Background paper on environmental and risk aspects of nanotechnology

June 2004

Foreword

A background paper in English language has been prepared by Kim Christiansen, 2.-0 LCA consultants[1] commissioned by Per Dannemand Andersen[2] from Risoe, to outline state-of-the-art of environmental, risk and ethical aspects of nanotechnology. This includes

- A literature search as well as own experiences and publications in this field will be the basis for the preparation of the background paper.
- Review of short to midterm toxicological (e.g. toxicity of nanomaterials and particles) environmental (e.g. benefits through more efficient industrial production and energy generation, material savings or better environmental sensing as well as risks through new and potentially persistent and hazardous substances) and safety issues (e.g. technological abuse by military or terrorists).
- Review of long term/visionary aspects including (such as self-replicating systems and robots „nanobots“). This includes ethical aspects as far as international references were available.

Thanks to all for your contributions – the commissioner, the steering committee, The Danish Board of Technology and also to friends of colleagues in the European network on Cleaner Production, Prepare, for your help and input.

After finalizing the literature collection by the mid May, other draft documents from the technology forecast on nanotechnologies have been presented e.g. Feidenhans’l et al. (2004), Stubkjær et al. (2004) and Wengel et al. (2004). Discussions on environmental, health, safety and ethical issues in these documents are assessed to be covered by the information presented in the following.

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Content

1 Introduction

A literature search based on input from the steering committee and others involved in the ongoing Technology Foresight studies of nanotechnologies (NT) in Denmark is the basis for the preparation of this background paper.

The sources of information found are listed in the reference list, and some of them include further sources for information although as noted by Mnyusiwalla et al. (2003) there is a paucity of serious, published research into the ethical, legal, and social implications of NT. The characterize NT as a rapidly progressing field, with advances that will have a tremendous impact on fields such as materials, electronics, and medicine. In annex 1 a definition and an illustration of "nano" taken from Holister (2002) is included, and in annex 2 a table indicating the potential applications areas of NT is also included (based on several references).

The background paper is not a comprehensive overview, but a "sample" into the issue of health, environmental, safety and ethical aspects of NT. The most recent and comprehensive overview and discussion on the subject can be found in Arnall (2003); both Nanoforum (Bøgedal, 2004) and The Royal Society (Ward, 2004) are publishing similar comprehensive reviews during mid 2004; a good literature overview can be found in Dürrenberger et al. (2003).

In a study of the potential use of the US chemical regulation, the Toxic Substances Control Act, on NT, Wardak (2003) concludes:

> *The very nature of NT – its ability to alter the fundamental properties of substances – is likely to challenge the existing regulatory structure and cause confusion both on the side of industry and the government concerning the role of regulation. To date, very few people or organizations have addressed the adequacy of our current regulatory system to protect human health and the environment or thought about possible alternatives to existing regulatory regimes (beyond extreme positions such as complete bans on NT). A lack of adequate and conclusive research on the health risks of nano-based substances makes the need for a dialogue on regulatory adequacy, inadequacy, or possible alternatives more urgent. A wrong or ill-conceived approach to regulation could have enormous economic consequences given the revolutionary nature and potential of NT.*

The time perspective on both development of NT – and the applications being technology pushed and not market-pulled could indicate a longer perspective – and of the potential impacts on health, environment and safety being mainly in the "chronic toxicology" area, could indicate that we have time to consider. But as stated by Holister (2002), some applications are already here:

> *Areas that are already seeing commercial application of NT, or could well do within the next five years, include: drug delivery; solar energy (photovoltaic or direct hydrogen production); batteries; display technologies and e-paper; composites containing nanotubes (multi-walled); various nanoparticle composites; catalysts (many applications); coatings (extra hard or with novel properties); alloys (e.g. steel or those used in prosthetics); implants that encourage cell growth; insulation (thermal and electrical); sensors (bio and chemical); single photon generators and detectors; new solid-state lasers; bioanalysis tools; bioseparation technologies; medical imaging technologies; filters; abrasives; glues; lubricants; paints; fuels and explosives; textiles; higher capacity hard drives; new forms of computer memory; printable electronic circuits; and various optical components. This list is by no means complete.*

Boegedal et al. (2003) investigated NT applications in health care e.g. diagnostics, drug discovery and delivery, surgery, tissue engineering and implants. NT investment is increasing worldwide and is forecasted to be worth over a trillion euros within the next 10 to 15 years. Applications in use are:

- *Atomic force microscope (AFM) technology (which can move single atoms about) is being used to create smaller and more sensitive micro arrays for use in diagnostics and drug discovery. AFMs can also be used to nanostructure surfaces, and for example make them more biocompatible.*
- *Nanoparticles such as fullerenes (molecules based on a 60 carbon atom cage) and quantum dots (complexes of semi-conductor material that have unique fluorescent properties) are being exploited in many areas including imaging (e.g. enhancement of magnetic resonance imaging [MRI] and ultrasound) and drug delivery (e.g. a modified fullerenes is entering clinical trials as an anti-HIV agent). Formulating drugs with nanoparticles can also improve their solubility (many drugs are not marketed because they are not very water-soluble), increase their resistance to stomach acid and enzymes (allowing better uptake from the small intestine), and allow controlled release (e.g. over days rather than minutes and hours). Nanotubes represent another mechanism for drug delivery, both as a "container" and potentially a system for "nano-injection" into cells.*
- *Nanocomposites of titanium alloys, for example, can be used to improve the biocompatibility and longevity of surgical devices and implants.*
- *Nanostructuring surfaces can improve cellular attachment (e.g. etching surfaces with nanoscale grooves or using instruments such as an AFM to imprint surfaces with cell attachment molecules), and direct cells to grow into defined structures. By incorporating biodegradable polymers to act as a scaffold these structures can be assembled into 3-dimensional "tissues". Nanostructuring can also be used to provide an anti-microbial coating on implants.*

Boegedal et al. (2003) states that NT will allow us to rapidly sequence an individual's DNA (nanosequencing) and thereby determine genetic susceptibility to disease, drug intolerances and drug metabolism rates. Also molecules will be able to target individual cells within the body for drug delivery or imaging purposes. Patient illnesses will be diagnosed more rapidly through advancements in lab-on-a-chip devices, and at the same time a patient's vital signs could be monitored more closely through similar devices. Damaged body parts could be replaced through advances in tissue engineering (with physiological tissues and organs grown in the clinic in bioreactors) and improved implants will allow patients to regain sight and hearing. Their report gives an excellent overview of the pharmaceutical and medical device sectors of the healthcare market and the impact that NT is having, but gives no information on health, environmental or risk issues. This will be addressed in the next report from nanoforum.org (Boegedal, 2004), although already stated

> *The goal (...) is not to establish an exhaustive list of all potential risks linked to nanotechnologies, but rather to give some elements of reflection on this subject. In fact, this part will comprise many questions and assumptions, because neither scientists nor researchers could yet affirm that nanotechnologies involved risks on human health or environment. It is really too early for these specialists to come to any conclusion about this huge topic.*

Ward (2004) reports on a workshop conducted by the Royal Society in UK. On application status the following was reported:

> *A paint industry representative at the workshop indicated that nanoparticles could be incorporated in energy-saving coatings that would help to reduce heat loss by reflecting infra-red radiation, or to produce 'smart paints' that change colour when exposed to changes in temperature or light. However, these products were likely to be more expensive than those currently available, and it was possible that they could become a source of nanoparticles in the environment as the paints eroded.*
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> *According to a representative from the telecoms industry, NT could make the use of materials in manufacturing more efficient and could advance the miniaturisation of sensors with a wide range of applications from monitoring agricultural chemicals to easing the flow of traffic.*

Miniature sensors developed through NT could also be used to detect specific pollutants accidentally or deliberately released into the environment. The removal of pollutants may be achieved through filters incorporating nanoparticles, the first of which may be available within a couple of years. NT might also be used in catalysts that promote key chemical reactions within fuel cells that might be used with sources of renewable energy.

Schuler (2004) takes a prospective look at NT and risk communication and summarises:

As pressure groups have started to publicise the potential dangers of nanomaterials for human health and the environment, scientists, policy-makers and industry have begun to reflect on the actions necessary to assess nanomaterials' impacts on human health and the environment and to set adequate safety guidelines and protocols. NT may also have to deal with the kind of scepticism that biotechnology has faced. Communication among stakeholders is very important in this regard.

Harremöes et al. (2001)[3] gives a comprehensive insight to lessons learnt during the last more than 100 years of the benefits of precaution and prevention. The use of systematic technology assessments, including involvement of the public, combined with sufficient requirements for and funding of research into potential health and environmental impacts of new technologies or new applications of existing technologies can be highly recommended. As stated by the former director of the European Environmental Agency in the foreword of the report:

It is therefore my hope that this report contributes to better and more accessible science based information and more effective stakeholder participation in the governance of economic activity so as to help minimise environmental and health costs and maximise innovation.

Two core learning's are emphasised in the conclusions:

Regulatory appraisal and control of technologies and economic development involves balancing the costs of being too restrictive on innovation with the hazards and costs of being too permissive, in situations of scientific uncertainty and ignorance. The case studies provide many examples where regulatory inaction led to costly consequences that were not — and sometimes could not have been — foreseen.

The case studies also provide many examples where ‘early warnings’, and even ‘loud and late’ warnings, were clearly ignored; where the scope of hazard appraisal was too narrow; and where regulatory actions were taken without sufficient consideration of alternatives, or of the conditions necessary for their successful implementation in the real world.

Finally, the late lessons can be quoted

1. Acknowledge and respond to ignorance, as well as uncertainty and risk, in technology appraisal and public policymaking.
2. Provide adequate long-term environmental and health monitoring and research into early warnings.
3. Identify and work to reduce ‘blind spots’ and gaps in scientific knowledge.
4. Identify and reduce interdisciplinary obstacles to learning.
5. Ensure that real world conditions are adequately accounted for in regulatory appraisal.
6. Systematically scrutinise the claimed justifications and benefits alongside the potential risks.
7. Evaluate a range of alternative options for meeting needs alongside the option under appraisal, and promote more robust, diverse and adaptable technologies so as to minimise the costs of surprises and maximise the benefits of innovation.
8. Ensure use of ‘lay’ and local knowledge, as well as relevant specialist expertise in the appraisal.
9. Take full account of the assumptions and values of different social groups.

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[3] Fisheries, radiation, benzene, asbestos, PCBs, halocarbons, DES, growth promoters, sulphur dioxide, MTBE, the Great Lakes, tributyltin, growth promoters, mad cow disease

10. Maintain the regulatory independence of interested parties while retaining an inclusive approach to information and opinion gathering.
11. Identify and reduce institutional obstacles to learning and action.
12. Avoid 'paralysis by analysis' by acting to reduce potential harm when there are reasonable grounds for concern.

2 Short to midterm perspective

In this chapter short to midterm toxicological (e.g. toxicity of nanomaterials and particles), environmental (e.g. benefits through more efficient industrial production and energy generation, material savings or better environmental sensing as well as risks through new and potentially persistent and hazardous substances) and safety issues (e.g. technological abuse by military or terrorists) are addressed.

2.1 Health (toxicological) aspects

According to New Scientist (2004), researchers found in 2003 that nanotubes can damage lung tissue of mice if inhaled, and buckyballs can cause cell death in test-tube experiments.

Wardak (2003) summarizes the research into health aspects of NT. Five studies cover the inhalation and dermatological risks associated with carbon nanotubes and ultra-fine particles. Three of these studies were presented at a recent conference of the American Chemical Society (ACS). The first series of studies that are reviewed have to do with the toxicity of ultra-fine particles.

Dr. Gunter Oberdöster at the University of Rochester has studied the effects of ultra-fine particles (<0.1 micrometers in diameter). Nanoscale particles fall clearly into this realm, so the question arises as to whether research on UFP's may be relevant to understanding the behavior and toxicity of nanoparticles. Oberdöster's research used ultrafine carbon particles and found greater lung penetration than with larger particles. His recent paper raised the possibility of ultrafine particles crossing the blood-brain barrier and impacting the central nervous system. Oberdöster stated, "With the emergence of so many unanswered questions, the health consequences of inhalation of UFP [ultra-fine particles] remain an important area of investigation." Of those questions, the two most important were the impact of inhalation of ultra-fine particles on the central nervous system and the daily exposure to such particles. The rest of the studies reviewed here examine carbon nanotubes specifically.

Dr. Chiu-Wing Lam at Wyle Labs of the NASA Johnson Space Center and Robert Hunter at the University of Texas (Houston) studied the impact of carbon nanotubes on lung tissue by instilling a suspension of nanotubes directly into the lungs of mice. They found that the nanotubes clumped together into bundles and stimulated an immune response, which left scar tissue in the lungs. Hunter's message was that "People should really take precautions. Nanotubes can be highly toxic".

Dr. David Warheit at Dupont's Haskell Labs performed a slightly different experiment. He instilled single-walled carbon nanotube soot mixture into the trachea of rats. For comparative purposes, he also instilled a group with carbonyl iron and quartz, respectively. Fifteen percent of the rats treated with carbon nanotubes suffocated to death within twenty-four hours due to clumping of the nanotubes that obstructed the bronchial passageways. Granulomas and legions formed as a reaction to the foreign substance. The quartz-instilled and carbonyl iron-instilled rats had some toxicity and no toxicity, respectively. The main conclusion was that carbon nanotubes might be irrespirable. All three of these researchers recommended inhalation studies as the next step, since these studies involved instillation, not inhalation, into the lungs of animals.

A year and a half ago at the University of Warsaw, two studies released at the same time studied the dermatological and inhalation effects of carbon nanotubes. In the study on dermatological effects, which used rabbits, the researchers "did not [find] any signs of health hazards related to *skin irritation and allergic risks." The study recommended no special precautions with respect to carbon nanotubes in the working environment; in fact, the article was titled "Carbon Nanotubes: Experimental Evidence for a Today, there is no real regulatory policy formulated to deal with NT. No stakeholder in this arena has taken the initiative to change the status, although some experts believe it is an issue in the immediate future. Null Risk of Skin Irritation and Allergy".*

In the next study, "Physiological Testing of Carbon Nanotubes: Are They Asbestos-Like?" the researchers found that carbon nanotubes do not exhibit effects similar to asbestos. "Thus working with soot containing CNTs [carbon nanotubes] is unlikely to be associated with any health risks." The study instilled a carbon nanotube soot mixture into the tracheas of guinea pigs.

Wardak (2003) comments, that the five studies show conflicting results concerning the toxicity of carbon nanotubes among other reasons because of the lack of the associated issue of exposure. A recent collaborative study done by the National Institute for Occupational Safety and Health (NIOSH), NASA, Rice University, and Carbon Nanotechnologies Inc., indicated that worker exposure to carbon nanotubes would be low at low agitation levels, but urged caution until more is known about toxicity. This obviously points to the important relationship between both toxicity and exposure in determining the overall risk to humans and the environment.

Wardak (2003) concludes, that further research is needed to determine the health and environmental effects of these and other types of nanoparticles.

In USA, the Office of Research and Development at the EPA has requested studies to be done on the environmental effects of NT. The next round of studies should be independent, inhalation studies, and Wardak (2003) recommends starting with the workers at industrial factories that produce significant amounts of carbon nanotubes or other nanoscale substances for either research or commercial sale. Colvin (2003) argues for detailed studies into the potential effects on human health of nanomaterials based on experiences with asbestos and man-made fibres, but also e.g. the solvents used in the gases produced in the manufacture of carbon nanotubes should be addressed. Examples of health impacts could be that ingested nanoparticles may cause liver damage as ingested nanoparticles (i.e. or oral drug delivery) have been found to accumulate in the liver. Excessive immune/inflammatory responses cause permanent liver damage. Another example would be induction of autoimmune disorders as seen with e.g. industrial workers breathing particulate mater (e.g. silica dust).

In its proposal for a European strategy on nanotechnology, the EU Commission (2004) also emphaise the potential risk for human health and the need for research and precaution and the recommendations for member states are clear:

As a result, addressing the potential risks of nanotechnologies to public health, the environment and consumers will require evaluating the possible re-use of existing data (on chemicals, kc) and generating new, nanotechnology-specific data on toxicology and ecotoxicology (including dose response and exposure data). This also calls for examining and, if required, adjusting risk assessment methods. In practice, addressing the potential risks associated with nanotechnologies necessitates that risk assessment be integrated into every step of the life cycle of nanotechnology-based products.

In support of a high level of public health, safety, environmental and consumer protection, the Commission highlights the need:
(a) to identify and address safety concerns (real or perceived) at the earliest possiblestage;
(b) to reinforce support for the integration of health, environmental, risk and other related aspects into R&D activities together with specific studies;
(c) to support the generation of data on toxicology and ecotoxicology (including dose response data) and evaluate potential human and environmental exposure.

The Commission calls upon the Member States to promote:
(d) the adjustment, if necessary, of risk assessment procedures to take into account the particular issues associated with nanotechnology applications;
(e) the integration of assessment of risk to human health, the environment, consumers and workers at all stages of the life cycle of the technology (including conception, R&D, manufacturing, distribution, use, and disposal).

2.2 Environmental aspects

The use of NT to create new types of miniature sensors, pollutant filters and fuel cell catalysts could benefit the environment, according to evidence, that is being considered by the Royal Society and Royal Academy of Engineering working group on NT. However, the testimony from industry and academic experts and regulators in a workshop suggests there is still uncertainty about the impact of releasing nanoparticles into the environment (Ward, 2004).

The benefits are expected to rise from better end-of-pipe technologies for cleaning of air emissions, wastewater discharges and polluted soil and other hazardous wastes as well as from more efficient energy production and storage technologies. Also for developing countries, the options for decentralised and more efficient energy supply is of potential benefit. More examples of the technology options can be found at e.g. www.nanoforum.org.

Masciangioli (2002) also lists some examples of the potential benefits to the environment of NT:

- *Synthetic or manufacturing processes which can occur at ambient temperature and pressure.*
- *Use of non-toxic catalysts with minimal production of resultant pollutants.*
- *Use of aqueous-based reactions. Build molecules as needed --"just in time."*
- *Nanoscale information technologies for product identification and tracking to manage recycling, remanufacture, and end of life disposal of solvents.*
- *Iron walls used in groundwater treatment can be made more efficient using nanosized iron that enhances the reaction. Enhanced further by coupling with other metals (Fe/Pd)* on the nanoscale. Nano Fe0 is more reactive and effective than the microscale. Smaller size makes it more flexible -- penetrates difficult to access areas.*
- *Dual role of ZnO semiconductor film as a sensor and photocatalyst: Nanosized zinc oxide (ZnO) "senses" organic pollutants indicated by change in visible emission signal and the ZnO "shoots" the pollutants via photocatalytic oxidation to form more environmentally benign compounds.*
- *Single Molecule Detection sensors where molecules adsorbed on surface of micro cantilever, causes a change in surface stress and cantilever bends.*
- *Used to detect chemicals using either a specific reaction between analyte and sensor layer or chem/physisorption processes. Applications to bio-toxins as well.*

Nanoparticles can cause brain damage in fish, according to a study using two standard toxicological tests on carbon molecules called "buckyballs", reported by New Scientist (2004) based on a presentation at an American Chemical Society meeting in Anaheim, California. Eva Oberdorster of Southern Methodist University in Dallas, US, who led the study, found modest concentrations of buckyballs in water (800 parts per billion) caused significant harm to two aquatic animals. Water fleas were killed by the addition of the tiny carbon balls, and fish showed up to a 17-fold increase in brain damage compared with unexposed animals when exposed to 500 ppb in the three-week tests. This damage, known as lipid peroxidation, can impair the normal functioning of cell membranes and has been linked to illnesses such as Alzheimer's disease in humans.

Industry is just beginning to exploit the potential of buckyballs - more formally known as fullerenes - and their chemical kin, single-walled nanotubes. Though only a handful of factories worldwide are now producing such molecules, experts see them as having the potential for wide use ranging from drug delivery to cosmetics to environmental remediation. Oberdorster states that much further work is needed to establish the extent of this risk, but that results indicate a moderate toxicity.

Colvin (cited in Arnall, 2003) also addresses the need for research into the potential environmental impacts:

> *It is critical that more organisations and people devote time and money to these questions. This requires a change in the current climate: of the [US$710 million in funding for the NNI in the fiscal year 2003, less than [US$500,000 is devoted to the study of environmental impact. It is difficult to convince scientists, or funding managers, to support environmental impact studies. The immediate payback for research that demonstrates ways of using nanomaterials to cure disease, for example, is greater than the reward for uncovering that a nanomaterials may cause disease.*

Arnall (2003) concludes:

> *A more in-depth analysis of environmental concerns is warranted. This is because public acceptability of such risk is likely to vary considerably in relation to the application being considered. For example, the application of nanotechnology to computerisation is less likely to cause concern than those practices, which might lead to the release of nanoparticles into the environment.*
>
> *It is possible to conceive of a number of environmental goods that may arise. For example, the potential for gains in energy generation and efficiency have already pointed out above, and it is conceivable that dramatic improvements in environmental sensing and modelling could also be achieved.*

Masciangioli (2002) presents the use of cadmiumsulfide in nanodots as a potential problem due to release of these quantum dots into the environment from production, use and disposal. Knowing the problems with cadmium in general, it can be argued that alternative substances should be applied:

> *Are there measures that can be taken now to minimize or avoid the negative impact quantum dots (or other nanotechnologies) may have on the environment? Are there more benign precursor materials or synthetic methods that can be used to make the quantum dots? Will it be possible to recover the quantum dots for reuse?*

Colvin (2002) is also giving examples of the dual implications of NT between sustainability and liability. On the one side, NT can help improving efficiency and opportunities for water, and wastewater treatment, treatment of hazardous waste, resource recovery and in pollution prevention, but we need to be proactive and investigate the releases, transport and fate of nanomaterials in the environment. Colvin argues based on past failures to consider environmental consequences early, which have shown to be costly:

- *Semiconductor industry (metals, solvents)*
- *Synthetic chemicals (PCB, DDT, Freon)*
- *Applications of natural compounds (chlorine, asbestos)*
- *Transportation, energy (air pollution, global warming, nuclear wastes)*

Colvin (2002) also discuss the mechanism of biouptake of nanoparticles i.e. by impact to the receptors of cell membranes (endocytosis), membrane penetration of hydrophobic particles or formation of transmembrane channels of small nanoparticles (< 5 nm). But no specific examples are given, only more generic examples. In aquatic environments, nanoparticles can be expected to aggregate which in a cell can giveextensive damage and induce cell death; a similar mechanism is seen with proteins. Also nanoparticles may function as "vehicles" for toxins into the cells.

Bøgedal et al. (2004) will include a comprehensive review of ungoing research and initiatives into environmental and other aspects of NT.

2.3 Safety aspects

Altmann and Gubrud (2002) discuss the risk aspects of military uses of NT (in some literature e.g. Feidenhans et al. (2004) this is categorised as en ethical aspect):

> *In the field of NT, warnings have been sounded against excessive promises made too soon, lest the public become disillusioned with "nanohype," but the roughest criticism has been dealt to those who not only foretold bountiful results from this new technology, but also warned of grave dangers. Such warnings, many believe, will lead the public to exaggerated fears of the unknown, undercutting support for NT funding. We believe it is essential to get beyond this battle over atmospherics, and to commence balanced and careful scholarship to assess the actual prospects for good or evil, and to consider what should be done in response to them. We write to address the question of dangers arising from the military use of NT.*
>
> ***NT holds great promises, but also poses grave risks.*** *This applies even when considering only the evolutionary advances expected from current laboratory research and generally accepted extrapolations of historical trends. It is strongly apparent in the context of visions such as nanoassemblers, self-replication, and artificial intelligence of human capability and beyond, robotics from nano to macroscale, super-automated production, and nanodevices within the human body, perhaps to eradicate illness, perhaps to interact with the brain. Although there are disputes about the realizibility of these latter concepts, caution demands serious consideration of such prospects unless they can be shown to be physically or technically impossible. To prevent irreversible damages, regulatory measures must be taken in advance of dangerous developments. The risks of NT span a wide range: environmental pollution, increase of inequality, displacement of human workers or even of the human species have been mentioned. Interdisciplinary studies should be undertaken to address these various risks. Here, we want to draw attention to risks linked to military NT activities that could create specific dangers as well as accelerate general developments in such a way that in-depth study and informed decision become more difficult. Military exploitation of NT has barely begun , but there are strong indications it may expand rapidly, driving and in turn being driven by the technology. Given that the US National Nanotechnology Initiative (NNI) has stimulated similar initiatives in many other countries, the USA may also provide a role model for military R&D there.*
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> ***Weapons of mass destruction.*** *Self-replicating nanorobots, aggressively consuming organic material, are perhaps the most oft-mentioned, and perhaps overstated concept, but would probably require an advanced stage of NT development. In the nearer term, NT will provide possibilities in coming decades for more efficient storage, dispersal, and transport of chemical and biological agents into the body and cells of humans, animals, or plants. New agents may remove previous operational difficulties of biological warfare. Advanced capabilities may include the use of genetic markers to target an ethnic group or even a specific individual. New options for nuclear weapons might include NT-based materials extraction and processing, weapons production, and perhaps new types of nuclear weapons. NT manufacturing based on self-replication could produce conventional weapons in such large quantities that they acquire the character of mass-destruction weapons.*
>
> ***Other weapons.*** *NT will provide stronger, lighter materials, smaller computer components, new sensor technologies, and - together with and beyond microsystems technologies - many options for miniaturization. NT manufacturing methods may enable mass production of sophisticated expendable systems at low cost. One can foresee greater projectile velocities, stronger light armor, and precision-guidance systems even in small munitions. Low-cost military robots of mini and micro sizes, including biological-technical hybrids, would bring even more radical changes. Such*

robots would necessarily be capable of autonomous decision and action and could be used for purposes from reconnaissance to attack. In outer space, very small satellites could act as antisatellite weapons.

General military applications. *NT will have applications in energy storage and generation, propulsion, displays, sensors and sensor nets, combat information systems, logistics, maintenance, self-repair, smart materials, and more. Some more visionary concepts foresee systems implanted into soldiers' bodies, first for biomedical analysis and reaction, later for information exchange.*

When taking a preliminary look at NT under the criteria of preventive arms control, several dangers come to mind, in all three problem areas. These concern:

- *Arms control agreements (e.g., Biological Weapons Convention through new NT-genetics-based agents, limits on conventional forces by new weapons types outside of treaty definitions) or the international law of warfare (e.g., through introduction of autonomous fighting systems not reliably recognizing non-combatants or combatants hors de combat),*
- *Stability (arms races from technological innovation, pressure for preventive attack and fast action, proliferation of cheap microsystems),*
- *Humans, the environment, or society (microrobots for eavesdropping, crime, and terrorism; uncontrolled self-replication; implanted systems altering human nature).*

In the third category dealing with peacetime civilian life, military research and deployment of systems could create "facts" before society is able carry out a thorough debate about the desirability of particular technological developments.

Altmann and Gubrud (2002) recommends to take measures to prevent production or release of systems capable of self-replication in the wild by concluding internationally, binding agreements both the civilian and military sectors; and to work together across national programmes on concerns such as arms control, safety protocols, and social implications.

Chen (2003) lists a series of dangers of NT:

- *Weapons*
    - *Miniature Weapons and Explosives*
    - *Disassemblers for Military Use*
- *Rampant Nanomachines*
    - *The Gray Goo Scenario*
    - *Self Replicating Nanomachines*
- *Surveillance*
    - *Monitoring*
    - *Tracking*

Weapons are an obvious negative use of nanotechnology. Simply extending today's weapon capabilities by miniaturizing guns, explosives, and electronic components of missiles would be deadly enough. However, with nanotechnology, armies could also develop disassemblers to attack physical structures or even biological organisms at the molecular level.

Arnall (2003) states:

Safety concerns on nanotechnology should be addressed by a regime based on the monitoring of the sale of such technologies, rather than control. This situation is analogous to biotechnology: the DNA experience, for example, suggests that a combination of self-regulation and government co-ordination can answer legitimate safety concerns while allowing scientific research to flourish.

As part of The Royal Society study on nanotechnology, a workshop was organised with participation of representatives of academia, industry, regulators and civil society (TRS, 2003). On the safety issue they raised the following issues:

- *Eradication of disability – for example cochlear implants to improve hearing, improved eyesight for soldiers. A CS representative argued that this was a concern with respect to nanotechnology, particularly in US policies that focus on 'improving human performance', and that such technologies contribute to societal expectation and judgements of what is or is not normal. A member of the working group suggested that, given that these types of improvements (eg glasses, contact lenses) have existed for a while, it could be argued that nanotechnology did not necessarily pose any new ethical dimensions in this area. The working group also suggested that people could be said to have a choice as to whether or not to use these technologies. Given the fact that none of the attendees were experts in this area, the working group were alerted to the need to seek additional input from a representative of a disability rights organisation.*
- *Sensors – for example the use of micro and nanosensors in agriculture, which could collect information about farmers' activities and contribute to increased control of their activities. However, it was acknowledged that many farmers are already highly computerised (eg connected to satellite systems).*
- *Toxicity- the issue of toxicity of nanoparticles was raised as an area in which more research is needed, particularly in terms of whether the regulatory system is sufficient.*
- *'Grey goo'. The image of nano robots that can self-replicate has been in the media, and in popular science fiction such as Michael Crichton's novel Prey.*
- *Military uses*

The upcoming study by nanoforum.org will address the following safety issues (Boegedal, 2004):

- *Cyborgs, or man-machine interactions lead to issues of control between people and machines: these are relevant to medical devices, especially active implants, or neural implants. Some researchers have already asked for a moratorium on the development of non-medical implants, until a consensus is reached about their desirability and ways to control their use (Jürgen Altmann, BICC, Bonn).*
- *Military NT and arms control (defence community vs peace movement)*
- *Privacy, especially related to nanoelectronics, sensors, NEMS/MEMS, diagnostics and medical testing, etc. (crime prevention vs human rights, the right to know vs the right not to know…)*
- *Distribution of benefits and risks over different social groups (demographic)*
- *Who controls the development of NT (insiders and outsiders, techno-economic networks, actor networks, constructive technology assessment)*
- *Potential implications of NT for social groups (e.g. some deaf or blind people claim they are part of a minority which should be accepted by society, and not treated as patients who suffer from a disease).*

3 Longterm perspective

In this subchapter more long term or visionary aspects such as self-replicating systems and robots „nanobots" should be adressed, but information is very scarce and mostly part of what is already stated as being part of short- and medium-term perspectives – or as pure science fiction. Therefore only ethical issues are adressed.

3.1 Ethical aspects

MacDonald (2004) introduces, although in a popular form, the ethical issue of nanotechnology by the carriers of the optimism versus the scepticism:

One type of hype comes from enthusiasts who argue that nanotech is a wonderful thing. One day, they aver, "nanoassemblers" will convert coal into diamonds, turn grass clippings into beef, and restore the world's ecology. Poverty, illness, even mortality itself, will be mere memories. This utopian vision, they say, is a powerful argument in favour of zealously developing these technologies.

At the opposite, apocalyptic extreme are those who argue that if we're not careful, nanotech could run amok, as self-replicating nanoassemblers turn from their assigned tasks and begin feeding on ... well, everything. This risk, they say, constitutes a powerful argument in favour of halting nanotechnology research immediately.

The issues to be addressed as part of the ethical discussion are, according to MacDonald (2004):

EFFECTS ON HUMAN HEALTH We need more basic research on the physiological effects of nanoparticles and nanomaterials. Nanotechnology is based, in part, on the idea that nanoscale particles and macroscale particles, though made from the same materials, behave differently. Therefore, presumptions that nanoparticles are "just the same" in terms of safety seem questionable in the face of the claim that those particles are "radically different," in terms of performance.

EFFECTS ON THE ENVIRONMENT What effects will nano-technologies have on the environment? Carbon nanotubes (essentially rolled-up sheets of carbon, just a few nanometers wide) are already in production. Their unique electrical properties and strength imply many potential uses, but caution seems warranted. Too little is currently known about the effects of nanotubes on organisms, waterways, or ecosystems.

PRIVACY AND SECURITY If surveillance technologies become too small to see with the naked eye, what will the implications be for privacy? Will cheap, mass-produced nanocameras be a boon or a disaster? Now, simply to ask the question does not automatically imply a negative conclusion. Perhaps ubiquitous, unseen surveillance technologies will lead to a more stable, secure world. But that's a question, rather, a set of questions, that needs further examination.

MacDonald recommends to use the same ethics on nanotechnologies, in short

Researchers must continue focusing on informed consent, risk minimization, and the protection of vulnerable populations.

Mnyusiwalla et al. (2003) discusses the status and perspectives nanotechnology from the ethical dimension under the following categories:

Equity

Who will benefit from advances in NT? Today we talk of the digital divide as something that is harmful and that we should attempt to correct. We have also talked about the emerging 'genomics divide' in a similar fashion. This is because we have come to understand that technology and development are intricately linked, and that what at first appears to be very 'high-tech' and costly and therefore perhaps irrelevant for developing countries, in the end might come to be of most value for those same developing countries. Thus NT, were it to develop in the way it ought, might ultimately be of most value for the poor and sick in the developing world. At the Johannesburg summit, the main issues for developing countries were poverty reduction, energy, water, health, and biodiversity. NT has the potential to make a positive impact on all of these if its risks either do not materialize or are appropriately managed. The poor could benefit from NT, for example, through safer drug delivery, lower needs for energy, cleaner energy production, and environmental remediation. It is also possible that health could be improved by better prevention, diagnosis, and treatment. One of the biggest health problems in developing countries is trauma, especially from road traffic accidents, and absence of rehabilitation facilities: better nanomaterials for making *safer tyres, or NT-based scaffolds to grow bone may be extremely important, especially if the promise of mass production at very low cost materializes. Furthermore, if developing countries were to see the potential of NT and became early players in the field (e.g. China's increased expenditure on NT R&D), NT might have an impact on their economic development and obviate the need quite soon for these countries to become net importers of NT. This is similar to what is happening in biotechnology, a field in which countries such as India, China,*

Privacy and security
NT is capable of dramatically improving surveillance devices, and producing new weapons. How would individual privacy be protected if near-invisible microphones, cameras, and tracking devices become widely available? Will these new technologies increase security or add to the arsenal of bio- and techno- or even nano-terrorism? Who will regulate the direction of research in defensive and offensive military NT? How much transparency will be necessary in government and private NT initiatives to avoid misuses? There are also very interesting legal questions involving monitoring, ownership, and control of invisible objects.

The next asbestos? Environmental issues
NT has already generated novel types of matter such as fullerenes and carbon nanotubes. Where do these and other nanomaterials go when they enter the environment and what are their effects? This year, the US environmental protection agency (EPA) has added the funding of research projects that explore potential environmental dangers of NT to its list of priorities. 'There are always possibilities for environmental or health harms', said an EPA official.

Human or machine?
Some avenues of research in NT include the incorporation of artificial materials or machines into human systems, as is beginning to happen with implanted computer chips. The modification of living systems is met with great scepticism by much of society. How acceptable will technologies such as implantable cells and sensors be for the general population? What are its implications and what are our limits?

They recommend better funding of research into ethical, health and environmental aspects of NT, to establish large-scale interdisciplinary research platforms, to support capacity strengthening, to use an intersectorial approach, to involve developing countries and to foster public engagement.

The issue of ethics of NT is discussed intensively on several homepages; one example of the perspectives raised:

> *Molecular nanotechnology (MNT) will be a significant breakthrough, comparable perhaps to the Industrial Revolution—but compressed into a few years. This has the potential to disrupt many aspects of society and politics. The power of the technology may cause two competing nations to enter a disruptive and unstable arms race. Weapons and surveillance devices could be made small, cheap, powerful, and very numerous. Cheap manufacturing and duplication of designs could lead to economic upheaval. Overuse of inexpensive products could cause widespread environmental damage. Attempts to control these and other risks may lead to abusive restrictions, or create demand for a black market that would be very risky and almost impossible to stop; small nanofactories will be very easy to smuggle, and fully dangerous. There are numerous severe risks—including several different kinds of risk—that cannot all be prevented with the same approach. Simple, one-track solutions cannot work. The right answer is unlikely to evolve without careful planning. (http://crnano.org/dangers.htm)*

Oud and Malsch (2003) introduces the ethical dimension of bionano techniques although still in the in-vitro stage. Application of these technologies raises questions as to safety (e.g. particles passing through the blood-brain barrier), and ethics (use of embryonic cells).

Chen (2003) has developed an ethical checklist for NT and concludes his analysis:

> *Nanotechnology research should be allowed to continue but with a non-government advisory council to monitor the research and help formulate ethical guidelines and policies. Generally, nanomachines should NOT be designed to be general purpose, self-replicating, or to be able to use an abundant natural compound as fuel. Furthermore, complex nanomachines should be tagged with a radioactive isotope so as to allow them to be tracked in case they are lost.*

A recent workshop among Swiss scientist discussed the responsibility of the scientific community to encounter the inherent risks of the research in this new field, and to communicate with one language in a frank and honest manner to the society. From the conclusions, the following recommendations can be drawn:

1. *Transparency of all activities*
2. *Communicate with stories focusing on customer value*
3. *Assure an excellent scientific level of research on risks of nanotechnologies*
4. *Balanced communication between risks and benefits*
5. *Framework conditions for fruitful communications:*
    a. *Create a "Gene Suisse" like organization*
    b. *Raise awareness of the Nano science community for the need of communication to the public*
    c. *Learn from Biotech: divide Nanotechnologies in green and red*
    d. *Use existing frameworks like 'science et citée'as communication platform to the public*
    e. *Maintain an ongoing dialog with all stake holders*
6. *Avoid yuck words such as:*
    a. *"atomically modified" rice*
    b. *"terminator technology"*
7. *Communication topics:*
    a. *Take care of the losers*
    b. *Stories, not education*
    c. *Attract viewers*
    d. *Science is self correcting, the press not*
    e. *Solve important problems with science, not without!Give the correct and adequate answers!*
8. *Road Map addressing safety and risk issues of:*
    a. *fullerences, nanotubes and other nanoparticles, that have already been developed, commercialised and distributed in the environment in the past*
    b. *ongoing and future research, aiming at the development and implementation of new nanomaterials or other nanotechnological products*

van Es et al. (2004) states that the public debate on nanotechnology is clearly still in its infancy but being pushed by a combination of strong growth in financing and patents, high scientific expectations and related social hopes and concerns. They especially focus on the issue of privacy:

> *In this so-called 'ambient intelligence' scenario products and people will always be 'online', and connected internationally by wireless communication methods. Such extensive technical possibilities to detect, localise and communicate clearly involve privacy implications and consequences in terms of safety, economics, schooling, employment, responsibilities, roles, and so on.*

van Es et al. (2004) adresses similar issues as listed above:

- *Nano-electronics and privacy*
- *Bio-electronics and the makability of humans*

- *Nano (and gene) technology in the medical and pharmaceutical environment*
- *Military technology e.g. "killer robots"*

In its newly published communication, "Towards a European strategy for nanotechnology", the EU-Commission also stresses the importance of public or societal involvement:

> *5. Highlighting the need to devote due attention to the societal aspects of nanotechnology, the Commission:*
> *(a) calls upon Member States to pursue an open and proactive approach to governance in nanotechnology R&D to ensure public awareness and confidence;*
> *(b) encourages a dialogue with EU citizens/consumers to promote informed judgement on nanotechnology R&D based on impartial information and the exchange of ideas;*
> *(c) reaffirms its commitment to ethical principles in order to ensure that R&D in nanotechnology is carried out in a responsible and transparent manner.*

Also the perspective of marketing could be addressed as an ethical aspect, but this is much more relevant in a very short time horizon, as the potential of another "IT bubble" is clearly at hand.

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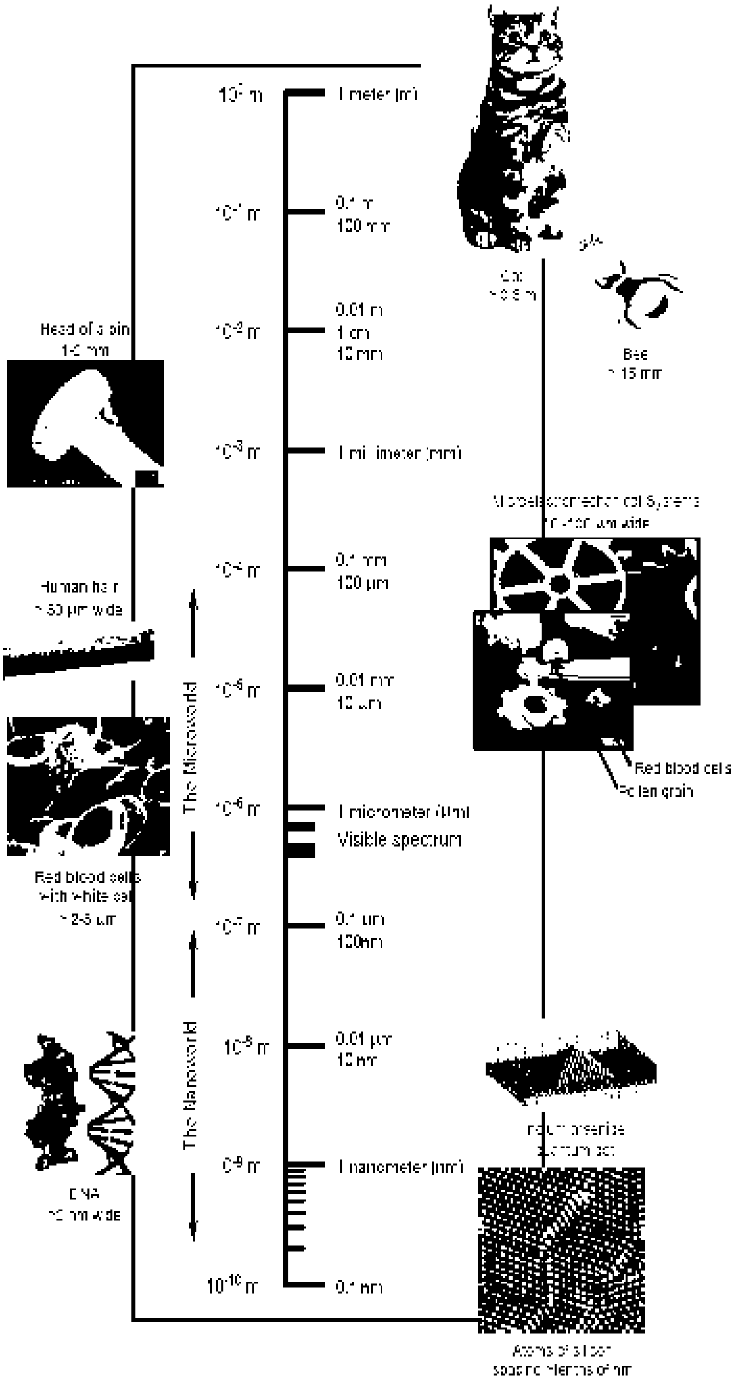
Links

* - included but not used for information search or nothing readily available

Cea-Leti (France) – research network*	http://www.minatec.com/minatec_uk/minatec/recherche.htm
Center for Biological and Environmental Nanotechnology, Rice University, Chemistry Department, Texas, USA	http://www.environmentalfutures.org/nanotech.htm
Center for Responsible Nanotechnology; started in December 2002	http://crnano.org/
CMP Cientifica (Spain) - Cientifica is the world's largest supplier of nanotechnology information	http://www.cmp-cientifica.com/
ETC - The Action Group on Erosion, Technology and Concentration, formerly RAFI, is an international civil society organization headquartered in Canada. The ETC group is dedicated to the advancement of cultural and ecological diversity and human rights.	http://www.etcgroup.org/search.asp?slice=english&srch=nano
EU activity area (new strategy just published)[4]	www.cordis.lu/nanotechnology
European Union sponsored Thematic Network	http://www.nanoforum.org/
Institute of Nanotechnology[5] (UK)	http://www.nano.org.uk
Malsch Techno Valuation (Netherlands) - Malsch Techno Valuation is a result-oriented consultant on technology and society.*	http://www.malsch.demon.nl/
NANOSAFE, NANOGATE TECHNOLOGIES GMBH*	http://www.nanogate.de
Nordic Nanotech (Denmark)	http://www.nanotech.dk/
Ron Epstein homepage on NT	http://online.sfsu.edu/~rone/Nanotech/nanotech.htm
TEMAS, the independent trusteeship company for services focusing on new technologies and the effective application of scientific findings for innovation	http://www.temas.ch/
Teknologisk Fremsyn om Nanoteknologi*	http://www.teknologiskfremsyn.dk/
The Ethics Web is a collection of ethics-related websites, run by philosopher-ethicist Chris MacDonald. Chris has been administering respected ethics-related websites since 1994.	http://www.ethicsweb.ca/NT/
The Royal Society (UK), working group on nanotechnology	www.nanotec.org.uk
VDI Technologiezentrum (Germany) – networks, funding programmes etc. on nanotechnologies and nanobiotechnologies	http://www.vditz.de/

[4] A survey of networks can be found at http://www.cordis.lu/nanotechnology/src/networks.htm
[5] The Nanoforum Consortium has 54 partners in Austria, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Lithuania, Netherlands, Sweden, Switzerland, and UK.

Annex 1 What is nano?



(Holister, 2002)

Annex 2 What is nanotechnologies (NT)?

The ability to do things—measure, see, predict and make—on the scale of atoms and molecules and exploit the novel properties found at that scale. Traditionally, the NT realm is defined as being between 0.1 and 100 nanometers, a nanometer being one thousandth of a micron (micrometer), which is, in turn, one thousandth of a millimetre (Holister, 2002).

Fabrication of nanoscale structures by machining and etching techniques (Saxl, 2000).

Area of science and technology where dimensions and tolerances in the range of 0.1nm to 100 nm play a critical role. It encompasses precision engineering as well as electronics; electromechanical systems (eg 'lab-on-a-chip' devices) as well as mainstream biomedical applications in areas as diverse as gene therapy, drug delivery and novel drug discovery techniques. (http://www.nano.org.uk/nano.htm)

"Nanotechnology cannot be defined in terms of dimensions alone. In fact, it represents a convergence of the traditional disciplines of physics, chemistry and biology at a common research frontier." Commisioner Busquin, in the Proceedings of Joint EC/NSF workshop on Nanotechnologies, Toulouse, 19-20 October 2000. http://www.cordis.lu/nanotechnology/

"At this moment there is no such thing as an unequivocal, commonly used definition of nanotechnology. All definitions however refer to its physical scale. Nanotechnology is that technology based on the nano-scale, that is to say on dimensions of less than one hundred nanometres in one direction (a nanometre (nm) = one billionth metre). Some definitions refer to new phenomena and material properties manifesting themselves at the nanometre scale. Others refer to how (top-down and bottom-up) products are made on that scale. Top-down refers to achieving the nano-scale through miniaturisation. Bottom-up refers to processes on the nano-scale which are studied and which lead to new phenomena and new products." (van Es et al., 2004)

Dürrenberger et al. (2003) emphasises not only the size, but also new properties and shapes (sherical with core, spherical wothout core e.g. fullerenes), cylindrical (single wall, multiple walls), and non-spherical (nanoplates)

An overview table is given below based on several of the references (Altmann and Brugud, 2002; Arnall, 2003; Colvin, 2003; Masciangioli, 2002; Höhener, 2004; BioNyt 123, 2004[6]). The applications are not restricted to one or the other area of technology but structured according to the most likely application.

[6] BioNyt is a popular scientific and technology journal; references (4-digit numbers) are available at www.bionyt.dk

<table>
<tr><th>Technology area</th><th>Current</th><th>1-5 Years</th><th>6-10 Years</th><th>10-50 Years</th><th>Environment</th><th>Health</th><th>Safety</th><th>Ethics</th></tr>
<tr><td rowspan="5">Medical technology
Nanobiotechnology
Nanomedicin</td><td rowspan="5">Sun screens[7]
Antigen-sensors for cancer etc.[8]</td><td rowspan="5">Biological nano-(bio)sensors for measurements[9] and diagnostics (medicine, vira, bacteria)
Nanocrystal and amorf materials for implants</td><td>Artificial muscle</td><td>Nano-machines for in vivo treatment</td><td rowspan="5">Medium risks</td><td rowspan="5">Medium risks
Dunford et al. (1997) [10]</td><td rowspan="5">Low risks</td><td rowspan="5"></td></tr>
<tr><td>Lab on a chip technology for more efficient drug discovery (nanofluidic)</td><td>Nanopumps and -valves for tissue</td></tr>
<tr><td>Targeted drug and gene delivery, nanomedicine</td><td>Engineering/artificial organs</td></tr>
<tr><td>More efficient solar cells using NT</td><td>Nanomaterials for hydrogen storage fuel cells</td></tr>
<tr><td>Carbon nanotubes in electronic components</td><td>Nanomaterials in light emitting diodes/fsts and PV devices single electron/molecule devices</td></tr>
</table>

[7] Zinc oxide and titanium dioxide nanoparticles block UV light, ETC (2002)
[8] Science, 26.9.2003
[9] Nano-bars bends when molecules adhere to surface; cells damaged by radiation can be traced using nano-particles with CD-95 markers; BioNyt 123 (2946); cells used as transistors (Møller et al., 2003)
[10] Titanium dioxide/zinc oxide nanoparticles from sunscreen are found to cause free radicals in skin cells, damaging DNA. (Oxford University and Montreal University) Dunford et al. (1997)

Technology area	Current	1-5 Years	6-10 Years	10-50 Years	Environment	Health	Safety	Ethics
Environmental technology	Groundwater treatment (catalysts, particles, filters[11]) Air emission cleaning (catalysts) Surface cleaning by bacteria and fungi		New measurement technologies (smaller samples, more specific) New end-of-pipe technologies (filters, reactors, catalysts)					
Energy technology	Nano-catalyst enhanced fuels for better efficiency Nanotubes for fuel cells/batteries (energy storage) e.g. mobile phones and laptops (methanol based low-temperature fuel celle)		Flat panel flexible displays using NT high density data storage using nanomagnetic effects	Faster processing using quantum computing DNA computers				
Process technology	Catalytic nanoparticles in materials, fuel and food production, health and agriculture; e.g. iron and zink particles used in groundwater treatment for removal of chloro-organic pollutants Carbon nanotubes (single wall and multilayer) (50-100 times stronger than steel) in space and aircraft manufacture, automobiles and construction.		Nano-catalysts based on natural processes at ambient temperature and pressure Nano-membranes (chemical, petrochemical, food and drink industries)					
Surface technology New materials Nanomaterials Surfaces	Nanoparticulate dry lubricant for engineering (nanocapsules)	Smart/responsive nano-coatings for food Self-assembling monolayers leading to laminates applicable based on properties from chemical activity to wear	Nanoparticle coatings e.g. metallic stainless steel coatings sprayed using nanocrystalline powders with increased hardness; can be used in sensors, reactions beds, liquid crystal manufacturing,		High risks	High risks	Medium risks	

[11] Nanofibres can reduce pore size from 3μm to 0,1 μm

Technology area	Current	1-5 Years	6-10 Years	10-50 Years	Environment	Health	Safety	Ethics
		resistance	lubrication, protective layers, anticorrosion coating, tougher and harder cutting tools Self-repairing structures e.g. airplane wings with protein-filled nano-tubes					
Material technology	Photographic films[12] Self-cleaning windows Nanoparticles for pigments (paints)[13] Nanocomposites used in carbon black used in e.g. vehicle tyres Weather resistant textiles Tooth fillings Sports equipment[14]	Incorporation of nanoparticles and capsules into clothing leading to increased lightness and durability, and "smart" fabrics, that change their physical properties according to the wearer's clothing			Brown (2002)[15] Brumfiel (2003)[16] New Scientist (2004)[17]	Hogan (2003)[18] ETC (2003)[19] Kirby (2004)[20] Wootliff (2004)[21]		

[12] 90% of Kodak B/W films uses nano-layer-technologies; also used in optical filters; BioNyt 123, 2004
[13] Antimony tin oxide; ETC (2002)
[14] Golf balls; tennis rackets
[15] March 2002 – Researchers from the Center for Biological and Environmental Nanotechnology (CBEN, Rice University, Houston) report to US EPA that engineered nanoparticles accumulate in the organs of lab animals and are taken up by cells. “We know that nanomaterials have been taken up by cells. That sets off alarms. If bacteria can take them up then we have an entry point for nanomaterials into the food chain.” Dr. Mark Wiesner. Brown (2002)
16 July 2003 – Nature reports on work by CBEN scientist Mason Tomson that shows buckyballs can travel unhindered through the soil. “Unpublished studies by the team show that the nanoparticles could easily be absorbed by earthworms, possibly allowing them to move up the food-chain and reach humans” – Dr. Vicki Colvin, the Center’s director; Brumfiel (2003)
17 March 2004 – Dr. Eva Oberdörster reports to American Chemical Society meeting that buckyballs cause brain damage in juvenile fish along with changes in gene function. They also are toxic to small crustaceans (water fleas). “Given the rapid onset of brain damage, it is important to further test and assess the risks and benefits of this new technology before use becomes even more widespread.” – Dr. Eva Oberdörster.New Scientist (2004)

Technology area	Current	1-5 Years	6-10 Years	10-50 Years	Environment	Health	Safety	Ethics
Security technology		Nano bar coding and tagging nanotubes for thermal protection	Flat panel flexible displays using NT high density data storage using nanomagnetic effects	Faster processing using quantum computing DNA computers				High risks
Electronic technologies (computing, communication etc.) Bioelectronics	Flat screen monitors Batteries Optic cables CD players (quantum wells; ultra-thin layers of semiconductor material for lasers)	Low-cost telecommunications and optics (quantum wells in fibre optics) Nanocomposites used for purity and conductivity (prionproteins)[22] in microelectronics Carbon nanotubes used for memory (one book on a stamp) and storage in electronics; flat screens	"Lab on a chip" NT for analytical processes, synthesis and catalysis; e.g. environmental monitoring Fluorescent nanoparticles (quantum dots) for telecommunications and optics[23] Cells used as transistors	Ultra-light materials for cheaper construction and transportation Single atom transistor Mobile phones in the ear Nanobioconductors Cryptographic applications of quantum computers	Low risks	Low risks Mullins (2004)[24]		

18 March 2003 – Researchers from NASA/Johnson Space Center report that studies on effects of nanotubes on the lungs of rats produced more toxic response than quartz dust. Scientists from DuPont Haskell laboratory present varying but still worrying findings on nanotube toxicity. “The message is clear. People should take precautions. Nanotubes can be highly toxic.” – Dr. Robert Hunter (NASA researcher); Hogan (2003)
19 March 2003 – ETC group publishes first scientific literature survey on nanoparticle toxicity by toxicopathologist Vyvyan Howard. Dr. Howard concludes that the smaller the particle, the higher its likely toxicity and that nanoparticles have various routes into the body and across membranes such as the blood brain barrier. “Full hazard assessments should be performed to establish the safety of species of particle before manufacturing is licensed. We are dealing with a potentially hazardous process.” – Dr. Vyvyan Howard; ETC (2003c)
20 January 2004 – Research by Dr. Günter Oberdörster is published showing that nanoparticles are able to move easily from the nasal passageway to the brain. “The nanotechnology revolution may design particles that are very different chemically from the ones we are exposed to, and they might have very different properties that made them more harmful. We should be vigilant.” – Professor Ken Donaldson, University of Edinburgh; Kirby (2004)
21 January 2004 – At the first scientific conference on nanotoxicity, Nanotox 2004, Dr. Vyvyan Howard presents initial findings that gold nanoparticles can move across the placenta from mother to fetus. Woofliff (2004)
[22] Not destructed by boiling, solvents or denaturation
[23] 2-10 nm particles where change in energy status produces fluorescent light
24 February 2004 – Scientists at University of California, San Diego discover that cadmium selenide nanoparticles (quantum dots) can break down in the human body potentially causing cadmium poisoning. “This is probably something the [research] community doesn't want to hear.” – Mike Sailor, UC San Diego. Mullins (2004)

Technology area	Current	1-5 Years	6-10 Years	10-50 Years	Environment	Health	Safety	Ethics
Military technology		Nanoscale Machines and Motors Nanostructures for Catalysis Biomolecular Control of Nanoelectronic and Nanomagnetic Structure Formation Polymeric Nanocomposites for High-Speed and Space Systems Nano-System Energetics; Organic Nanophotonics and Nanoelectronics; Characterization of Nanoscale Elements, Devices and Systems; Quantum Computing and Quantum Devices; Synthesis, Purification, and Functionalization of Carbon Nanotubes; Molecular Recognition and Signal Transduction in Bio-molecular Systems; Nanoscale Electronic Devices and Architectures; Synthesis and Modification of Nanostructure Surfaces; Nano-Porous Semiconductors – Matrices, Substrates, and Templates; Magnetic Nanoparticles for Application in Biotechnology; Deformation, Fatigue, and Fracture of Nanostructures and Interfacial Materials						

Technology area	Current	1-5 Years	6-10 Years	10-50 Years	Environment	Health	Safety	Ethics
Nano-bots		Nanorobots of Ti/Ni alloys ("arms" and "legs" move due to laser or ultrasound energy but remember original form)[25]		Self-replicating machinery Nano-factories				High risks

[25] Technology Innovations, NY, BioNyt 123 (2942)

Annex 3 Terminology in Danish technology forecast on nantechnologies

Terminologi m.m. fra ekspertnotater til det teknologiske fremsyn om nanoteknologi (2004)

Feidenhans'l et al (2004) Nanomaterialer

- nanopartikler
  - katalyse (afbrænding af dieselolie,
  - brint og brændselsceller – katalyse med billigere og ugiftige materialer, batterierstatninger = brændselsceller med methanol
  - pigmenter, kosmetik
  - magnetiske nanopartikler (processorhastighed og datalagring)
- nanofase og nanokrystallinske materialer
  - termoelektriske materialer (køling)
  - nanokrystallinske materialer (hårdhed bestemt af kornstørrelse, amorfe legeringer til implantanter og sportsudstyr)
  - plastik elektronik (silicium i halvledere og solceller erstattes af lang billigere elektrisk ledende plastik til fx prismærkater, elektronisk papir, displays (på markedet, men indkapslede; problem med levetid)
  - (blokco)polymerer (amfifile molekyler – blokke med forskellig affinitet overfor forskellige opløsningsmidler, som kan bruges til molekylær selvorganisering; bruges i dag i skosåler, lim, selvklæbere og til kontrol af viskositet i motorolie, tandpasta m.m.; selvreparerende overflader)
  - nanostrukturerede magenetiske materialer (grænsefladeegenskaber) (læsehoveder til magnetiske harddiske (Gigantisk Magnetisk Resistans) (keramer, som båd er magnetiske og elektrisk ledende som ikke-flygtige datalagringsmedier og hukommelser)
  - spintronics (ny type elektronik baseret på keramer i stedet for silicium og elektronspin i stedet for ladning)
- coatings, belægninger, overflader (slid- og korrosionsbestandige overflader til bevægelige dele i mekaniske og elektroniske komponenter) (energiglas; smudsafvisende vinduer)
- nanofibre og kompositter (vindmøller, rørledninger, skibe, luftfart, biler) (nanorør som fiberforstærkning af polymerer – stivhed og styrke som metaller, men meget lettere; bedre styring af genanvendelighed) (tekstiler)
- nanorør og nanofibre (halvleder eller fuldt ledende afhængig af struktur) (elektronstrålekilder til fladskærme, lamper, lysstofrør, røntgen- og mikrobølgegeneratorer; transistorer, lsydioder) (overfladebelægning af metaller, radioaktivt materiale m.m. med kul)
- nanoporøse mateialer (katalysatorer, kunstige zeolitter, membraner

Stubkjær et al. (2004) Nanoelektronik og nanooptik

- integrerede kredse (50 nm)
- hukommelseselementer (50 nm)
- kvantepunktslasere (10 nm)
- optiske fibre (100 nm)

- polymerelektronik og –optoelektronik
- halveleder kvantepunkter
- nanoskala sensorer
- finstruktur i optiske materialer
- organisk elektronik der samler sig selv

Wengel et al (2004) Nanobiosystemer

- analyse af enkeltmolekyler
- selvansamling af nanostrukturer
- procesteknologi for nanofabrikation
- drug delivery og drug targeting
- nanomedicin
- nanobiosensorer
- nanofluidik
- nanoelektronik
- nanocomputere
- nanomotorer
- biokompatible overflader
- selvansamling af nanostrukturer
- katalyse og syntese
- avancerede nanorobotsystemer