ObservatoryNANO

Environmental, Health and Safety (EHS) Impacts

Technology Sector Evaluation: Construction

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1. Introduction

The construction sector deals with immense quantities of raw materials; for example, concrete is the most widely used man-made material on earth with a production volume of 14 billion tonnes per annum. Material innovations are continuously finding their way into modern building structure, and recent developments in pioneering nanomaterials will undoubtedly also contribute to this.

The construction sector technical sector report[1] addresses developments and applications for nanotechnologies. In particular, it examines developments in cement and concrete based materials, and coatings – especially those used on glass or steel surfaces.

The Environment, Health & Safety analysis of the construction technology sector considers the nanomaterials outlined therein within the context of their application, and provides commentary on the exposure potential for the material within that application.

The present report covers five major sub-sectors, classified within the ObservatoryNANO construction technology sector report according to application and societal needs as follows:

- Cement-based materials
- Coatings
- Civil engineering
- Sustainability & environment
- Living comfort & safety

The key common knowledge gap across all nanoparticle applications is the lack of exposure measurements. As the ObservatoryNANO Project progresses, it is expected that this knowledge gap will be addressed (at least in part). This, coupled with additional information on nanomaterial toxicology should enable later EHS reports 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 hospitalisation 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 (Aitken et. al., 2009a). For example, in Europe the Framework 7 NMP programme has funded more than 20 major projects, with a total budget of more that €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) x 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) he 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 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 exposure in applications

CONSTRUCTION									
Application & NP - Basic Info				**Exposure potential - Use (e.g. activity, exposure route, what)**				**Exposure potential - Disposal (e.g. incineration, landfill, recycled, STP)**	
Sub-sector	**Application**	**Types of NP**	**Incorporation in products**	**Manufacturer**	**Professional user**	**Consumer**	**Environment**	**Human**	**Environment**
Cement based materials (section 1.2.2)	Cement Additives - High Performance Concrete (HPC) Production using Gaia	Nanosilica	Addition of NPs to the concrete mix, particle size 3-150 nm	High - Release during manufacture is possible, exposure predominantly via air	Medium - dermal exposure possible if in liquid/slurry form	Low - Exposure potential very small, no release during use unless via wear and tear	Low - Exposure potential very small, no release during use unless via wear and tear	Low / medium (dependant on process of demolition). Specifically here there is a link to silicosis historically	Low / medium (dependant on process of demolition). Specifically here there is a link to silicosis historically
Cement based materials (section 1.2.2)	Ultra-high performance concrete (UHPC)	Silica, industrial by-products e.g. silica fume or fly ash	Addition of NPs to the concrete mix - liquid slurry or powder likely	High - Release during manufacture is possible, exposure predominantly via air	Medium - dermal exposure possible if in liquid/slurry form	Low - Exposure potential very small, no release during use unless via wear and tear	Low - Exposure potential very small, no release during use unless via wear and tear	Low / medium (dependant on process of demolition). Specifically here there is a link to silicosis historically	Low / medium (dependant on process of demolition). Specifically here there is a link to silicosis historically

Cement based materials (section 1.2.2)	Reinforcing material in various concretes	CNTs	Addition of NPs to the concrete mix - liquid slurry or powder likely	High - Release during manufacture is possible, exposure predominantly via air	Medium - dermal exposure possible if in liquid/slurry form	Low - Exposure potential very small, no release during use unless via wear and tear	Low - Exposure potential very small, no release during use unless via wear and tear	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Cement based materials (section 1.2.2)	Self-Compacting Concrete	Super plasticizers (e.g. polycarboxylate ether)	Addition of NPs to the concrete mix	High - Release during manufacture is possible, exposure predominantly via air	Medium - dermal exposure possible if in liquid/slurry form	Low - Exposure potential very small, no release during use unless via wear and tear	Low - Exposure potential very small, no release during use unless via wear and tear	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Coatings [section 1.3]	Low-Emmissivity coatings	Silver nanocoating	Vapour deposition techniques e.g. magnetron sputtering	High - Release during manufacture is possible, exposure predominantly via air	Medium - inhalation possible if coating in powder form or sprayed	Low - Exposure potential very small, no release during use unless via wear and tear	Low - Exposure potential very small, no release during use unless via wear and tear	Low / medium (dependant on process of demolition).	Low / medium (dependant on process of demolition).
Coatings [section 1.3]	Smart Glazing - Coating of the inner surface of glazing units.	Tungsten Oxide (WO_3) layers chromic glazings, polymer-dispersed liquid crystals (PDLC) for privacy glass	Not specified	High - Release during manufacture is possible, exposure predominantly via air	Medium - inhalation possible if coating in powder form or sprayed	Low - Exposure potential very small, no release during use unless via wear and tear	Low - Exposure potential very small, no release during use unless via wear and tear	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Coatings [section 1.3]	Self cleaning Glass Windows	TiO_2	Not specified	High - Release during manufacture is possible, exposure predominantly via air	Medium - inhalation possible if coating in powder form or sprayed	Low - Small possibility of release into air, especially if the matrix is photochemically degraded	Low - Small possibility of release into air, especially if the matrix is photochemically degraded	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Coatings [section 1.3]	Façade paint binder based on nanocomposite material	Silica nanoparticles	Intercalation of Silica NPs to composite	High - Release during manufacture is possible, exposure predominantly via air	Medium - inhalation possible if coating in powder form or sprayed	Low - Exposure potential very small, no release during use unless via abrasion	Low - Exposure potential very small, no release during use unless via abrasion	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)

Coatings [section 1.3]	Anti-Reflective Coatings for solar cells	Silicon nitride (SiNx), SiO_2, TiO_2, nanorods	Plasma-enhanced chemical vapour deposition (PECVD) or sputtering	High - Release during manufacture is possible, exposure predominantly via air	Medium - inhalation possible if coating in powder form or sprayed	Exposure potential very small, no release during use unless via abrasion or photocatalytic degradation	Low - Exposure potential very small, no release during use unless via abrasion	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Living comfort and Building safety	Flame retardant coatings for wooden surfaces and cables	Nanocomposites	Intercalation of Silicate NPs to montrnorillonite clay	High - Release during manufacture is possible, exposure predominantly via air	Medium - inhalation possible if in powder form or sprayed	Low - Exposure potential very small, no release during use unless via abrasion	Low - Exposure potential very small, no release during use unless via abrasion	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Living comfort and Building safety	Fire protection glazing	Modified SiO_2 particles	Interluminescent interlayer of fumed SIO_2 NPs (sandwiched between glass panels)	High - Release during manufacture is possible, exposure predominantly via air	Medium - inhalation possible if in powder form or sprayed	Low - Exposure potential very small, no release during use unless via abrasion or photocatalytic degradation	Low - Exposure potential very small, no release during use unless via abrasion or photocatalytic degradation	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Living comfort and Building safety	Antibacterial surfaces	Silver	Not specified	High - Release during manufacture is possible, exposure predominantly via air	Low - Exposure potential very small, no release during use unless via abrasion	Low - Exposure potential very small, no release during use unless via abrasion	Low - Exposure potential very small, no release during use unless via abrasion	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Living comfort and Building safety	Scratch resistant & easy-to-clean surfaces	SiO_2	Not specified	High - Release during manufacture is possible, exposure predominantly via air	Low - Exposure potential very small, no release during use unless via abrasion	Low - Exposure potential very small, no release during use unless via abrasion	Low - Exposure potential very small, no release during use unless via abrasion	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Civil engineering	Ultra-high performance concrete in Bridges	Nano silica	Addition of NPs to the concrete mix	High - Release during manufacture is possible, exposure predominantly via air	Medium - dermal exposure possible if in liquid/slurry form	Low - Exposure potential very small, no release during use unless via wear and tear	Low - Exposure potential very small, no release during use unless via wear and tear	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)

Civil engineering	White Toppings - UHPC	Silica	Addition of NPs to the concrete mix	High - Release during manufacture is possible, exposure predominantly via air	Medium- dermal exposure possible if in liquid/slurry form, or inhalation exposure if applied using spray	Low - Exposure potential very small, no release during use unless via wear and tear	Low - Exposure potential very small, no release during use unless via wear and tear	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Civil engineering	White Toppings - Photo-catalytic	TiO_2	Addition of NPs to the concrete mix - liquid slurry or powder	High - Release during manufacture is possible, exposure predominantly via air	Medium - dermal exposure possible if in liquid/slurry form	Low - Exposure potential very small, no release during use unless via wear and tear or photocatalytic degradation	Low - Exposure potential very small, no release during use unless via wear and tear or photocatalytic degradation	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Sustainability and environment	Innovative façade materials with photocatalytic activity to harvest energy from sunlight, and to reduce soiling, staining and pollution	TiO_2	Not specified	High - Release during manufacture is possible, exposure predominantly via air	Medium - inhalation possible if in powder form or sprayed	Low - Exposure potential very small, no release during use unless via abrasion	Low - Exposure potential very small, no release during use unless via abrasion	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)
Sustainability and environment	Less intensive use of cement clinker in innovative concrete materials, to reduce green house gas emission	Nanosilica	Addition of NPs to the concrete mix	High - Release during manufacture is possible, exposure predominantly via air	Medium - dermal exposure possible if in liquid/slurry form	Low - Exposure potential very small, no release during use unless via abrasion	Low - Exposure potential very small, no release during use unless via abrasion	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)

Sustainability and environment	Thermal Insulation	Nanoporous fumed silica in Vacuum Insulation Panels (VIPs)	Not specified	High - Release during manufacture is possible, exposure predominantly via air	Medium - inhalation or dermal possible if NPs released via abrasion/cutting during installation	Low - Exposure potential very small, no release during use unless via abrasion/degradation of insulation material	Low - Exposure potential very small, no release during use unless via abrasion/degradation of insulation material	Low / medium (dependant on process of demolition)	Low / medium (dependant on process of demolition)

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 are titanium dioxide and silicon dioxide.

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

	Nanosilica	Carbon Nanotubes	Titanium Dioxide	Silicon Dioxide	Silver	Zinc Oxide	Nanocomposites	Silicon Nitride	WO_3	Polycarboxylate - ether based
Cement	•	•								•
Façade paint	•									
Self-cleaning sheet glass			•							
Photovoltaic material			•							
UV protective coatings			•	•						
Easy to clean coatings							•			
Scratch-resistant coatings			•	•						
Low emmissivity coating					•					
Anti-reflective coating								•		
Anti-voltaic cell coatings			•	•						
Flame Retardants							•			
Smart Glazing coatings									•	
Antibacterial Surfaces					•					

Areas in which potential EHS issues were identified for nanomaterials used within the construction sector are mainly those applications where nanomaterials are likely to be incorporated into the production process in the form of a powder or slurry. For these, there exists a potential for higher exposure without sufficient occupational hygiene controls in place.

For further information on the hazard of those nanomaterials listed, readers are directed to the ObservatoryNANO baseline studies document[8] which provides key information on toxicity, ecotoxicity, fate and behaviour, and characterisation considerations for each.

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

- inhalation of powder, or of aerosolised NPs during production of the particles or manufacturing of matrix to which the NP are bound;
- Dermal exposure to spills or dusts from the production of nanomaterials or their incorporation into the final product;
- exposure following any degradation/abrasion during use;

- at disposal or recycling of the product, mainly if this is done in such a manner which may allow release of matrix-bound NP e.g. explosion / combustion.

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

- via release of free particles added within the manufacturing processes into the manufacturing plant waste streams, release into surface/drinking water may occur;
- at disposal or recycling of the product, mainly if this is done in such a manner which may allow release of matrix-bound NP e.g. shredding / explosion / combustion.

For personnel involved in manufacture of the products, the risk of exposure is generally greater than for any other user group or stage of life cycle, as they are more likely to come into contact with free NPs. At this stage, the principal risk of exposure appears to be by inhalation of e.g. powder, however dermal exposure can also not be excluded. For the general public, exposure is more likely to be dependant on abrasion of the product during its use, or via release during or following the product's demolition/disposal. Environmental exposures may potentially result from any of the stages listed above.

The following list details those applications in which there exists the highest exposure potential: these are cement additives, surface coatings, insulation and fire retardants. In all of these processes free nanoparticles are likely to be used, either in dry form or as slurry. Exposure is thus likely for manufacturers and professional users, either to dust or spills, from handling slurries or from inhalation during spray application. This should be controlled using appropriate hygiene measures.

- **Cement Additives**. Raised exposure potential to professional users either via air or dermally possible (depending on method of NP addition to the cement). Exposure at disposal only raised if process of demolition likely to result in NPs being freed from the cement matrix. These include:
    - Si, CNTs, super plasticizers (e.g. polycarboxylate ether) used in Cement additives and high/ultra-high performance concrete.
- **Coatings**. Greater exposure to professional users possible via inhalation if coating in powder form or sprayed, or dermally if in liquid/slurry form. Exposure at disposal only raised if process of demolition likely to result in NPs being freed from the surface to which the coating is bound. These include:
    - Silver in Low-Emmissivity coatings.
    - TiO_2 in building coatings.
    - Silica in façade binders based on nanocomposite material.
    - TiO_2, WO_3 and liquid crystals in glass coatings.
    - Silicon nitride (SiNx), and nanocomposites (e.g. layered silicates, Montmorillonite) in Anti-Reflective Coatings for solar cells.
    - Modified SiO_2 particles in fire protection glazing.
    - Silver in antibacterial surface coatings.
    - SiO_2 in scratch-resistant and easy to clean surfaces.
    - Si and TiO_2 in UHPC and photo-catalytic white toppings.
- **Flame retardants**. Inhalation exposure to professional users possible if retardant coating applied in powder form or sprayed. Exposure at disposal only raised if process of demolition likely to result in NPs being freed from the surface to which they are bound.
    - Nanocomposites (e.g. layered silicates, Montmorillonite) within flame retardants.
- **Insulation**. Inhalation exposure possible to professional users if NPs released via abrasion/cutting during installation. Exposure at disposal only raised if process of demolition likely to result in NPs being freed from the matrix to which they are bound.
    - Fumed silica in VIPs used within thermal Insulation.

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