



Environmental, Health and Safety (EHS) Impacts

Technology Sector Evaluation:
Environment

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V 1.0 June 2010

<http://www.observatorynano.eu/>

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1. Introduction

Maintaining and restoring the quality of air, water and soil is one of the great challenges of our time. The scarcity of water, both in terms of quantity as well as quality poses a significant threat to the well-being of people - especially in developing countries. Conventional remediation technologies have so far shown only limited effectiveness in reducing the levels of pollutants - especially in soil and water. Nanomaterials will be able to perform significantly more effectively than larger particles because of the much greater surface area. Most effective will probably be a combination of more than one (nano)technology in a hybrid system and membrane technologies are expected to play a role in this.

So far only few industrial companies consider environmental technologies as a core business, even though there is obvious potential for market applications (e.g. drinking water purification) (MORRISON, 2006; RICKERBY and MORRISON, 2007). A large hurdle are the initial costs for the material, pilot run and facilities. Morrison (2006) suggests to link environmental issues with public health as a driver for creating markets.

Various applications have been successfully demonstrated at the laboratory scale but most of them still require verification of efficacy and safety in the field and are thus still far from market. Further research is also needed to assess the environmental impact of the nanoparticles released (NOWACK and BUCHELI, 2007). There are also serious concerns about the release of free nanoparticles in the environment used for remediation purposes (NOWACK, 2008).

The ObservatoryNANO report on the technology sector Environment summarises the technologies and applications used for the treatment of air, water and soil (Mueller and Nowack, 2009). This EHS analysis considers those nanomaterials outlined within the context of their application and provides a summary of what is known in relation to potential hazard of and exposure to the material in question. Finally, the analysis outlines some key EHS considerations and basic guidance for those developing or using the technologies outlined within the report.

For all of those nanoparticles identified as having potential EHS impact, toxicological knowledge is still emerging, although based on what is known to date a reasonable approximation of potential hazard may be made. The key common knowledge gap across all nanoparticles however is the lack of exposure measurements for the scenarios and applications in question. As the ObservatoryNANO Project progresses, it is expected that these knowledge gaps will be addressed (at least in part) and thus that later EHS reports will be able to reach more resolute conclusions on the risks posed by those nanomaterials in consideration.

2. General Considerations for the Environment, Health & Safety Impact of nanomaterials

The key benefit from nanotechnologies is the ability to exploit the specific, novel and sometimes unpredictable properties that arise from structuring matter at this scale. Over the last 10 years, nanotechnologies have received extensive investment, and have emerged as major drivers of science based innovation and industry. This has led to the development of new processes, products and materials for a wide range of applications.

In 2004 the UK's Royal Society and the Royal Academy of Engineering (RS/RAEng) published a seminal review of the "opportunities and uncertainties" presented by nanotechnologies (RS/RAEng, 2004). Whilst indicating that for many nanotechnologies, there were no foreseeable risks to health or to the environment, the report concluded that for "nanoparticles and nanotubes" there were potential risks, and that not enough was known about them. This conclusion was based on evidence gained from many years of research that exposure to particles can cause ill health within individuals or exposed populations. For example, within the occupational setting, exposure to coal dust is evidentially linked to the onset of lung diseases including pneumoconiosis and chronic obstructive pulmonary disease (COPD), and exposure to asbestos is causative of asbestosis, mesothelioma and lung cancer. In an environmental context, evidence suggests that exposure to the particulate component of atmospheric pollution may be associated with increased hospitalization rates and cardio-vascular disease (Seaton et. al, 2009).

Publication of the RS/RAEng report led to a huge increase in research activity concerning both human health and environmental consequences (Lee et. al., 2008). For example, in Europe the Framework 7 NMP programme has funded more than 20 major projects, with a total budget of more than €50million. This research activity has addressed *inter alia* the toxicity and ecotoxicity of many types of nanoparticles, the kinetics of nanoparticles within biological and environmental systems, the extent to which individuals or the environment can become exposed and the level of risk which would result. These investigations have examined numerous mechanisms, end points and processes and materials, and have generated an extensive body of literature, particularly in relation to toxicology and ecotoxicology.

2.1 Establishing a knowledge on the potential hazard and exposure to nanomaterials

Scientific data compiled to date demonstrates that adverse health effects due to exposure to nanoparticles cannot be ruled out (Aitken et. Al., 2009a; 2009b; van Zijverden & Sips (eds.), 2009). However, although awareness for the importance of risk research has increased, critical information still is lacking to enable estimation of the risks posed by nanoparticles with equal certainty to those of other non-nano substances. Nevertheless, hundreds of products containing nanomaterials are currently available commercially, a situation which clearly necessitates investigation of the exposure and toxicity of these materials in the near future. Unfortunately, the research questions to be answered are so numerous that it will take years to compile the relevant data.

The potential for nanoparticles to cause damage has also been implicated within the environment, both directly via uptake into plants or organisms (including soil bacteria, eukaryotes, invertebrates and vertebrate species), and indirectly via changes in environmental variables such as pH of aquatic systems, ionic strength or dissolved organic carbon content (Aitken et. al., 2009a). Carbon nanotubes (CNT) and silver nanoparticles have been shown to cause detrimental effects in zebrafish development (Cheng et. al., 2007), and copper nanoparticles have been shown to be highly toxic to fish, daphids and algae (Griffitt et. al., 2008), and to induce stunting of exposed plant seedlings (Lee et. al., 2008).

Man and the environment can come into contact with the use of nanotechnology through a wide range of application areas. Some of these applications are produced only with the aid of nanotechnology, others contain nanomaterials. For the risk assessor, this second category is important, particularly when the applications contain non-degradable, insoluble, and freely available nanoparticles. For this category of products there are already a great many different areas of potential use, including medical applications, food, and consumer products as well as environmental and energy technology. These applications can improve the quality of life and the environment and can also lead to significantly more sustainable products, but for which it is of particular importance to understand and control potential risk.

There are already hundreds of nanotechnology applications on the market. For example, nanoparticles of titanium oxide and zinc oxide are regularly used as UV reflectors in sunscreen creams. Nanotechnology is also used to make clothing crease- and dirt-resistant, and to make electronics ever smaller, faster and more multifunctional. However, the majority of potential applications for nanotechnologies are currently still in the research and development phase and are expected to appear on the market over the coming years.

Understanding and effective management of potential risks posed by manufactured nanoparticles and nanomaterials is pivotal for responsible and sustainable development of nanotechnology. This in turn is mandatory for societal acceptance and exploiting the significant economic potential of this technology to the full.

2.2 Risk Assessment considerations for nanomaterials

In assessing the risks of non-nano chemical substances and nanomaterials alike, the following general approach is applied:

$$RISK = HAZARD (TOXICITY) \times EXPOSURE$$

The intrinsic hazard (toxicity) of a nanomaterial is determined by a number of factors, such as the ability of a nanoparticle to pass through certain barriers in humans, plants or animals and cause damaging effects. The actual exposure is also determined by various factors such as the form in which the nanomaterial occurs (e.g., either bonded or as 'free' particles) the specific setting in which the nanoparticle is being manufactured applied or used (and thus likelihood of contact). Thus, a specific nanomaterial may be hazardous, but if the level of exposure is very small, the ultimate risk will always be limited. For example, a specific nanoparticle bound within ultra-high performance concrete used to construct a bridge will pose less of a potential risk to consumers (i.e. those using the bridge), than the same NP used within antimicrobial food packaging, where the potential for consumer exposure may be increased due to their close contact with the product in which the NPs are bound.

Two areas can be distinguished within risk research for nanotechnology. One area aims at risks related to exposure to nanomaterials and the second area aims at risks related to the rest of nanotechnology and its products. There is consensus that the uncertainties about these risks need to be addressed most urgently.

In 2009, the Dutch Knowledge and Information Point "Risks of Nanotechnology" (RIVM/KIR nano) recommended to focus research primarily on those questions that provide information critical to the assessment of risks to man and the environment (van Zijverden & Sips (eds.), 2009). Depending on the perspective - worker, consumer, patient, or the environment - the starting points can then be defined for controlling or limiting the risks.

From this and other literature on the topic, there may be identified several key challenges for the EHS appraisal and risk management of nanomaterials:

1. *There is a high urgency for relevant risk information:* One of the pitfalls of emerging technologies is the imbalance between technological development and attention for human health and environmental safety issues as is the case for nanotechnology. Risk information needs to be generated and shared as quickly as

possible for products on the market, underpinning the societal acceptance of further applications of this technology.

2. *Validity of known test systems is questionable, and detection of nanomaterials still problematic.* Nanomaterials create a challenge for risk research as they (might) behave differently in regular assessment and testing systems. Equipment and methods to detect nanomaterials allowing large-scale application are lacking.
3. *National, international and interdisciplinary integration is a prerequisite.* A large variety of research questions need to be addressed before uncertainties about risks for man and the environment are at the same level as for other chemical substances.

Whilst this brief introduction provides an outline of the key issues, it is impossible to outline the current knowledge on the hazard, exposure and risk assessment for nanoparticles in full. Instead the reader is directed towards the ObservatoryNANO Baseline Studies (Ross et. al., 2009) where many of the seminal studies from the last few years are identified and described.

2.3 The ObservatoryNANO Approach: Integrating EHS considerations with development of novel applications for nanotechnologies

ObservatoryNANO is concerned with mapping scientific and technological development across 10 core technology sectors, and a key task of WP5 is to undertake an appraisal of these reports and to identify potential emerging environment, health and safety issues therein, thus integrating the development of novel applications with risk research, an approach which is urgently required.

There is considerable overlap between those nanoparticles used across these 10 sectors - what differs is their use, which varies according to the application. Therefore the aspect which is specific to the technical sector in considering those novel risks which may arise from development of novel applications, is the potential for exposure. For this reason, the approach which we have adopted is to consider the potential exposure which may arise from the new applications identified.

As far as possible, we have considered the life cycle of the applications identified, whether there were possible exposures within the occupational setting, or to consumers or release to the environment. We also considered whether there was the potential for release from disposal.

Our review process involved extraction of information from each technology sector report & gathering of additional information from their lead authors. This data was then analysed, and our findings outlined within the subsequent sections of this report. In addition to a short summary of the key exposure issues identified from our analysis, our report includes three key tables as follows:

1. A table summarising all information gathered together with consideration of the potential for exposure arising throughout the lifecycle of each application
2. A table outlining those nanoparticles/nanomaterials in use within each technology sector, according to application
3. A table highlighting those applications where we consider there to be a high potential for release.

Detailed information of the type required to make strong evidence judgments about possible exposures was only very rarely available, and this is indicated in table. In none of the scenarios was actual exposure data available. However, for some applications additional information was available from the peer reviewed literature, and where this has been used this is again indicated within the table. In the majority on settings identified, due to the paucity of data assessment of whether or not exposure is plausible is based on expert judgement and information available from other similar scenarios. In this respect, these judgements should be considered provisional and where possible, effort should be placed on collecting relevant specific primary exposure data. As the ObservatoryNANO

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Project progresses, it is expected that these knowledge gaps will be addressed (at least in part) and thus that later EHS reports will be able to reach more resolute conclusions on the risks posed by those nanomaterials in consideration.

3. Potential for exposure

The following table outlines and ranks the *potential* for exposure associated with the use of nanomaterials in the applications shown. In the absence of real exposure data, it is based primarily upon expert evaluation of the information provided in the technical reports. As a default we have indicated that there is a high potential for exposure in all occupational settings associated with the manufacture of nanomaterials unless adequate control measures are applied. In applications where the hazard (toxicity) of the nanomaterials are similar, those with the highest potential exposure will have the highest potential risks.

Table 1: Potential EHS Impacts Identified

ENVIRONMENT									
				Exposure potential Use (e.g. activity, exposure route, what)				Exposure potential Disposal (e.g. incinerated, landfilled, recycled, STP)	
Sub sector	Application ¹⁾	Types of NP ²⁾	Incorporation in products ³⁾	Manufacturer	Professional user	Consumer	Environment	Human	Environment
Air purification	Catalytic traps	Many different metal oxides (LiCrO ₂ , CoCr ₂ O ₄ , CeO ₂ , MnCr ₂ O)	Bound in matrix	Release during synthesis and incorporation into matrix is possible, release into air (worker exposure) and wastewater	Exposure potential very small, no release during use	Exposure potential very small, no release during use	Exposure potential very small, no release during use	Possibility of release of particles if filters are shredded	Very low exposure potential (mainly during shredding into air)
	photocatalysis	TiO ₂ , ZnO	Bound in matrix	Release during synthesis and incorporation into matrix is possible, release into air (worker exposure) and wastewater	Small possibility of release into air, especially if the matrix is photochemically degraded	Small possibility of release into air, especially if the matrix is photochemically degraded	Small possibility of release into air, especially if the matrix is photochemically degraded	Possibility of release of particles if filters are shredded	Very low exposure potential (mainly during shredding into air)

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	Air filters	CNT	Bound in n polymer matrix	Release during synthesis and incorporation into matrix is possible, release into air (worker exposure) and wastewater	Exposure potential very small, if then into air	Exposure potential very small, if then into air	Exposure potential very small, if then into air	Possibility of release of particles if filters are shredded, very low release potential if incinerated	Very low exposure potential (mainly during shredding into air)
Wastewater purification, Drinking water treatment	Photocatalysis	TiO ₂ , ZnO	Bound in matrix, or thin films	Release during synthesis and incorporation into matrix is possible, release into air (worker exposure) and wastewater	No exposure to users as release would only occur into water	No exposure to users as release would only occur into water	Small possibility of release into water	Possibility of release of particles if products are shredded	Very low exposure potential (mainly during shredding into air)
	Nanofiltration	No particles but nanostructured material	No particles	No release possible because no particles are used	No release possible because no particles are used	No release possible because no particles are used	No release possible because no particles are used	No release possible because no particles are used	No release possible because no particles are used
	Adsorption	Various metal oxides (e.g. Si-Al oxides, Mn-oxides), CNT	Free particles	Release into air during synthesis and handling	Release into air during application possible	Release into air during application possible (if applied as powder), exposure small if used as suspension	If not properly removed from water significant release into natural waters or drinking water can occur, also release into air during spraying	Exposure possible when particles collected from water undergo further treatment (e.g. regeneration)	Release of collected particles possible, mainly into water
	Electrochemical	Boron doped diamond	Thin films on substrate	Direct growth on substrate, therefore no potential for release	Very small, if then into water	Very small, if then into water	Very small, if then into water	Exposure unlikely, possibility of release of particles if products are shredded	Unlikely, possibility of release of particles if products are shredded

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	Magnetic particles	Magnetite, maghemite	Free particles	Release into air during synthesis	Release into air during application possible	Release into air during application possible (if applied as powder), exposure small if used as suspension	If not properly removed from water significant release into natural waters or drinking water can occur	Exposure possible when particles collected from water undergo further treatment (e.g. regeneration)	Release of collected particles possible, mainly into water
Groundwater remediation		Zero-valent iron (nZVI), iron oxides	Free particles, but always used as slurry (nZVI)	Release into water during synthesis	Exposure only through spills from suspension	Only used in professional settings, very low exposure potential for consumers if particles end up in drinking water	Direct release into environment, removal by degradation	No disposal as particles are used up during use	No release during disposal as particles are used up during use
Soil remediation		Zero-valent iron (nZVI), iron oxides, dendrimers	Free particles, but always used as slurry (nZVI)	Release into water during synthesis	Exposure only through spills from suspension	Release into air during application possible	Direct release into environment, removal by degradation	No disposal as particles are used up during use	No release during disposal as particles are used up during use

¹⁾ group according to LCA; ²⁾ on the market ; ³⁾ e.g. bound, unbound, enclosed;

4.0 Conclusions

The key nanoparticles identified as carrying potential EHS impact across the construction technology sector are outlined in table 2. The two most commonly used nanoparticles within the sector were titanium dioxide and iron/ iron oxides.

Table 2: Nanoparticles carrying potential EHS impact, according to application

	Carbon Nanotubes	Titanium Dioxide	ZnO	nZVI	Iron oxides	Various
Catalytic traps (air)						Many different metal oxides (LiCrO ₂ , CoCr ₂ O ₄ , CeO ₂ , MnCr ₂ O)
Air filters	•					
Photocatalytic (air and water purification)		•	•			
Nanofiltration						
Adsorption	•				•	Various metal oxides (e.g. Si-Al oxides, Mn-oxides)
Electrochemical						Boron doped diamond
Magnetic					magnetite, maghemite	
Groundwater remediation				•	•	
Soil remediation				•	•	Dendrimers

Those applications in which potential EHS issues were identified for nanomaterials used within the environment sector are mainly those applications where free nanomaterials are used, i.e. the addition of nanoparticles to wastewater or drinking water for adsorption or destruction of pollutants and the release of nanoparticles into groundwater and soil for remediation purposes.

The main routes of potential human exposure to the NPs considered were found to be:

- inhalation of powder, or of aerosolized NPs during production of the particles or manufacturing of matrix to which the NP are bound to
- inhalation of powder if free nanoparticles are applied to water
- following any degradation/abrasion during use, however, this occurs mainly into water
- at disposal or recycling of the product, mainly if a product is shredded and thus release of matrix-bound NP is possible

The main routes of potential environmental exposure to the NPs considered were found to be:

- if free particles added to water are not removed after use from the water, significant release into surface/drinking water can occur.

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For personnel involved in manufacture of the products, the principal risk of exposure appears to be by inhalation. For the general public, exposure is more likely to be dependant on abrasion of the product during its use, or via release from the product during or following its demolition/disposal. Environmental exposures may potentially result from any of the stages listed above.

In Table 3 the applications with the highest exposure potential are listed: these are the use of nanoparticles in water or wastewater treatment to adsorb or degrade pollutants, the injection of nZVI into groundwater and the addition of nanoparticles to soils. In all three processes free nanoparticles are used, either in dry form or as slurry. Exposure of professional users is thus likely, either to dust or spills from handling slurries. In both soil and groundwater remediation complete release of the particles to the environment occurs. In the water and wastewater treatment technologies the particles are removed before using or discharging the water but a certain amount may not be removed and thus released to the environment.

Table 3: Applications with the highest exposure potential

Application	Exposure potential Use (e.g. activity, exposure route, what)			Exposure potential Disposal (e.g. incinerated, landfilled, recycled, STP)	
	Professional user	Consumer	Environment	Human	Environment
Water treatment with adsorptive processes using free nanoparticles or magnetic nanoparticles	Exposure through air or slurry, depending on way applied	Exposure through air or slurry, depending on way applied	If not properly removed from water significant release into natural waters or drinking water can occur	Exposure possible when particles collected from water undergo further treatment (e.g. regeneration)	Release of collected particles possible, mainly into water
Groundwater remediation using nZVI	Exposure to slurries possible		Complete release to the environment		
Soil remediation using free nanoparticles	Exposure through air or slurry, depending on way applied		Complete release to the environment		

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