Engineered Nanomaterials: Evidence on the Effectiveness of Workplace Controls to Prevent Exposure

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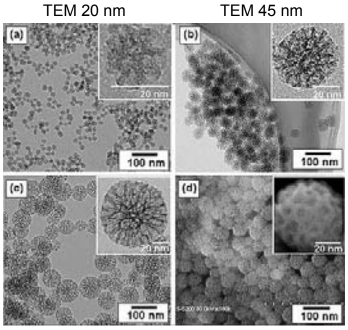
www.rmit.edu.au

Nanotechnology Background

- Fine Particles: 100 to 2500 nm in diameter
- Ultra Fine Particles: 1 to 100 nm in diameter
- Nanoparticles (NPs) have one dimension <100 nm
- Nanoparticles may or may not exhibit size-related properties that differ significantly from those seen in fine particles or bulk material

Prefix	Analog value
p (pico)	10^{-12}
n (nano)	10^{-9}
µ (micro)	10^{-6}
m (milli)	10^{-3}
k (kilo)	10^{3} (1000)
M (mega)	10^{6} (1,000,000)
G (Giga)	10^{9} (1,000,000,000)
T (Tera)	10^{12} (1,000,000,000,000)

TEM 20 nm TEM 45 nm



TEM 80 nm SEM 45 nm

Mesoporous silica NPs

TEM (a) 20 nm, (b) 45 nm & (c) 80 nm.

(d) SEM of 45nm shown in (b).

Insets: higher magnification.

Pei *et al.* (2008) *J. Sol. Sci.*

Nanotechnology Background

- Nanoparticles: a bridge between bulk materials and atomic or molecular structures
- Bulk materials (>1 micron) have constant physical properties regardless of size – as % of surface atoms is insignificant
- Nano-scale materials have size-dependent properties
  - as % of surface atoms becomes significant
  - due to large surface area of the material
- Enhanced material properties:
  - Including increased strength, optical, and electrical properties, etc.

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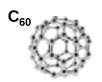
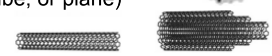
Nanoparticle (NP) Types

- R&D producing numerous engineered NPs

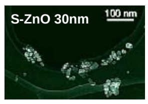
At least 1 dimension ≤100nm but very different physical characteristics



❑Fullerenes: carbon-only molecules (hollow sphere, ellipsoid, tube, or plane)

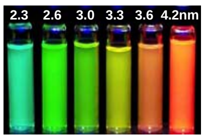


❑Carbon nanotubes (CNT): cylindrical fullerene (single or multi-walled, capped or uncapped)



❑Metals & metal oxides: ultrafine powders (e.g. Ag, Au, ZnO, TiO_2, CeO)

❑Quantum Dots (QD): semi-conducting crystal core (e.g. CdSe, CdS core, ZnS coat)



❑Nanowires: large aspect ratio

❑Nanocrystals: crystalline nanomaterial

❑Others: **dendrimers, graphene sheets, nanoscreen arrays; hybrids**

…Clearly NPs cannot be "lumped together", due to differences in size, shape, surface area & activity, nano-structure, etc.

- **These also affect bioactivity & toxic potential**
  - **So for RA processes, one size will NOT fit all !**

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Current & Potential Applications of Nanotechnology

- Some examples (and potential applications):
- Nanocomposites
  - Plastic nanocomposite for "step assists" in GM Safari & Astro Vans
  - For scratch-resistance, light-weight, rust-proof, improved strength, weight reduction, fuel savings and increased longevity
- Sunscreens using ZnO and TiO_2 NPs: ↓ particle size = ↑ efficacy
  - Sunscreens utilizing NPs are very effective at absorbing/reflecting light in UV range
  - ↓ Particle size: spread more easily, better cover, less ZnO used, transparent (compared with opaque traditional sunscreens)
  - NP-containing sunscreens in 2001 had 60% of the Australian market

More Current and Potential Applications of Nanotechnology

- Nanocrystals
  - Used to make stronger car bumpers & longer lasting bearings
  - Incorporated into aluminium to ↑ wear resistance
  - Used in new types of sensors and components for computers and electronic hardware
- Nanoparticles
  - Stain-repellent **Eddie Bauer Nano-Care**™ khakis:
    - surface fibres coated with 10 - 100 nm "nano-whiskers"
    - developed by Nano-Tex (Burlington Industries subsidiary)
  - Dockers also makes khakis, a dress shirt and a tie treated with nanoscale cloth treatment labelled as **"Stain Defender"**

Key OHS Requirements

- Are nanoparticles hazardous to workers?
- How can workers be exposed?
- Can nanoparticles be measured?
- Can worker exposures be controlled?

NIOSH

- NIOSH Web site

  www.cdc.gov/niosh/topics/nanotech/safenano/

Nanoparticle Production Routes

Method	Production Costs ($/Kg)	Process Issues	OHS&E Issues
Precipitation	1-20	Poor dispersity Separation	Liquid disposal, redispersion
Microemulsion	15-50	Separation, recycle	Liquid disposal, redispersion
Vapour phase reactions	20-200	High capital cost, scale-up poor dispersity	Free particulates redispersion
Attrition Milling	2-20	Energy costs contamination	Free particulates redispersion
Reactive Grinding	5-40	Separation, contamination	Free particulates redispersion

From Prof. Terry Turney, Centre for Green Chemistry, Monash University

Nanotechnology Risk Assessment in the Occupational Setting

Difficult due to:

- Much uncertainty about toxic potential of many engineered NM
- Lacking quantitative (surface) structure activity ratio (Q(S)SAR) & mechanistic toxicology studies of related NM as properties can vary within NM classes
- Also NT research activities generate many NM; most only briefly studied & discarded

Problem: How to handle NM safely when toxic properties are unknown & don't want to perform a full test battery unless new NM is of use beyond the research stage ?

NP of Concern (NPOC) Life-cycle Analysis

- Perform life cycle analysis for NPOCs

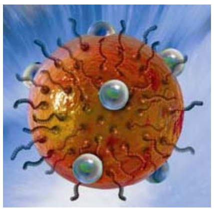
I.D. potential exposure risks during NPOC life-cycle:

1) Starting/precursor materials
2) Process of manufacture
3) Method of isolation/purification/separation
4) Storage & transport
5) Product applications
6) Potential for release in use/abuse of products
7) Disposal of product
8) Removal/clean-up of waste streams

- Additional components added to life-cycle as necessary

Nanotech Risk Assessment in Occupational Setting

- RA process needed for whole-of-life-cycle analysis & appropriate chemical + physical properties:
  - a) Hazard Identification
  - b) Dose Response Assessment
  - c) Exposure Assessment
  - d) Risk Characterisation



CBEN, RiceU, USA

- Risk Management: determine, implement & evaluate effectiveness of workplace controls

Current issue: How do we prevent workers from being exposed to engineered NM?

Nanotech RA in Occupational Setting

- How to develop methods for occupational setting so NMs can be safely handled and workers not exposed:
  - Step 1: consider evidence for workplace controls that have been successfully introduced to prevent exposure to engineered NM
  - Step 2: apply this (somewhat limited) knowledge to define control methodologies that work
  - Step 3: define the applicability of these control measures to broader applications than for those they have already been applied
  - Step 4: define (if possible) control measures that can be used across many NM and potential scenarios
- Strategies include '**control banding**', or to set defined controls that are required to work with engineered NM

[e.g. Schulte PS *et al.* (2008) *J Occ Env Hyg* 5:239-249]

What is Control Banding?

- **Control banding (CB)** = Qualitative risk management process used in pharmaceuticals industry
- Developed by UK Health & Safety Executive (HSE) in COSHH Essentials model (HSE, 1999; Oldershaw, 2001)
- **CB** is defined as:
  - A strategy (or process) using a single control technology (e.g. general ventilation or containment)
  - Applied to a defined range or band of exposure to a chemical (e.g. 1-10 mg/m^3)
  - That falls within a given hazard group (e.g. harmful by inhalation, or irritating to respiratory system)
- Especially used in the control of chemical hazards with limited toxicological information and workplace exposure limits are absent
- Effectively used to facilitate the control of chemicals in the workplace (Schulte et al., 2008)

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Example of Control Banding for NM: BSI

British Stds (BSI) PD 6699-2:2007. Nanotechnologies – Part 2 Guide to safe handling & disposal of manufactured NM (Dec 2007)

BSI approach is very conservative, i.e.:

- **Fibrous NM:** 0.01 fibres/mL (by EM) *(CNT → asbestos limit)*
- **CMAR NM:** 0.1 x OEL for bulk *(10x safety margin assuming incr. bioavail. of **C**arc./**M**utagen/**A**sthmagen/**R**eprotox bulk material)*
- **Insoluble NM:** 0.066 x OEL for bulk *(based on NIOSH TWA limits of TiO_2 for >100nm of 1.5 mg/m^3; for <100nm of 0.1 mg/m^3)*
- **Soluble NM:** 0.5 x OEL for bulk *(NP unlikely to differ)*
- **Hierarchy of controls:** eliminate, substitute, enclose, engineering controls, procedural controls only, using PPE

See BSI website for full document www.bsi-global.com (BSI uses WEL)

→ conservative Occ. Exposure Limits (OEL) until specific OELs defined for NM

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Step 1: Consider evidence of successful workplace controls preventing exposure to NM

Summarised according to hierarchy of controls:

a) **Elimination** – possible, if we do not want to use NM

b) **Substitution** – possible, if we do not want to use NM or can re-engineer NM (e.g. coating QD; make fullerenes more polar)

c) **Engineering controls**

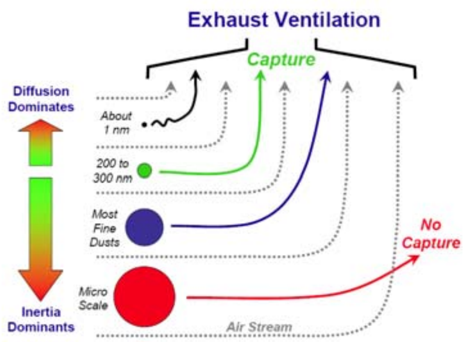
- **i)** **Enclosure** – good evidence of successful application in several situations/scenarios
- **ii)** **Local exhaust ventilation** (LEV) / **filtration** – good evidence of filtration removing NM – low 'rebound' effect (Aitken RJ *et al.* 2004; UK Health & Safety Executive HSE 2004; Wang & Kasper, 1991 *J Aerosol Sci*)

Likelihood of NP Exposure in the Workplace

- **Highest when handling free particles**
  - *Equipment maintenance*
  - *Cleanup of spilled nanomaterials*
  - *Transfer of nanomaterials in open systems*
  - *The cleaning of "dust" collection systems*
- **Lower when**
  - *Working with embedded nanoparticles*
  - *During manufacturing in enclosed systems*

Local exhaust ventilation & filtration processes

- Evidence indicates that local exhaust ventilation (LEV) can significantly reduce exposure
- Needs to be correctly designed and used
- Filtration:
  - methods include use of HEPA filtration and electrostatic precipitation



Impact of particle size on exhaust ventilation capture.
C. Geraci (2008)

Engineering controls

Expectations:

- Most traditional engineering controls are expected to be adequate, i.e.
  - Enclosure
  - Fume hoods
  - Biohazard cabinets

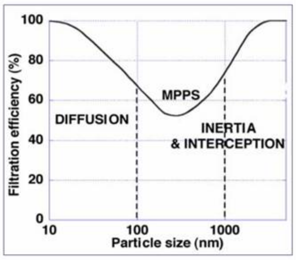
  (Laminar flow hoods are **not** protective)

- HEPA filters theoretically block nanomaterials, i.e.
  - Respirators should be effective
  - Historical use with vehicle exhaust fumes & viruses

  → Evidence: HEPA & personal cartridge filters can be appropriate measures for NP risk management [Kim, Harrington, Pui (2007) *J NP Res*]

Can filter materials capture nanoparticles?

- YES!
  - MPPS around 300 nm for HEPA filters but can be below 100 nm for other types of filters
  - Primary mechanism of capture is a function of particle diameter ***Nanosafe2, 2008***
- Capture efficiency depends on flow rate & type of filter material



- **Fibrous filters are efficient for NP**
- **Conventional filtration theory confirmed**
- **'Skimmer model' disproved**

Filter material type & certification	Filtration efficiency for particles <100 nm	Reference
N95 <5% penetration	<5% penetration	Martin & Moyer (2000)
	<5% for low flow rate Max >5%, high flow rate	Richardson et al. (2005)
	<5% for 30 L/min Max 5-6%, 30-80 nm, 85 L/min	Balazy et al. (2006)
P100 <0.03% penetration	<0.03% for low flow rate Max >0.03%, high flow rate	Richardson et al. (2005)

Administrative Controls

To supplement engineering controls

- *Even if engineering controls are very efficient, there could be exposure to NPs, e.g. during clean-up & maintenance*
- *Normal good hygiene practices applicable*

Some nanomaterial-specific practices

i) Work practices

- *sticky mats at room entrances to prevent transfer*

ii) Routine maintenance & clean-up of work areas, clean-up of spills

- *wet wiping & vacuum cleaning,*
- *dry wipe only for liquid spills*
- *use of respirators & dermal protection*

iii) Waste disposal (nanomaterials & used PPE, wipes, equipment)

- *separate disposal containers*
- *recycling nanomaterials*
- *incinerating waste nanomaterials on-site (carbonaceous)*
- *returning nanomaterials to suppliers*

ISO TR 12855: *Health and safety practices in occupational settings relevant to nanotechnologies* (2008)

Personal Protective Equipment

i) Respiratory protective equipment (RPE)

Good evidence that a range of facemasks & their filters effectively remove engineered NM (e.g. N95 cartridge filter pieces or better);
Main risk is from poor fitting
(lack of tightness between face & mask)

ii) Protection from dermal exposure

Good evidence that a glove protection plan (double-gloving) & other garments made of non-woven air-tight materials are effective if applied correctly

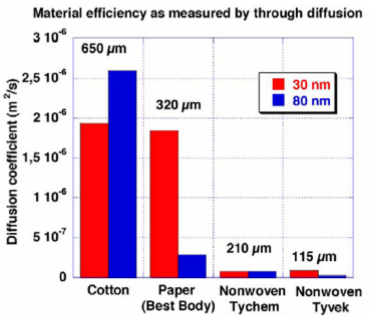
iii) Eye protection

Evidence that a range of eye protection devices have been successfully used in order to reduce ocular exposure

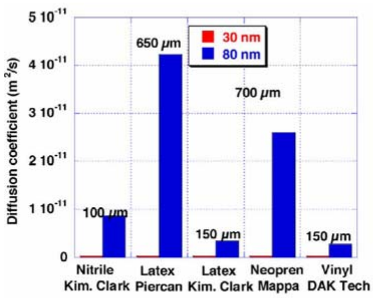
PPE Clothing & Gloves

- Non woven fabrics (air-tight materials) are more efficient against NP penetration
- Polyethylene textile (e.g. Tyvek) is better than cotton or paper
- Comfort issues

- NP may penetrate commercially available gloves – use 2 layers
- Glove material, elaboration process & thickness are major issues



Using graphite NP 30 & 80 nm without air flow

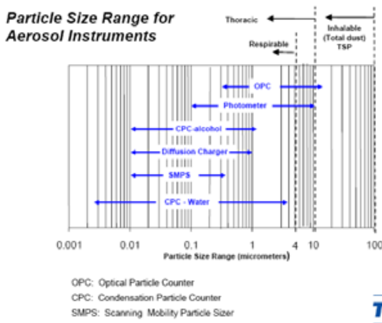


Diffusion of NP : 80 nm > 30 nm

(EU Nanosafe2 Jan 2008)

Other issues to consider…

- Nanovector effects:
  - delivery of other toxicants (i.e. fullerenes binding PAHs)
- NM disposal methods – environmental exposure issue:
  - best to convert or immobilise NM before disposal
- Monitoring effectiveness of workplace controls:
  - actual data needs to be generated in NM workplaces



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Control of NM safety hazards

- **Same principles as those applied to the management of fine powders, dusts & dusty materials should be considered**
  - Avoid dust becoming airborne
  - Handling combustible nanopowders in liquid form, when possible
  - Design of machinery to prevent ignitions and sparks
    - *operating temperature of electrical equipment*
  - Use of controlled-atmosphere production and storage processes
    - *risk of asphyxiation*
- **Working with potentially explosive nanomaterials, reports of:**
  - Anti-static shoes and mats used in areas where materials handled
  - Distillation system for evaporating solvent from a colloidal dispersion housed within explosion proof enclosure

ISO TR 12855: *Health and safety practices in occupational settings relevant to nanotechnologies* (2008)
European Agency for Safety and Health at Work: *Workplace exposure to nanoparticles (2009)*

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Preliminary Recommendations

- **Toxicological profiling** needed for priority NPOCs:
  - predictive profiling studies on important NM classes & hybrids
- **Risk Assessment of NPOCs**: for chemical and physical properties, processes and ALL parts of life cycle
- **Workplace controls**: move to higher order controls for scale-up from R&D to manufacturing phases; use 'control banding'
  - Hierarchy of controls: elimination, substitution, enclosure & engineering controls, administrative controls, personal protective equipment (PPE)
- **Develop appropriate monitoring**: (if feasible) to assess controls
  → but techniques not widely available yet

Two stage process:

a) Adopt ***Precautionary Principle*** when exposure std is unknown

b) Adopt ***As Low As Reasonably Practicable*** (ALARP) approach when exposure standard is known

People need information & to stay informed !

Acknowledgments

safe work australia

Safework Australia for funding project WR08/4059:

Jackson N., Lopata A., Elms T. & Wright P. (2009)
Engineered nanomaterials: Evidence on the effectiveness of workplace controls to prevent exposure.
ISBN 978-0-642-32884-7. 82 pages.

Available from the Safework Australia webpage:
http://www.safeworkaustralia.gov.au/swa/AboutUs/Publications/EngineeredNanomaterials-EvidenceontheEffectivenessofWorkplaceControlstoPreventExposure.htm

Or via the Link on the NanoSafe Australia webpage:

www.rmit.edu.au/nanosafe

Snet examples

Created by Alison Funston, **Neale Jackson**, Doug Rash & Peter Tregloan, Victorian Institute of Chemical Sciences ©2007

Snet: Hazards associated with use of Engineered Nanomaterials

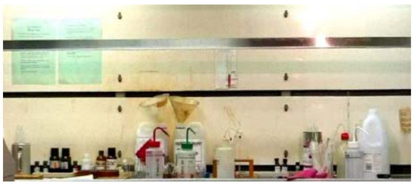
Argon Gas Cylinder

– Example gas used in NM fabrication

- **Hazards**
  - a) Contact with Chemical: Low risk
  - b) Asphyxiation: Medium risk
- **Controls**
  - a) Use gloves and eye protection to prevent contact with low temperature expanding gas
  - b) Use in a well ventilated area
    - – Ensure ready availability of SCBA
    - – Inspect the cylinder for obvious damage/leaks

Snet: Hazards associated with use of Engineered Nanomaterials

Housekeeping with Fumehoods



- Used for preparing NMR samples,
- Unknown toxicity for most chemicals

- **Hazards**
  - a) Contact with skin: High risk
  - b) Breakage of gloves: Low risk
- **Controls**
  - a) When working in fumehood wear appropriate PPE
    - Including lab specs, lab coat, covered shoes and gloves
  - b) Ensure all chemical samples are labelled
  - c) Ensure fumehood is kept neat and well organised with all excess glassware removed

Snet: Hazards associated with use of Engineered Nanomaterials

Autoclaved reaction vessel

- This apparatus contains a chemical reaction being carried out at increased temperature and pressure

- **Hazards**
  - a) Implosion: Medium risk
  - b) Burns: Low risk
  - c) Electrocution: High risk
  - d) Contact with chemical: High risk
- **Controls**
  - a) Ensure glassware in use is not weakened, e.g. cracks or scratches
    - Shield equipment from the rest of the room with a plastic or metal shield
  - b) Ensure use of heavy gloves and lab coat when using the apparatus
  - c) Ensure power leads are tested and secured away from heating element
  - d) Identify chemical being used & ensure MSDS is consulted prior to use

Snet: Hazards associated with use of Engineered Nanomaterials

Rotary Evaporator

– Used in chemical synthesis to concentrate solutions or remove solvents from chemicals

- **Hazards**
  - a) Burns: Low risk
  - b) Implosion/explosion of apparatus: Medium risk
  - c) Contact with chemical: Medium risk
- **Controls**
  - a) Check glassware prior to using rotary evaporator
  - b) Use a round bottom flask in order to evenly distribute forces
  - c) Place a shield around the rotary evaporator to prevent broken glass (and chemicals) from being scattered in the event of an implosion

Snet: Hazards associated with use of Engineered Nanomaterials

Disposable Nitrile Gloves left on Bench

– Gloves left on bench after having been used by a researcher

- **Hazards**
  - Contact with unknown Chemical: High risk
- **Controls**
  - a) Dispose of gloves immediately after use
  - b) Do not leave contaminated gloves on bench
  - c) Do not reuse contaminated disposable gloves
  - d) Use other appropriate PPE: lab coat, covered shoes, safety specs, unused disposable gloves
  - e) Ensure workplace is kept free of chemicals