might appear that we have not thought about yet, underlining the need for continuous and dynamic risk reviews.

6.2. Positive effects on human health and the environment

A fair assessment of the risks of any new technology must also consider positive contributions to increased safety. The basic innovations that come from nanotechnologies have the potential to contribute to human health and environmental safety in many ways. They have the potential to contribute to solve urgent issues like the provision of clean drinking water or more efficient energy conversion and energy storage. The potential of nanotechnologies regarding economic benefits, the potential to create jobs, wealth and well being is very high. At the moment, public awareness about nanotechnology is limited. What happens over the next few years will determine how the public comes to view it. A transparent discussion of benefits and risks will help people reach a considered, balanced view. This will enable a greater public acceptance, which, in turn, will enable society as a whole to profit from these fundamental technological developments while, at the same time, the risks are kept under control.

Especially in the field of medicine there are quite a few technological developments that promise enhanced diagnostic possibilities, new ways to monitor patients, new ways to treat diseases like cancer and to reduce side effects. To give a few examples:

- Nanoparticles can be used as carriers for targeted drug delivery. Their ability to penetrate certain protective membranes in the body, such as the blood-brain barrier, can be beneficial for many drugs. This could open the way for new drugs from active substances that have not been able to pass clinical trials due to less precise delivery mechanisms,
- Nanosensors and lab-on-a-chip-technologies will foster early recognition and identification of diseases and can be used for continuous monitoring of patients with chronic diseases,
- New therapeutic methods for the treatment of cancer with the help of nanoparticles are investigated.

Ultrasensitive detection of substances will have implications for safety in many other areas such as industrial medicine, environmental medicine and food safety. To give one example: it has recently been shown that bacterial pathogens can be detected in very low concentrations with the help of nanoparticles. Quick and accurate testing is crucial for avoiding potential infections, but in order to be effective many current tests require time-consuming amplification of samples. The new methods are very powerful: new findings indicate that specially treated nanoparticles could allow to detect a single E. coli bacterium in a ground beef sample.

The potential benefits for our environment range from resource-efficient technologies reducing waste to new ways to transform and detoxify a wide variety of environmental contaminants, such as chlorinated organic solvents, organochlorine pesticides, and PCBs.

6.3. Manufactured nanoparticles

The term ”manufactured nanoparticle” is used here to refer to particles that have a physical size of less than 100 nm in at least two dimensions and that are deliberately produced rather than merely emerging as a by-product in activities not targeted for the production of these particles such as combustion processes or welding. While a more rigorous definition would have to take more parameters such as size distribution, diffusion diameter into account, the term nanoparticles shall be used in a rather broad sense here, including agglomerates and aggregates of the primary particles. Nanoparticles exist in various forms such as powders, suspensions or dispersed in a matrix.

In theory manufactured nanoparticles can be produced from nearly any chemical; however, most nanoparticles that are currently in use have been made from transition metals, silicon, carbon (carbon black, carbon nanotubes; fullerenes), and metal oxides. Quite a few of these nanoparticles have been produced for several decades on an industrial scale, but various new materials such as carbon nanotubes, fullerenes or quantum dots that have only been discovered within the last two decades. The development of nanomaterials is rapidly progressing and the variety of ”makes” is increasing with considerable speed.

The following list gives a few examples of manufactured nanoparticles that are of commercial interest[47]:

Type	Examples for use
Metal oxides	
• silica (SiO_2) • titania (TiO_2) • aluminia (AL_2O_3) • iron oxide (Fe_3O_4, Fe_3O_3) • zirconia (ZrO_2) • zinc dioxide (ZNO_2)	• Additives for polymer composites • UV-A protection • Solar cells • Pharmacy / medicine • Additives for scratch resistance coatings
Fullerenes • C_{60}	• mechanical and trbological applications / additives to grease
Carbon Nanotubes • Single-wall carbon nanotubes	• Additives for polymer composites (mechanical performance, conductivity)
• Multiwall carbon nanotubes	• Electronic field emitters • Batteries • Fuel cells
Compound Semiconductors • CdTe • GaAs	• Electronic an optical devices
Organic Nanoparticles	• Micronised drugs and chemicals (vitamins, pigments, pharmaceuticals) • Polymer dispersions
Metals • Au • Ag • Ni	• Catalytic applications • Optoelectronics • Wound dressings

To fully exploit the properties of nanoparticles technologically, not the composition is important, but also parameters like the exact size, morphology

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[47] see for example: Wolfgang Luther (ed.), Industrial applications of nanomaterials – chances and risks VDI TZ Düsseldorf 2004

(spherical, nanotubes, nanowires, nanocrystals) and surface coatings.

6.4. Nanoparticles and human health

The economic growth in the field of nanotechnologies will lead to an increased variety and increased volumes of engineered nanoparticles that are produced. Even if exposure assessments and data are still lacking it is foreseeable that some degree of exposure to engineered nanoparticles -- for various segments of the population and for the environment – will occur to an increasingly extend over the coming years.

Keeping in mind that these ”free nanoparticles” can enter the human body over various pathways (inhalation, ingestion or via the skin) or disperse into the environment, it is important to understand the implications for human health and the ecosystems.

To assess the risks of nanoparticles, established methods of chemical safety assessments have to be modified to address the special characteristics of nanoparticles[48]. The main difference to the assessment of bulk materials is the fact that additional parameters like size, shape or surface properties will come into play. The same reason that makes nanoparticles technologically interesting leads to the fact that they represent a new category of (potentially) toxic substances. The interaction with the human body and their health effects are expected be different from molecules as well as from bulk materials of the same composition.

It is necessary to understand both, the hazards associated with nanomaterials and the levels of exposure, that are likely to occur. In both areas, the existing knowledge is quite limited and it will be necessary to generate and establish new data in the future.

In the following description the current status of the discussion on hazards and exposure of nanoparticles is summarised as a basis for the subsequent discussion of potential implications for the Allianz Group.

Hazards from engineered nanoparticles

When bulk materials are made into nanoparticles, they tend to become chemically more reactive – this is why they are very interesting as catalysts. Even chemically inert materials like gold or platinum are able to catalyse chemical reactions in nano-powder form.

Many studies indicate that nanoparticles generally are more toxic when incorporated into the human body than larger particles of the same materials. Experts are overwhelmingly of the opinion that the adverse effects of nanoparticles cannot be reliably predicted or derived from the known toxicity of the bulk material[49].

The biggest concern is that free nanoparticles or nanotubes could be inhaled, absorbed through the skin or ingested.

Uptake of nanoparticles via the lung

As pointed out in a recent review article by Hoet in the Journal of Nanobiotechnology[50], most nano-sized spherical solid materials will easily enter the lungs and reach the alveoli.

Inhaled particles can have two major effects on the human body:

- Their primary toxic effect is to induce inflammation in the respiratory tract, causing tissue damage and subsequent systemic effects[51,52]. The property that drives the inflammogenicity of nanoparticles is unknown but is expected relate to particle surface area and number of particles. Nanoparticles can impair the ability of macrophages to phagocytose and clear particles, and this may contribute to inflammatory reactions,

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[48] NANOTECHNOLOGIES: A PRELIMINARY RISK ANALYSIS ON THE BASIS OF A WORKSHOP ORGANIZED IN BRUSSELS ON 1–2 MARCH 2004 BY THE HEALTH AND CONSUMER PROTECTION DIRECTORATE GENERAL OF THE EUROPEAN COMMISSION.
http://europa.eu.int/comm/health/ph_risk/events_risk_en.htm

[49] Dreher, Kevin L., Health and Environmental Impact of Nanotechnology: Toxicological Assessment of Manufactured Nanoparticles. TOXICOLOGICAL SCIENCES 2004, 77, 3–5

[50] Hoet, Peter HM., Brüske-Hohlfeld, Irene, and Salata Oleg V. Nanoparticles – known and unknown health risks, Journal of Nanobiotechnology 2004, 2:12

[51] Lam C-W. et al. Pulmonary Toxicity of Single-Wall Carbon Nanotubes in Mice 7 and 90 Days After Intratracheal Instillation. TOXICOLOGICAL SCIENCES 2004, 77, 126–134

[52] Warheit D. B. et. al., Comparative Pulmonary Toxicity Assessment of Single-wall Carbon Nanotubes in Rats. TOXICOLOGICAL SCIENCES 2004, 77, 117–125

- Transport through the blood stream to other vital organs or tissues of the body[53]. This may result in cardiovascular and other extrapulmonary effects.

Some scientists have compared nanotubes with asbestos in terms of risks, because they resemble asbestos fiber in their needle like shape. The concern is particularly applicable to fibers of high biopersistence[54]. Although the comparison seems plausible, it has been pointed out, that the nanotube fibers tend to clump together rather than exist as single fibers, thus possibly significantly reducing exposure and their potential to do harm[55].

Uptake via other routes

The scientific literature shows that particles in the nano-size range can also enter the human body via other pathways, i.e. the upper nose and the intestines.

Penetration via the skin seems less evident[56], but research to clarify this is under way[57]. The chances of penetration again depend on the size and surface properties of the particles and also strongly on the point of contact. If nanoparticles penetrate the skin they might facilitate the production of reactive molecules that could lead to cell damage. There is some evidence to show that nanoparticles of titanium dioxide (used in some sun protection products) do not penetrate the skin but it is not clear whether the same conclusion holds for individuals whose skin has been damaged by sun or by common diseases such as eczema. There is insufficient information about whether other nanoparticles used in cosmetics (such as zinc oxide) penetrate the skin and there is a need for more research into this. Much of the information relating to the safety of these ingredients has been carried out by industry and is not published in the open scientific literature.

Distribution in the body

Once in the body, the distribution of the particles in the body is strongly dependent on the nanoparticle in question, e.g. the composition, the size and of the surface characteristics of the particles. It seems that translocation occurs from all uptake routes. Such translocation is facilitated by the propensity to enter cells, to cross cell membranes and to move along axons and dendrites that connect neurons. Surface coatings will have a major effect. The mobility of different types of nanoparticles requires detailed investigations, which have not yet been performed.

To give one example: it is not clear, whether nanoparticles can pass from a pregnant woman's body via the placenta into the unborn child.

It is possible that durable, biopersistent nanoparticles may accumulate in the body, in particular in the lungs, in the brain and in the liver.

For the majority of nanoparticles the toxicological, ecotoxicological data needed to perform a hazard analysis are still lacking. Even if the details are not yet clear, it is evident that the interaction with the human body will depend on various parameters such as chemical composition, particle size, surface area, biopersistence and surface coatings among others. Therefore, until a theory of the impact of nanoparticles on human health has been established, each nanomaterial should be treated individually when health hazards are evaluated. A systematic risk screening will be helpful to establish the basic know-how to understand the interaction with the human body and the environment and to establish the theoretical framework needed.

Besides toxic effects, the interaction of nanoparticles that have entered cells opens a wide field of potential effects resulting from the interaction with cell structures such as ribosomes and DNA.

Exposure to engineered nanoparticles

Injury can be caused by chemicals only if they reach sensitive parts of a person at a sufficiently high

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[53] Nemmar et al, "Passage of inhaled particles into the blood circulation in humans", Circulation 2002;105(4):411-41

[54] Hoet, Peter HM., Health Impact of nanomaterials? Nature Biotechnology 2004, Volume 22, Number 1

[55] Maynard, A. D. Exposure to Carbon Nanotube Material: Aerosol Release During the Handling of Unrefined Single-Walled Carbon Nanotube Material. Journal of Toxicology and Environmental Health Part A Volume 67, Number 1 / January 9, 2004

[56] Pflücker F., The human stratum corneum layer: an effective barrier against dermal uptake of different forms of topically applied micronised titanium dioxide. Skin Pharmacol Appl Skin Physiol. 2001;14 Suppl 1:92-7

[57] see for example the NANODERM research project funded by the European Commission http://www.uni-leipzig.de/~nanoderm/Brochure_NANODERM_WWW.pdf

concentration and for a sufficient length of time. Besides the physicochemical properties of the nanoparticles, the nature of exposure circumstances and the health state of the persons at risk have to be considered.

Nanoparticles exist in nature (e.g. from volcanic eruptions or forest fires) or can be produced by human activities. Intentional nanoparticles are manufactured under (normally strict) control while unintentional ones can come from high temperature combustion, explosions, mechanical abrasion or other industrial processes. The main source of unintentional nanoparticles (in this context also called ultra-fine particles) is automobile traffic.

We live surrounded by nanoparticles. To provide an example: a normal room can contain 10,000 to 20,000 nanoparticles per cm^3, whilst these figures can reach 50,000 nanoparticles per cm^3 in a forest and 100,000 nanoparticles per cm^3 in urban streets.

At present, the nanoparticles originating from dedicated industrial production are marginal in relation to those produced and released unintentionally, such as through combustion processes.

However, higher levels of exposure are expected with the industrial processes in which nanoparticles are intentionally produced or used. Furthermore, as manufactured nanomaterials become more widespread in use, the range of scenarios in which exposure becomes possible will increase.

Exposure assessments for engineered nanoparticles should be able to cover all identified uses for the entire life-cycle of the individual nanoparticle. This could include:

- processes involved in the production,
- processes involved in the identified use,
- activities of workers related to the processes and the duration and frequency of their exposure,
- risk management measures to reduce or avoid exposure of humans,
- waste management measures,
- activities of consumers and the duration and frequency of their exposure.

Nanoparticles are currently being produced in low volumes and, aside from their use in cosmetics, involve as yet little or no exposure to populations outside the workplace. However, keeping in mind the predicted growth in production volumes and the expected expansion of the product range, this situation is subject to change over the next few years.

With an increasing number of companies involved in nanotechnologies, the quality of risk management encountered in practice will be ranging from highly sophisticated to poor. The level of risk management often depends on the branch of industry, but mainly on individual management practises and management attention in the companies. Accordingly, the assessment of possible exposures must take into account poor risk management practises, especially in the absence of specific regulations.

With respect to hazards, there is enough evidence to suggest that exposure to nanoparticles, particularly to those insoluble in water, should be minimised as a precaution.

Occupational hazards

The US national nanotechnology initiative has estimated that around 20,000 researchers are working in the field of nanotechnology. For the UK, the Institute of Occupational Medicine has estimated that approximately 2,000 people are employed in new nanotechnology companies and universities where they may be potentially exposed to nanoparticles[58].

The primary production of nanoparticles takes places with the help of chemical and engineering processes that are well established. These are considered by various organisations to be relatively safe, except for accidental releases via leakages. During normal production, subsequent steps like product recovery and powder handling may result in respirable concentrations of agglomerated nanoparticles, to dermal exposure or to ingestion (mainly via hand-to-mouth contact).

So far only one study has addressed the exposure of workers to engineered nanoparticles. In the study into potential airborne and dermal exposure to carbon nanotubes samples were taken during typical activities in the production process like material removal, filling, pouring and clean up (techniques: laser ablation and high pressure carbon monoxide). The study has shown that the material only becomes airborne with a sufficient

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[58] Institute of Occupational Medicine. Nanoparticles: An occupational hygiene review Research Report 274. Edinburgh 2004

level of agitation. So-called Van der Waals forces make the nanoparticles ”sticky” and imparts a strong tendency to form agglomerates. Airborne concentrations found while handling unrefined material were considered to be ”very low” (between 0.7 and 53 µg/m^3). The released material seems to form larger agglomerates in the size range of 1 µm rather than leading to a high number concentration of fine particles. Up to 6 mg of nanotubes were found on individual gloves. While the gloves can minimise dermal exposure, airborne clumps of material can lead to exposure of less well protected parts of the skin[59].

Contrary to intuition, air filtration systems such as respiratory protective equipment should be effective when used correctly. Below a particle size of 100 nm filtration efficiency for High Efficiency Particulate Arrestor (HEPA) filters even increases with decreasing particle size. The reason for this is strong Brownian motion that leads to increased probability to contact the filter elements. Once a filter element is hit, strong Van der Waals forces keep the nanoparticle stuck to the surface.

It has been inferred by the UK Institute of Occupational Medicine that the primary route of exposure for many nanoparticles could be dermal exposure and subsequent ingestion exposure.

Generally accepted, realistic methods for exposure assessments are still lacking for workplaces. These methods must be biologically relevant—that is, they should be able to measure the most appropriate metric that characterises the exposure. That can be surface area in the case of airborne particles, but also mass or number of particles in the case of dermal exposure or ingestion. Size selective sampling methods will be needed to ensure that only the relevant size range is sampled. It remains a technical challenge to develop effective methods and standards for controls. For some nanoparticles it may be necessary to measure and control to very low levels on the order of ng/m^3.

As with hazard aspects of nanoparticles, also in the area of exposure there are many unknowns today and also technical challenges lie ahead. As an intermediate state between bulk material and individual molecules the characteristics of nanoparticles add some complexity to the exposure assessment (such as surface area, agglomeration, size distributions) which can be reduced once a better understanding, better measurement methods and standards for these particles will exist. It seems that existing precautionary measures are also effective for the control of nanoparticles, however in the absence of more evidence this is difficult to demonstrate.

To quote the report of the Institute of Occupational Medicine to the UK’s Health and Safety Executive: ”In summary, we conclude that there is little evidence to suggest that the exposure of workers arising from the production of nanoparticles has been adequately assessed.”

Exposure of consumers to products

There are a number of ways in which engineered nanoparticles from products can come into direct contact with consumers during their use. In some applications these nanoparticles are active parts of the product, in some applications only an accidental exposure is possible.

Due to the fact that nanoparticles in powder form are only used as intermediate products during stages of the production process, it seems likely that the exposure from consumer products will mainly occur via ingestion and via the skin. It is unlikely that engineered nanoparticles that are bound in a matrix or somehow fixed in a product are released. Manipulations like grinding or cutting do not necessarily release nanoparticles, but rather more likely particles of larger size in which the nanoparticles are still bound.

The following table gives some examples of existing end products and end products that will be marketed in the foreseeable future, and which can lead to an exposure to certain nanoparticles:

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[59] Maynard, A. D. Exposure to Carbon Nanotube Material: Aerosol Release During the Handling of Unrefined Single-Walled Carbon Nanotube Material. Journal of Toxicology and Environmental Health Part A Volume 67, Number 1 / January 9, 2004

Application	Functionality of nanoparticle	Example
Cosmetic products	• active ingredient	• suntan lotions (transparent UV protection) • lotions • tooth paste
Medical products / devices		• wound dressings
Food products	• improved production processes • pesticide • enhanced food properties • extended shelf life • transport of nutrients and flavours into the body	• drinks • ice cream • fish • …
Automotive	• explosive	• airbag gas generators
Sports articles	• enhanced gliding	• ski wax

Whether or not there are health risks involved from particular applications will probably be subject to considerable debate in the near future. It is a challenge to create an approach to exposure assessments that is fit for such diverse applications with differing nanomaterials and different potential exposure paths. Depending on the type of product different regulatory regimes apply and have to be accounted for. Comparative risk classification schemes will have to be developed that can serve as a guideline / road map in the overall risk identification process. Generally, to demonstrate the control of the exposure a life cycle assessment will be needed.

While the overall approach will probably not differ substantially from existing product safety assessments, it will take some time until the basis to follow this path has been established and answers related to the special characteristics of nanoparticles have been found.

Open points linked with the exposure to nanoparticles include:

- which parameters characterising the particles should be measured?
- the development of efficient measurement methods for these parameters,
- testing methods for various applications and situations during use of the products,
- fate of various types of nanoparticles in the environment
- fate of the nanoparticles when a product is destroyed, burnt or discarded,
- extent of uptake in the human body.

Conclusions about the safety of engineered nanoparticles

With the production of engineered nanoparticles we are confronted with a new class of materials that have novel properties compared to bulk material. Information describing the health risk of engineered nanoparticles is only evolving and many questions are still open.

The uncertainties involved have to be seen against the background of the ever more demanding public views regarding the safety of products from new technologies and an increasing potential for exposure as the quantity and types of nanoparticles used in society grow.

From animal experiments and analogies to studies on incidentally produced ultra fine particles (such as . from burning of fuels) it is possible that at least some nanoparticles are hazardous for the human body and that the exposure to these nanoparticles should be avoided or at least minimised.

One promising path to prevent potential health hazards proposed by a number of scientists is to make the particles biodegradable. Particles that are degradable either by water or by lysis with enzymes will greatly reduce the risks involved because they do not persist in the body. It is self-evident that the slower the particles are cleared (high persistence), the higher the tissue burden can be. With a short bio-durability, long-term effects can be minimised or even excluded. Biocompatability can serve as one major engineering parameter for nanomaterials in the future.

There is a broad variety of nanoparticles being investigated and a high number of parameters that influence the functionality of these nanoparticles as well as their interaction with the human body. It is expected that it will take several years until some major critical risk assessment issues regarding hazards and exposure can be answered. Accordingly, in a workshop in January 2005, the European Commission has identified a variety of research needs related to nanoparticles. The recommendations for research include:

- ecotoxicity of nanoparticles for cases of inadvented contact by children, adults and susceptible individuals,
- biomonitoring studies of specific biological impact of nanoparticles, according to their most likely routes of exposure,
- standards development and (certified) reference materials,
- sensors for detecting nanoparticles and assessing exposure, both stationary and portable with a focus on low-cost, highly specific sensors giving a real time response to environment an health relevant properties,
- a strategic concept for a comprehensive risk assessment.

The regulatory risk assessment of chemicals will in the future be carried out under the New European Union Chemicals Policy (Registration, Evaluation and Authorisation of Chemicals). In its current state REACH will be concerned only with the safe use of bulk materials, and will not take account of size. Additionally, under REACH production mass limits are planned (limited evaluation procedure for production of less than 100 tons, no registration for production volume below 1 ton). Many nanoparticles that are produced in low volume will therefore generally not be accounted for in the REACH framework. Further examinations of this regulatory situation might be required on the basis of new scientific evidence related to manufactured nanoparticles.

It will be a challenge for industry, legislators and risk assessors to fill all relevant knowledge gaps and to construct a set of high throughput and low cost tests for nanoparticles. In that way a risk assessment of each nanoparticle should be established before the larger quantities are manufactured. This process is unlikely to be fast enough without active steering and support by governments and the EU.

The uncertainties involved – especially long term -- will have to be addressed by all organisations involved in the process of the introduction of nanotechnologies. It will be a necessary for the various industries involved to perform life-cycle assessments and demonstrate the safety aspects to a broader public. Successful communication will depend on a general feeling of trust towards nanotechnologies. This in turn needs an open dialogue and interaction involving all different stakeholders, including a high degree of transparency regarding scientific results.

6.5. Nanoparticles and the environment

As nanotechnologies move into large-scale production in many industries, it is a just a matter of time before gradual as well as accidental releases of engineered nanoparticles into the environment occur. The possible routes for an exposure of the environment range over the whole lifecycle of products and applications that contain engineered nanoparticles:

- Discharge / leakage during production / transport and storage of intermediate and finished products,
- Discharge / leakage from waste,
- Release of particles during use of the products,
- Diffusion , transport and transformation in air, soil and water.

Some applications like cosmetic products or food ingredients will be diffuse sources of nanoparticles.

In addition, certain applications such as environmental remediation with the help of nanoparticles could lead to the deliberate introduction of nanoparticles into the environment. This is an area which will probably lead to the most significant releases in terms of quantity of nanoparticles in the coming years.

The main criteria used to assess the risks of chemicals for the environment and indirectly for human health are toxicity, persistence and bioaccumulation. Substances that can cause direct damage to organisms (high toxicity), that decay very slowly in the environment (high persistence) and that can concentrate in fatty tissues (high potential for bioaccumulation) are of particular concern. For engineered nanoparticles the particular characteristics of nanomaterials will have to be taken into account for a specific risk assessment. The existing information about properties of the bulk material will not be sufficient to classify the environmental risk of the same material in the form of nanoparticles. The possible environmental effect will therefore have to be assessed specifically for each type / class of nanomaterial.

Only few studies on this very complex subject exist. From a scientific point of view, the results should be seen as indications rather than a sound basis for decision making.

In the first study on the toxic effects of manufactured nanoparticles on aquatic organisms, fish (largemouth bass) were exposed to uncoated fullerene carbon 60 (C_{60}) nanoparticles[60]. The fullerenes are one type of manufactured nanoparticle that is being produced by tons each year. Significant lipid peroxidation (oxidation of fats) was found in the brain of the animals after exposure to 0.5 ppm uncoated nC_{60}. The study demonstrates that manufactured nanomaterials can have adverse effects on aquatic and possibly other organisms.

Nanoscale iron particles have been investigated as a new generation of environmental remediation technology[61]. Due to their high surface reactivity and large surface area they can be used to transform and detoxify environmental contaminants like PCBs. Field tests in the US have shown that the nanoparticles remain reactive in soil and water for several weeks and that they can travel in groundwater as far as 20 meters. The risks associated with free nanoparticles on ecosystems was not discussed in the original publication, but should be looked at in sufficient detail before environmental applications are brought to the market. The Royal Society has called for the prohibition of the use of free nanoparticles in environmental applications until appropriate research has been undertaken.

A very specific environmental issue in the case of nanoparticles is their propensity to bind with other substances, possibly toxins in the environment such as Cadmium. Their high surface area can lead to adsorption of molecular contaminants. Colloids (natural micro- and nanoparticles) are known for their transport and holdings capacity of pollutants. The adsorbed pollutants could possibly be transported over longer distances / periods of time by nanoparticles.

On the other hand nanoparticles are less mobile than we intuitively might think. It seems that their movement is very case specific and that that are generally less mobile than larger particles. Here again their large surface area and their maximised chemical interaction comes into play. Their sticky nature considerably slows their transport through porous media like soil.

In summary, the information about nanoparticles and the environment is only at an early stage. Among the research needs, there are topics like the effect of nanoparticles on species other than humans, about how they behave in the air, water or soil, or about their ability to accumulate in food chains. Taking into account the high number of parameters that characterise nanoparticles (like size, shape, specific surface treatment, chemical composition) as well as the variety of nanoparticles, it will need considerable research efforts to close the knowledge gaps. For cost efficient and quicker results, harmonisation of research is required that focuses on the most important materials and parameters and to concentrate on nanoparticles that are more likely to be produced.

6.6. Explosion hazards of nanoparticles

For many industries, the explosion of dust clouds is a potential hazard in the production process. A dust explosion occurs when a combustible material is dispersed in the air, forming a flammable cloud which is hit by a flame. The concentrations needed for a dust explosion are rarely seen outside of process vessels, hence most severe dust explosions start within a piece of equipment (such as mills, mixers, filters, silos).

Various materials that are not stable oxides can be involved in dust explosions, e.g. natural organic materials (grain, sugar, etc); synthetic organic materials (organic pigments, pesticides, etc) coal and peat metals (aluminium, zinc, iron, etc). There is a clear dependence on size and surface area of dust particles, it does however not vary linearly with the explosibility of the powders. Dust with a particle size above 0.4 mm is normally not explosive.

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[60] Oberdorster E. Manufactured nanomaterials (fullerenes, C60) induce oxidative stress in the brain of juvenile largemouth bass. Environ Health Perspect. 2004 July; 112(10): 1058-62

[61] Zhang W-X. Nanoscale iron particles for environmental remediation: An overview. Journal of Nanoparticle Research 5: 323–332, 2003

In certain applications, the stronger reaction of smaller particles can be used to pack more explosive power in a given volume. Today, microsize aluminium particles already gets incorporated into rocket fuels and bombs. Nanoaluminium is being investigated as advanced technology in these military applications. Aluminium nanopowders could also find their way into airbag gas generators. The toxicity is being investigated and has to be compared to the properties of existing propellants and their combustion products (particles and gases).

The explosibility of nanopowders has so far not received much attention in the public debate on health and safety risks of nanotechnologies.

A review of literature available on this topic has been performed by the Health and Safety Laboratory in the United Kingdom[62].The review could not find data for nanopowders with particle sizes in the range of 1 to 100 nm. It states that the extrapolation of existing data for larger particles to the nano-size range is not possible because of the changed physical and chemical characteristics on the nano-scale.

The report recommends that the explosion characteristics of a representative range of nanopowders be determined since an increasing range of materials that are capable of producing explosive dust clouds are being produced as nanopowders. It is foreseen that the production of nanopowders is likely to increase significantly over the next few years.

The report of the Royal Society recommends that the explosion risks be managed by ensuring that large quantities of combustible nanoparticles do not become airborne until the explosion hazard has been properly evaluated. As long as nanopowders are produced in small quantities of grams, the explosion hazard will be negligible.

Besides property damage, workers safety and business continuity issues, one major concern about the explosion of nanopowders is the release of larger quantities of nanomaterial into the environment and the resultant potential pollution problem.

6.7. Self replication of miniature machines

In 1986 Eric Drexler published an influential book called ”Engines of Creation: The Coming Era of Nanotechnology,” in which he imagined the fabrication of molecular machines[62]. These machines would be able to produce any (macroscopic) item from molecular building blocks. For this plan to work, these machines would have to be able to produce machines of their own kind, a process called self replication. His most compelling argument about the feasibility of these machines is the observation that biology gives us many examples of nanoscale machines that function on this scale.

The idea that engineering a synthetic form of life with self-replicating machines has, in turn, created the fear that once designed, these nano-robots could spread across the biosphere. Drexler called this scenario the ”gray goo”.

This view has been challenged by many scientists. Most scientists have dismissed the ”gray goo” scenario as ”science fiction”. There are fundamental questions that have not been resolved so far, like the energy management, the strong surface forces on the nanoscale or Brownian motion. After all, biological systems in our environment have been optimised over billions of years of evolution and make extensive use of the particular physical characteristics that govern the nanoscale world, which we are just beginning to understand. Our knowledge even of the processes in a simple cell is limited.

It seems therefore safe to say that the construction of self-replicating nano-robots will remain beyond our capabilities for the foreseeable future. From an insurance perspective the risks associated with self-replication of machines will therefore remain futuristic and will -- in all probability -- have no relevance over the next decade.

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[62] D K Pritchard, Health and Safety Laboratory. Literature review – explosion hazards associated with nanopowders HSL/2004/12

[62] K. Eric Drexler Engines of Creation: The Coming Era of Nanotechnology, Anchor Books 1986 ISBN 0-385-19973-2

6.8. Regulatory considerations of authorities and other stakeholders

In September 2004, a paper on possible emerging safety issues of nanotechnologies was submitted to the Joint Meeting of the OECD's Chemicals Committee and Working Party on Chemicals, Pesticides and Biotechnology[65]. The paper points out that nanotechnology exploits properties not generally seen in large-scale solids of the same chemical composition, and that these same properties have led to health and safety concerns. For example, the high surface reactivity of nanoparticles and the ability to cross cell membranes might have negative human health impacts. On the other hand, not all nanoparticles, and not all uses of nanotechnology, will necessarily lead to new human health or environmental hazards. A distinction can be already be made, for example, between free and fixed nanoparticles. Fixed nanoparticles are less likely to pose a problem because they are immobilised within a matrix and cannot freely move or disperse within the human body or the environment. In other words, there is likely to be low human exposure.

It may be possible to assess many products involving nanoparticles from the chemicals industry using existing mechanisms or techniques for risk assessment, but it may often be necessary to adapt existing techniques or devise new risk assessment methods. In any case, the OECD paper argues, it will be important to address safety issues in a proactive way in order to avoid public uneasiness about the new technology as a result of a lack of information and attention to safety aspects which could lead to limitations on the safe development of a promising technology. There will be a Special Session of the Joint Meeting in June 2005 to investigate in more detail the potential safety implications of manufactured nanomaterials for human health and environmental safety.

The International Risk Governance Council (IRGC) discussed nanotechnology at a meeting of its Scientific and Technical Council in February 2005[65], agreeing that it is a broad technology which raises important long-term issues (including societal issues) but arguing that grouping all nanoscale R&D and potential products within the single term ”nanotechnology” makes it difficult to distinguish between technologies with different risk governance issues. The situation is complicated by the fact that some possibly harmful commercial applications, such as in cosmetics, already exist and are subject to little new control, while potentially beneficial technologies may be retarded. Drug delivery, which may turn out to be the most important area economically, will take some time to come to market because of the time needed to complete approval processes. The drug example raises the possibility that nanotechnology may suffer from a new problem, termed ”toxicology bottleneck” as the science advances too fast for the risk assessment processes of organisations such as the US FDA. This is further complicated by the difficulty in both measuring and modelling nanoscale particle behaviours in both air and fluids.

The report by the UK's Royal Society and Royal Academy of Engineering on nanotechnologies expects the likelihood of nanoparticles or nanotubes being released from products in which they have been fixed or embedded (such as composites) to be low, but recommends that manufacturers assess this potential exposure risk for the lifecycle of the product and make their findings available to the relevant regulatory bodies[66]. The report highlights the lack of knowledge about the behaviour of nanoparticles — for example, the effects of inhaling free manufactured nanoparticles have not been studied extensively. Analogies with results from studies on exposure to other small particles such as the pollutant nanoparticles in urban air and mineral dusts in some workplaces suggest that at least some manufactured nanoparticles will be more toxic per unit of mass than larger particles of the same chemical. It also seems likely that nanoparticles will penetrate cells more readily than larger particles. The report also emphasises the diversity of technologies lumped together under the term ‘nanotechnology' and the implications of that diversity for the approach to public dialogue, research and regulation.

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[64] OECD: 2004 ”Nanotechnology: Emerging safety issues?” ENV/JM (2004)32

[65] Unpublished. The IRGC's June 2004 factsheet on nanotechnology can be found here http://www.irgc.org/_cgidata/mhscms/_images/12384-3-1.pdf

[66] The Royal Society & The Royal Academy of Engineering: 2004, ”Nanoscience and nanotechnologies: opportunities and uncertainties” www.nanotec.org.uk/finalReport.htm

In its response to the Royal Society and Royal Academy of Engineering Report from February 2005 the Minister of Science and Innovation sets out the UK's government's agenda on nanotechnologies[67]. Planned steps to ensure a safe and ethical development of nanotechnologies include:

- setting up a research co-ordination group to investigate risks from nanoparticles,
- Initiatives for public dialogue to help the scientific community and the public to explore issues relating to the regulation of nanotechnologies,

It is also planned to review the adequacy of the current regulatory frameworks. Specifically, the government wants to work with the EU regulatory authorities with respect to:

- the assessment of risks associated with medicines and medical devices,
- the safety of unbound nanoparticles in cosmetics and other consumer products,
- disclosure of testing methodologies used by industry,
- labelling requirements on consumer products,
- sector specific regulations for products of nanotechnologies in addition to REACH at a European level.

At present no specific regulations exist in Europe which refer specifically to the production and use of nanoparticles either for workers or consumers' safety or for environmental protection. Current rules and operational practices are applied.

There are several research projects funded by the European Commission which deal with nanoparticles (eco)toxicity and risk. The NanoDerm project investigates the quality of skin as a barrier to ultra-fine particles. NanoSafe and NanoSafe2 (in negotiation) study risk in production and use of nanoparticles. NanoPathology investigates the role of micro- and nanoparticles in inducing biomaterial disease. Other projects are currently being negotiated such as the specific support action NanoTox that aims to provide support for the elucidation of the toxicological impact of nanoparticles on human health and the environment, and the co-ordinating action Impart that aims to improve understanding of the impact of nanoparticles on human health and the environment. Moreover, the German project NanoCare will develop an inhalation toxicity model for testing of nanomaterials.

In the proceedings of a workshop from January 2005, the EU Commission states that further examinations of the regulation may be needed on the basis of new scientific evidence.

6.9. Position of the industry

Over the last few years national nanotechnology associations have been established and / or industry associations have formed subsections that deal with nanotechnologies in various countries. A number of theses associations have initiatives that deal with risks and risk management related to nanotechnologies.

As one example, the German DECHEMA (Society for Chemical Engineering and Biotechnology) and the VCI (German chemical industry association) have founded a working group on "Responsible Production and Use of Nanomaterials". The two organisations represent the interests of 1,600 German chemical companies as well as 5,000 private members. The working group has actively promoted a risk management approach to nanotechnologies. The group aims at the successful realisation of the economical and technological chances by initiation of suitable measures, taking into account ethical, ecological, social and health care aspects. The tasks of the working group are:

- To identify and prioritise research topics which have to be addressed in order to assess possible risks of nanomaterials,
- To prepare project proposals on the basis of identified research topics and to support their realisation,
- International co-operation to gain synergies and to widen the database,
- Dialogue with stakeholders,
- Promoting related communication.

On the risk management agenda, the emphasis of the working group lies on identifying possible risks of chemical nanotechnology focusing on nanoparticles and nanotubes in both their free and bounded state

The working group favours a structured approach by assessing hazards and exposure and implementing risk management measures such as:

- occupational protection measures (organisational, technical, and individual) for workers,

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[67] HM GOVERNMENT UK. RESPONSE TO THE ROYAL SOCIETY AND ROYAL ACADEMY OF ENGINEERING REPORT:'Nanoscience and nanotechnologies:opportunities and uncertainties', February 2005

- use of embedded nanomaterials, use of nanomaterials chemical fixed / covered at surfaces for consumer products as well as individual toxicological testing and governmental authorisation.

This approach reflects the attitude of industry representatives, who generally call to explore the potential risks case by case, application by application and material by material. One basis for this approach is establishing databases for the scientific evaluation of risks. It is not clear whether public access to this kind of databases is intended.

Industry associations on an international basis are still in their very early stages. A new European association to represent the nanotechnology business, the Nanotechnology Trade Association (ENTA), will be set up in June 2005. ENTA is an association formed for the nanotechnology industry in Europe and aims to liaise between governments, science and industry. It is supported by several major multinational companies such as British Petroleum, and Proctor and Gamble, and it will share information explore, networking opportunities, disseminate news and also perform risk evaluations.

6.10. Position of pressure groups

One small non-government organisation called the ETC group has published several reports raising concerns about nanotechnology that have been regularly quoted in the international press[69,70]. The head of ETC, Pat Mooney, is best known for his role in the fight against Monsanto's genetically modified seeds.

In 2002, the ETC Group called for a moratorium on the commercialisation of new nano-scale materials until laboratory protocols and regulatory regimes are in place that take into account the special characteristics of these materials, and until they are shown to be safe.

In a recent publication called ”Down on the Farm”, the ETC Group recommends specifically that all food, feed and beverage products incorporating manufactured nanoparticles be removed from the shelves and new ones be prohibited from commercialisation until companies and regulators have shown that they have taken nano-scale property changes into account. They also call for the prohibition of nano-scale formulations of agricultural products such as pesticides and fertilisers from environmental release until a regulatory regime specifically designed to examine these nano-scale products finds them safe.

A report for the Greenpeace Environmental Trust called for a commitment by industry to environmentally sound practises and to fund relevant research on human health on a far greater scale than currently witnessed. Greenpeace does not, however, echo the call for a nanotech moratorium, because that ”seems both unpractical and probably damaging”[71].

6.11. Position of reinsurers and insurers

The topic of nanotechnologies has been taken up by the major re-insurers, mainly Swiss Re[72], Munich Re[73] and GenRe[74].

They all agree that the insurance industry is going to have to live with the uncertainties of nanotechnology related risks for a longer period of time and that it will not be able to quantify the probability of potential losses occurring and their possible extent.

In principle, many lines of business are considered to be potentially affected, including:

- Workers’ compensation,
- General and products liability
- Products recall,
- Environmental liability,
- Property (dust cloud explosion).

It is assumed that if health effects from certain engineered nanoparticles become ever manifest and causation can be established, then series of claims will almost certainly follow.

Currently, there are no specific policy exclusions or terms in regular use that are tailored to address risks from nanotechnologies.

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[69] ETC Group. Nanotech: Unpredictable and Un-Regulated 2004

[70] ETC Group. DOWN ON THE FARM: The Impact of Nano-Scale Technologies on Food and Agriculture. November 2004

[71] Greenpeace Environmental Trust / Imperial College London. Future Technologies, Today's Choices. Nanotechnology, Artificial Intelligence and Robotics. A technical, political and institutional map of emerging technologies July 2003

[72] Swiss Reinsurance Company. Nanotechnology Small Matter - Many Unknowns 2003

[73] Munich Re Group Nanotechnology – What’s in store for us? Topics 2003/1

[74] GenRe, Nanotechnology: Will Minute Items have a Huge Impact on the P/C Industry? Hazardous Times 2004

One major issue for the re-insurers is the fact that the extent of nanotechnology risks will become apparent only in the long term. Dangers will be chronic rather than acute. The fears here are that ”unforeseeable, ruinous loss accumulation unleashed by a flood of late claims” might build up. As nanotechnology becomes pervasive and certain nanomaterials are found to cause illness, many insureds (policy holders) are likely to be affected.

From the fact that the risk is considered to be incalculable, Swiss Re concludes that the insurance industry will have to work with loss scenarios and certain loss-limiting measures to protect the balance sheet.

A major issue is the ”stacking of limits” problem: insurers using traditional occurrence policies in some jurisdictions may face trigger obligations under multiple policies over several years. Both Swiss Re and GenRe call for an avoidance of this problem by ”claims made” covers and exact descriptions under which a loss may be said to have occurred. GenRe states that today most nanotechnology risks are written on occurrence policies.

7. Chances and risks for the Allianz Group

7.1. Nanotechnologies and investments

The predicted strong overall economic impact of nanotechnologies means that probable commercial success stories will run parallel to a demand for financing solutions. On the other hand, as with other new technologies, business risks depend not only on selecting promising business concepts but also on the timing of investments.

Private equity and venture capital

A survey by the VDI (the Society of German Engineers) shows that one of the major barriers for innovation by small- and medium-sized enterprises in Germany in the area of nanotechnology is a lack of capital. To develop new products and processes and also to penetrate new markets, sizeable investments are needed, especially in the seed phase. The VDI calls for closer co-operation between the financial community and nanotechnology companies[75].

Venture capital firms in nanotechnology will have a key role in transferring technology knowledge from the research centers to the industry and the markets. According to Business Week, at the end of 2004 venture capitalists had already invested $1 billion in nano companies, nearly half of it alone in 2003 and 2004.. It is expected that the majority of nanotech exits will be through trade sales.

For successful investments, two factors will be of critical importance: timing and target selection.

Timing

The overwhelming majority of observers agree that, looking at the broad picture, the question is not whether nanotechnologies will reach the market, but how long they will take to make a broad impact on real products and, in turn, create sizeable turnover and profits

This time scale is likely to vary widely for individual products and companies simply because of the vast number of activities bundled together under the term ”nanotechnologies.”

This can be illustrated by three examples:

- Short term: equipment manufacturers already have a broad customer base as their tools are used in nanotech laboratories all over the world. They are creating the basis for progress in nanotechnologies.
- Mid term: several major electronics companies plan to produce TV and computer displays featuring carbon nanotubes. These screens will be lighter, cheaper, brighter, and more energy-efficient than today's models and the market associated with this application is huge. These screens will be in stores around 2006.
- Long term: even after successful tests on animals, it will take years until a general medical clearance is given for nanobiotechnological cancer therapy. On average, its takes more than 10 years for a drug to reach the market.

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[75] W. Luther, N. Malanowski ”Nanotechnologie als wirtschaftlicher Wachstumsmarkt, Innovations- und Technikanalyse”, VDI, Düsseldorf September 2004 (in German)

Selection

In contrast to the insurance sector, with its high number of insureds (policy holders), private equity and venture capital give detailed consideration to a smaller number of ”targets.”

Careful target selection will be necessary to minimize early stage investment risks. This should involve in-depth analyses not only of market, legal, and financial aspects, but also of technical and environmental factors in a process of ”acquisition due diligence”
In many cases, a sound scientific understanding combined with know-how about commercialisation will be key factors.

The health and environmental risks outlined above can create secondary risks for companies that produce and market nanotech products. The discussion on nanotechnology will strongly influence the marketability – and thereby the commercial success -- of certain products. The likelihood of bad investments should be minimized by carefully reviewing the evidence about risk.

Public companies

Because nanotechnology is an enabling technology, it offers new possibilities for thousands of materials and products that already exist. This necessarily involves large industrial companies such as Degussa, Bayer, DuPont, and General Electric. Already, 19 of the 30 companies in the Dow Jones industrial index have launched nanotechnology initiatives. But, while some of these companies are enthusiastic about the opportunities, they cannot be said to be nanotechnology driven.

Investment company Nanostart AG has identified more than 180 small and medium-size listed companies whose operations are mainly in the nanotechnology field, while Merrill Lynch has created a Nanotech Index (NNZ) to help it keep track of the industry. The index includes firms which state in public documents that nanotechnology initiatives form a significant component of business strategy. Most firms in this category are in the fields of semiconductors, biotechnology, instrumentation, sensors, diagnostics, drug delivery, drug development, genomics, and materials.

The large performance spread of firms on the index underlines the importance of selection and timing.

The influence of nanotechnologies on existing industries

In the medium to long term, new nanotechnology enabled products will strongly influence existing industries. This influence is likely to include the deployment of enhanced products that compete with existing ones as well as, in the case of some firms, disruptive changes. The impact of this influence could well extend beyond the immediate area of application.

If economically viable, the following examples of nanotech applications (which have been mentioned earlier) are likely to exert an influence on established industries:

- Clothing that is able to rid itself of dirt, pollutants and micro-organisms is likely to affect the entire laundry industry.
- Low-cost photovoltaic films and sprays for buildings, cars, bridges etc. will have a possible disruptive influence on silicon photovoltaic cell manufacturers and battery makers among others.

It will be necessary constantly to exercise technical due diligence to isolate the opportunities, risks and possible impact of nanotechnologies. This process also holds true for ”traditional” investments.

7.2. Nanotechnology and industrial insurance: Managing Chances and risks

What are the implications of nanotechnology for commercial and industrial insurance? The commercialisation of products that either contain nanoparticles or use nanotechnologies is an ongoing process. Today, Allianz is insuring many industrial and commercial clients active in this field. The activities of our insureds(policy holders) range across all field of nanotechnologies from chemical companies that produce nanoparticles to manufacturers of consumer products. Over time, the insurance portfolio will contain an increasing number of insureds (policy holders) with an increasing proportion of their commercial activities in nanotechnologies.

By carrying these risks, the insurance industry is already contributing to the early commercial phase of nanotechnologies. Especially for small- and medium-sized enterprises. adequate insurance cover is an important prerequisite for entrepreneurial activity.

This approach is straightforward insofar as the overall risk that is carried is only a very small fraction of the overall risk portfolio. The ”innocent” acceptance of risks is typical of the insurance industry in the early phase of many new technologies. With an increasing proportion of nanotechnology risks in the portfolio, questions about adequate risk assessment procedures, control of accumulation risks and of insurability become more and more relevant over time. A balance needs to be kept between managing a sustainable insurance portfolio with adequate returns and a maintaining a responsible approach towards economic development. This is because the insurance industry, in its risk carrying capacity, is always an enabler of new technologies.

Looking at possible risk scenarios related to nanotechnologies, the following basic features can be distinguished:

- an increasingly high number of persons will be exposed to engineered nanoparticles,
- potential harmful effects will evolve over longer periods of time,
- a high number of companies from various branches of industry could be involved,
- in individual cases it will be difficult to establish a causal relationship between action or omission of a company and the resulting damage, injury or financial loss,
- potential loss scenarios resemble major product liability cases from the past
- occupational exposure is a main concern.

In the context of insurance, the primary area of discussion will therefore be industrial liability insurance with its different types of cover.

There is a class of risks related to new and sometimes revolutionary technologies that is typical of problematic fields in industrial liability insurance. Typically, this class of risk has an inherent mass tort potential which is difficult to specify. The time scale potential here is simply incalculable.

Scenarios like the asbestos claims – especially in the USA – come into mind. The three waves of asbestos claims have cost US insurers and re-insurers approximately $135 billion. The estimates for the fourth wave of claims are as high as additional 200 to $275 billion.

However, to include nanotechnology risks in this context does not seem helpful as the sheer size of the sums tend to mitigate against any sound risk analysis and constructive dialogue between the different stakeholders.
As outlined in the chapter on risks, the – limited – evidence base does not imply that such a direct and broad comparison is valid. The public dialogue and political solutions will gain from differentiation rather than from sweeping arguments. This will be a difficult task for all parties involved – including the media, the industry and the NGOs – but a lot can be gained in terms of economic, social and ecological sustainability along this path.

One of the major legal issues will be causality. Epidemiological studies on ambient fine and ultra fine particles reveal a correlation between ambient air concentration and mortality counts. There does not seem to be a monocausal relationship. Instead, the issue is rather the effects of fine particles on the health of susceptible persons exposed to many other factors such as cigarette smoke, genetic disposition, or lifestyle. It is becoming increasingly clear that long-term illnesses are caused by a complex interplay of different risk factors. The traditional laws and rules that govern liability and compensation are based on a one-to-one assignment of injury and damaging agent. They clearly reach their limits here. This also means limits for traditional liability insurance schemes.

It is likely that any health effects from engineered nanoparticles will be subject to this changed perception. In many cases of illness it might be extremely difficult to clarify whether the exposure to nanoparticles is just one of many contributing factors or a more central factor. In the European legal framework the latter would have to be proven – at least as the situation is today.

How far the burden of proof will be changed remains open. In 1948 the World Health Organisation, in its constitution, defined health as a state of ”complete physical, mental and social well-being,” and not consisting only of the absence of disease or infirmity. Monitoring changes—whether they are scientific, technical, social or legal—is one of the major tasks of risk management. It is a task well suited for insurers.

What risk management measures will be taken by the Allianz Group in relation to new technologies in general and nanotechnologies in particular?

Risk management approach to nanotechnology from an insurer's perspective

Risk awareness

There is a much uncertainty about emerging risks associated with nanotechnologies. It will take years for studies about exposure routes, the effects on human health and the environment to reach conclusive results. While it is still too early to make conclusive statements, our own risk management will need constantly to "put its feelers out."

The first step in our risk management toolbox is to create an awareness of the risks and an understanding of the hazards. The first step is to determine how underwriters and risk engineers should deal with critical issues such as direct exposure to nanoparticles or their release into the environment.

Risk identification and risk evaluation

The next step is to identify and evaluate the risks in a continuing process that considers scientific, technical, legal and regulatory factors. Public opinion is also important because that influences many political, industrial, and legal decisions.

Yet close scrutiny of the individual risk, often with support from risk-consulting units, is a prerequisite to taking economically sustainable decisions. Often more important than the underlying basic risk, the risk management practices in these companies will range from very basic to highly sophisticated. The last point is of key importance: even if a certain technology creates new risks, the quality of risk management practices will determine whether these hazards will actually materialise. This is an area where the insurer can contribute through his experience with a multitude of clients from various industries.

Risk handling and accumulation control

Given the knowledge gap about risks outlined above, it is a matter of debate whether one main criterion of insurability – namely the assessability of risks with respect to probability and severity – is or can be fulfilled. The combination of limited evidence about the hazards and potential latency claims again warrants close monitoring of the risk.

On the other hand, it seems neither feasible nor appropriate to start a debate about a general exclusion of nanotechnologies from the insurance coverage today. There are several arguments for this:

- nanotechnologies cover a very broad field with far from uniform risk characteristics,
- the terminology used in nanotechnologies is very broad. No uniform language or set of definitions exist,
- the sheer variety of nanotechnologies and their applications across broad sections of industrial segments mean a positive diversification effect for insurance portfolios,
- the exposure of the general population to nanotechnologies is still comparatively low.

But all this does not rule out specific applications such as the use of nanoparticles in environmental remediation from being subject to more intense risk analysis—and possibly even being excluded from cover.

Furthermore, Allianz has a wide range of measures at hand to optimally manage the risk and "sculpt" a portfolio. The appetite for certain classes of risk can be defined, and details of coverage can be tailored, both to meet client demands and protect Allianz's assets.

A major challenge with nanotechnologies as well as with other emerging risks will not only be selection and pricing, but also adequate risk capital allocation.

A "wait-and-see" attitude is not appropriate, especially because of the existence of latent risks, which can take many years to show.

7.3. Conclusions for industrial and commercial insurance

Several steps should get high priority for all stakeholders involved in nanotechnologies in the next few years. These include:

➡ Independent research into the risks of nanoparticles, exposure routes and the effects on humans and the environment. Strengthening the evidence base and allowing public access to the results. Transparency will be a key factor for adequate risk management and public trust,

Developing comparative risk classification schemes and databases, possibly for cross-cutting use by different organisations. Focusing underwriters’ and risk engineers’ efforts on critical issues such as direct exposure to nanoparticles or their release into the environment.

- Bringing the discussion about nanotechnology to the front line of insurance, that is, to meetings between clients and underwriters and risk engineers,
- Encouraging a willingness to discuss the subject in a way that is not dominated by ideology, and making good use of reviews by independent organisations. Using sustainability as a vision and success criterion.

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