

AC 2007-387: ENVIRONMENTAL IMPACT OF NANOTECHNOLOGY

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Environmental Impact of Nanotechnology

Introduction

The emerging field of Nanotechnology is leading to a technological revolution in the new millennium. It could revolutionize the way our society manufactures goods, generates energy and cures diseases. Nano scale materials are currently being used in consumer goods, computers, electronics, information and biotechnology, aerospace, defense, energy, medicine and many other sectors of our economy. Areas producing the greatest revenue for Nanotechnology applications are chemical-mechanical polishing, magnetic recording tapes, sunscreen, automotive catalyst, bio-labeling, electro-conductive coatings and fiber optics.¹

The enormous promise and potential benefits of Nanotechnology also poses major risks to workers, consumers and the environment. Many published reports stated that the “Biological activity of Nanoparticles – including potential adverse as well as beneficial effects – tend to increase as their size decreases”.² Nanomaterials have a relatively larger surface area that can make nanoparticles more reactive. Quantum effects can begin to dominate the behavior of matter at the nanoscale, affecting the optical, electrical and magnetic properties. The very properties of nanoscale particles being exploited in certain applications (such as high surface reactivity and the ability to cross cell membranes) might also have negative health and environmental impacts.³ As a result; nanomaterials may present new health and environmental risks that have not been encountered before. The potential environmental impact of nanotechnology creates a challenge for the academic community to educate environmental engineering students with necessary knowledge, understanding and skills to interact and provide leadership to protect the environment and minimize risk from products of nanotechnology.

The purpose of this paper is to discuss the development of a teaching/learning module on the environmental impact of nanotechnology. The developed module consists of four units:

1. Overview of nanotechnology, applications and manufacturing processes.
2. Sources of nanoparticles and occupational exposure.
3. Human health effect of nanomaterials and environmental risk assessment.
4. Nanoparticle pollution controls and regulations.

Each unit includes learning objectives, overview, suggested study topics and list of reading materials. This module is intended to be integrated to an existing sophomore/junior level environmental engineering course.

Unit I: Application of Nanotechnology and Manufacturing Processes

Learning Objective:

Upon completion of this unit students will be able to do the following:

1. Understand the new frontier of nanotechnology and engineered nanomaterials.
2. Identify the various applications of nanomaterials.
3. Recognize the basic principles of nanomaterials manufacturing processes.
4. Analyze the environmental benefits of nanotechnology.

Overview:

Nanotechnology can be defined as technology that involves imaging, measuring, modeling, and controlling matter at dimensions about 1 to 100 nanometers.⁷ At the nanoscale, the physical chemical and biological properties of matter significantly differ from their bulk properties primarily due to increased relative surface area and quantum effect. Nanotechnology involves exploiting these new properties, manipulating individual atoms and molecules to design and create new improved materials, nano-machines and nano-devices for application in all aspects of our lives.

Nanomaterial can be categorized into one, two and three dimensions. One dimensions nano materials such as thin films and engineering surface have been used in electronic industry and in fuel cells respectively.¹ Two dimensional nano materials such as carbon nano tubes, nano wires and biopolymers have range of potential applications: computerize sensors, electronic display devices, catalysis, energy storage, drug deliveries, etc.¹ Three dimensional nanomaterials such as fullerenes (carbon), nano-metal oxides, dendrimers, quantum dots also have varieties of potential applications: electronic circuits, drug delivery, water purification, soil remediation, composites, fuel cells, chemical reagents, etc. A list of nanomaterials, origin, unique properties and potential applications are summarized in Table 1.^{1,2,3}

Nanomaterials manufacturing processes can be classified into two categories (based on the starting point of the process): 1) top down and 2) bottom up. Top down manufacturing processes primarily used by semiconductor industry for production of computer chips. It starts with a large scale object or pattern and gradually reduces to a nano structure by using precision engineering and lithography.¹ In a bottom-up manufacturing process, nano-structures are built by assembling individual atoms or molecules. Bottom-up manufacturing process can be divided into: 1) chemical synthesis, 2) self-assembly and 3) positional assembly.¹ A flow chart of top-down and bottom-up manufacturing process is given in figure 1¹.

Suggested Topics of Study:

- Introduction to nanotechnology
- Nanomaterials: types and application
- Nanotechnology manufacturing processes
- Environmental benefits of nanotechnology

Suggested Reading Materials

- Poole Jr., P. Charles and Owens J. Frank., Introduction to Nanotechnology, John Wiley & Sons, 2003
- National Nanotechnology Initiative. Available at <http://www.nano.gov/>
- Nanotechnology: Societal Implications – Maximizing Benefits for Humanity. Available at: <http://www.nano.gov/>

- The Royal Society & The Royal Academy of Engineering, 2004. Nanoscience and nanotechnologies: opportunities and uncertainties. London: The Royal Society & The Royal Academy of Engineering. Available at: www.royalsoc.ac.uk/policy.

Table 1. Nanomaterials: Categories, Origins, Properties and Applications^{1,2,3}

Nanomaterials	Origins	Unique Properties	Application
Nano-tubes (hollow sphere, ellipsoid, or cylindrical tube): Spherical fullerenes are known as Buckyballs. Cylindrical fullerenes are called nanotubes	Entirely composed of Carbon	High conductivity High tensile strength High surface area, Novel electronic property High molecular adsorption capacity	Polymer composites, Structural composites, Coatings, Electromagnetic shielding, Flat panel displays, Batteries, Hydrogen storage
Nanowires: A nanowire is a single crystal conductor or semiconductor.	Gold, Cobalt, Copper, Silicon, Oxides, Sulfides, Nitrides	Conductors Semi-conductors	Used as interconnectors for the transport of electrons in nanoelectronic devices
Quantum Dots: A quantum dot is a closely packed semiconductor for crystal. The number of atoms in a quantum dot can range from 1000 to 10,000	Metals (gold, silver) Oxides (titanium oxides)	Exhibit novel electronic, optical, magnetic and catalytic properties due to distinct quantum size effect.	Insulators Semi-conductors Magnetic material
Dendrimers: These are three dimensional branched macromolecules.	Dendrimers are produced by chemical synthesis through a special stepwise, repetitive reaction sequence	Exhibits unique molecular architecture, high degree of structural symmetry, three dimensional interior molecular cavity.	Catalysis Drug delivery
Nano composites	Metal, metal oxides, ceramics, polymers	Unique mechanical, thermal, electrical, and flame-retardant properties.	Packaging Auto-parts

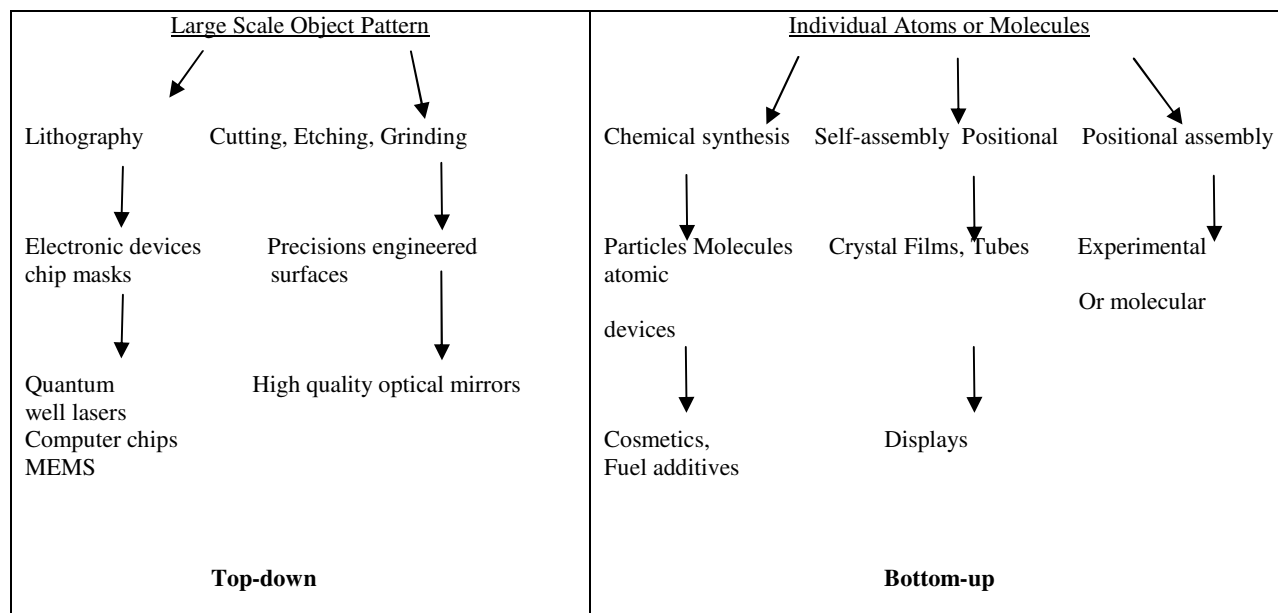


Figure 1. Flow chart of Top-down and Bottom-up manufacturing processes. (Adopted from The Royal Society Report ¹).

Unit II: Sources of Nanoparticles and Occupational Exposure

Learning Objectives:

Upon completion of this unit students will be able to do the following:

- Understand the various sources of nanoparticles in the environment
- Recognize the sources for engineered nanoparticles
- Predict the potential risks and occupational exposure of nanoparticles.

Overview:

Nanoparticles are created by nature, industrial process (by products), and by engineered production of nanomaterials. They can be classified as stationary, mobile, occupational settings and atmosphere conversion.⁴ Stationary emissions are mainly from energy industry such as power plants, combustors, incinerators, etc. High energy processes and diesel engines are primary sources for mobile nanoparticles. Two stroke engines also emit considerable amount of nanoparticles into the environment. Occupational settings can be classified into: industrial by products (thermal spraying and coatings, welding, synthesis of carbon black, high temperature combustion, bioaerosol, etc) and engineered nanoparticles (carbon nanotubes, nanowires, quantum dots, dendrimers, nanocomposite) for application in various consumer goods, computer, electronics, medicines, aerospace and defense industry. Engineered nanoparticle production process can be categorized into four main groups: gas-phase, vapor disposition, colloidal and

attrition.³ Nanoparticles have significantly long life in the air due to lack of gravitational setting, there by increasing the chances of human exposure and health risks.⁴

Nanoparticle production processes have the potential to cause exposure by inhalation, dermal and ingestion during production, recovery, and handling of products.³ Potential risks of exposure in nanoparticles production process is summarized in Table 2.³

Suggested Topics of Study:

- Nanoparticles in the environment
- Sources of nanoparticles (stationary, mobile atmosphere, conversion and occupational settings)
- Occupational exposure to nanoparticles
- Potential routes for human exposure (inhalation, dermal and ingestion)
- Level of exposure, health and ecological risks
- Effective control measures

Table 2: Potential risks of exposure in nanoparticle production processes (Adopted from Nanoparticles: An Occupational Hygiene Review³).

Synthesis Process	Particle Formation	Potential Risks	Potential Dermal/Ingestion Risks
Gas Phase	In air	Direct leakage from reactor Product recovery Post recovery processing and packing	Airborne contamination of workplace Handling of product Cleaning/maintenance of plant
Vapour Phase	On substrate	Product recovery Post-recovery processing and packing	Dry containment of workplace Handling of product Cleaning/maintenance of plant
Colloidal	Liquid suspension	Drying of product (processing and spillage)	Spillage/containment of workplace Handling of product Cleaning/maintenance of plant
Attrition	Liquid suspension	Drying of product (processing and spillage)	Spillage/containment of workplace Handling of product Cleaning/maintenance of plant

Suggested Reading Materials:

- The Royal Society & The Royal Academy of Engineering, 2004. Nanoscience and nanotechnologies: opportunities and uncertainties. London: The Royal Society & The Royal Academy of Engineering. Available at: www.royalsoc.ac.uk/policy.
- Nanotechnologies: A preliminary risk analysis on the basis of a workshop organized in Brussels on 1-2 March 2004 by the Health and Consumer Protection Directorate General of the European Commission. Report available at http://europa.eu.int/com/health/ph_risk/events_risk_en.htm.
- Nanoparticles: An occupational hygiene review. Available at: www.hse.gov.uk/research/rrhtm/rr274.htm.
- Biswas, Pratim; Chang-Yu Wu. Nanoparticles and the Environment. Journal of the Air & Waste Management Association, Jun 2005, Vol. 55 Issue 6, p708-746.
- Baronetal. 2004, Exposure to Carbon Nanotube Material: Aerosol Release During handling of unrefined single walled carbon nanotube material. Journal of Toxicol Environment Health, Par A, 67:87-10.

Unit III: Human Health Effect of Nanomaterials and Environment Risk Assessment.

Learning Objective:

Upon completion of this unit students will be able to do the following:

- Recognize the potential human health effects and toxicity of engineered nanomaterials.
- Analyze the information available on the physical and chemical properties of nanomaterials
- Analyze the scientific information available on hazardous properties of engineered nanomaterials.
- Assess the potential risk of nanomaterials.

Overview:

The enormous promise of benefits of nanotechnology also poses potential risks to workers, consumers and the environment. Potential health and environmental risks due to exposure to nanomaterials have been published in several recent reports.^{1, 2, 3, 4, 5} Interactions of nanoparticles between human and the environment and the potential exposure routes is illustrated in figure 2.

Nanoparticles can interact with human and their environment through lungs, skin and gastrointestinal tract.³ High dose of nanoparticles may lead to lung disease such as asbestosis, severe skin rashes due to allergic reactions and formation of high acidity in the gastrointestinal tract. High dose of nanoparticles inhaled from the air is deposited in the deep lung and may pass into cells directly through the cell membrane may cause disruptions to important cell functions.⁶ Examples of potential sources of general population and consumer exposure associated with the use of nanoparticles consumer products is given in Table 3.⁵ The principal determinants of toxicity of nanoparticles are³: 1) the large surface area, 2) the chemical reactivity, 3) the physical dimensions and 4) the solubility.

There are significant knowledge gap and uncertainties on the understanding of the human health effects of engineered nanomaterials.^{1, 2, 3, 4, 5} Therefore, teaching materials of this unit should be constantly revised as new information and data becomes available.

Suggested Study Topics:

- Human health effect and toxicity of engineered nanomaterials.
- Physical and chemical properties of engineered nanomaterial (molecular weight, melting point, boiling point, upper and lower flammability point, vapor pressure, water solubility, reactivity profile size distribution, surface to volume ratio, diffusivity, etc)⁵
- Chemical identification and characterization of nanomaterials (existing analytical tools and techniques and future need)⁵.
- Environmental fate of nanomaterials in Air, Soil and Water (biodegradation, bioaccumulation, toxic metabolic transformation, interaction with organic and inorganic containments, etc.)⁵

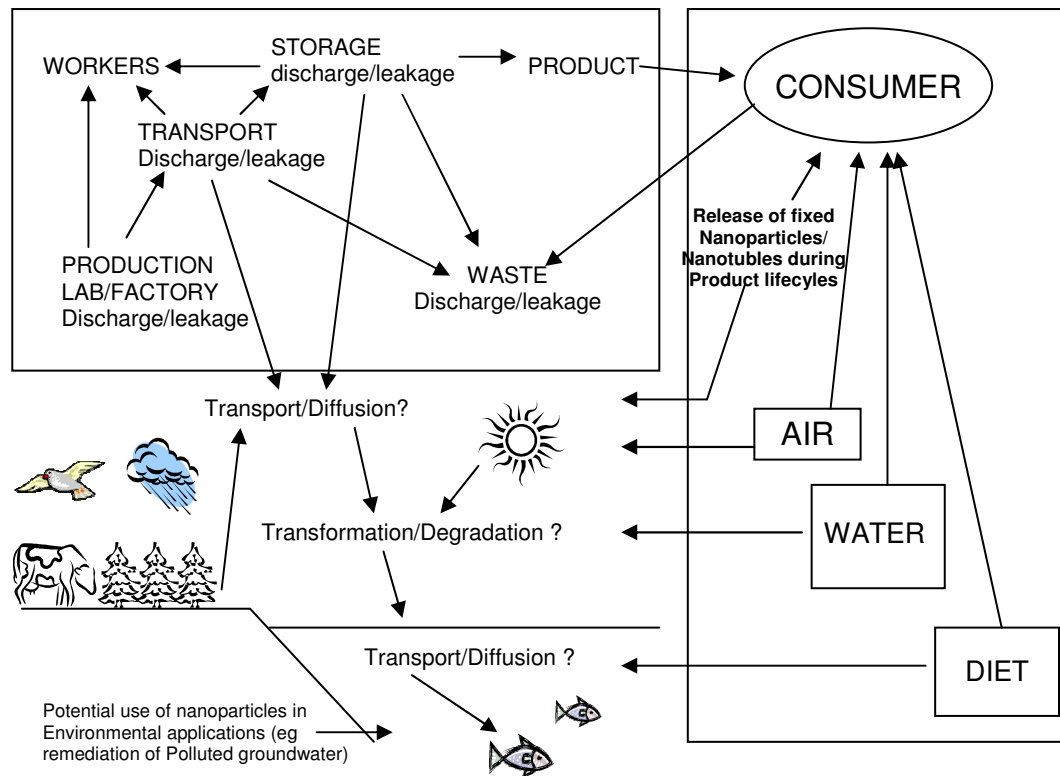


Figure 2. Potential exposure routes and interaction of nanoparticles between human and the environment (Adopted from the Royal Society Report¹).

Table 3. Examples of potential sources of general population and consumer exposure associated with the use of nanoparticles consumer products (Adopted from Nanotechnology White Paper⁵).

Product Type	Release and/or Exposure Source	Exposed Population	Potential Exposure Route
Sunscreen Containing Nanoscale Material	Product application by consumer to skin	Consumer	Dermal
	Release by consumer (e.g. washing with soap and water) to water supply	General Population	Ingestion
	Disposal of sunscreen container (with residual sunscreen) after use (to landfill or incineration)	General Population	Ingestion or Inhalation
Metal catalysts in gasoline for reducing vehicle exhaust*	Release from vehicle exhaust to air (then deposition to surface water)	General Population	Inhalation or Ingestion

Suggested Reading Materials:

- Biswas, Pratim; Chang-Yu Wu. Nanoparticles and the Environment. Journal of the Air & Waste Management Association, Jun 2005, Vol. 55 Issue 6, p708-746.
- Nanotechnology White Paper. External review draft prepared for the U.S. Environmental Protection Agency by members of the nanotechnology workgroup, a group of EPA's Science Policy Council. December 2005.
- Renwick L.G., Donaldson K C Clouter A, Impairment of alveolar macrophage phagocytosis by ultrafine products. Toxicology and Applied Pharmacology 172, 2001, p119 – 127

Unit IV: Nanoparticle Pollution Control and Regulations

Learning Objectives:

Upon completion of this unit students will be able to do the following:

1. Understand the availability of current technologies for nanoparticle pollution control.
2. Analyze the design needs for advanced unit operations and instrumentation for nanoparticle pollution control.
3. Evaluate the adoptability of existing government regulations for environmental protection of nanoparticles.
4. Recognize the need for future government regulations for environmental protection of nanoparticles.

Overview:

Strategies for control of nanoparticles should be developed based on the assessment of risks arising from their exposure. Strategies to control exposures to nanoparticles may include: control of nanoparticle emissions from the process, use of specifically designed nanoparticle ventilation systems, use of nanoparticle protective masks and gears at the workplace and proper health and safety education for the workers³. Enclosures, local exhaust ventilation, fume hoods, currently used by the chemical industry (such as carbon black) to control poisonous gases can also be adopted to for control airborne nanoparticles.³ Use of high efficiency particulate arrester (HEPA) filtration unit operation can also be very effective to control airborne nanoparticles. These units must be designed for an extremely high efficiency to capture the smallest nanoparticles (<2nm). Many research projects are currently under consideration to develop new filtration system for collecting nanoparticles. Electrostatic precipitators (ESP) can also be used to control the emission of nanoparticles effectively.

There are several existing federal laws (The Substances Control Act, The Occupational Safety and Health Act, The Food, Drug and Cosmetic Act, The Clean Air Act, The Clean Water Act, and Resource Conservation and Recovery Act) that can provide a legal bias for controlling and regulating engineered nanomaterials. However, these laws lacks specific guidelines for nanoparticles production, handling or labeling. New regulations for nanoparticles should be addressed after a rigorous evaluation of risks and hazard assessments of nanoparticles. If it is deemed necessary regulatory options should be considered in the following areas: 1) workplace controls, 2) classification and labeling measures, 3) control of emissions to air, water and land, 4) waste disposal restrictions, 5) marketing and use restrictions and 6) prohibition³.

In September 2005, US Environmental Protection Agency (USEPA) proposed a voluntary program for controlling engineered nanoparticles.⁸ The program would ask producers of engineered nanoscale materials to submit to the USEPA, for materials chosen by the producer, information on: 1) material characterization, 2) hazard information, 3) use and exposure potential, and 4) risk management practices⁸. The voluntary program is designed to help USEPA eventually develop a permanent regulatory program for nanotechnology⁸.

Suggested Study Topics:

- Strategies and methods to control emissions of nanoparticles at the workplace.
- Design and analysis of internal control devices (such as particle trap impactors, cyclones, etc.) for capture and control of nanoparticles.
- Design and analysis of HEPA filters
- Design and analysis of ESP
- The Toxic Substances Control Act (TSCA) and the Occupational Safety Health Act (OSHA) liability in engineering nanomaterials.

Suggested Reading Materials:

- The Royal Society & The Royal Academy of Engineering, 2004. Nanoscience and nanotechnologies: opportunities and uncertainties. London: The Royal Society & The Royal Academy of Engineering. Available at: www.royalsoc.ac.uk/policy.
- Nanotechnologies: A preliminary risk analysis on the basis of a workshop organized in Brussels on 1-2 March 2004 by the Health and Consumer Protection Directorate General of the European Commission. Report available at http://europa.eu.int/com/health/ph_risk/events_risk_en.htm.
- Nanoparticles: An occupational hygiene review. Available at: www.hse.gov.uk/research/rrhtm/rr274.htm.
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Teaching Strategies and Assessment

The module on Environmental Impact of Nanotechnology should be taught by creating both knowledge centered and learning centered environment inside and outside of the classroom. Because nanotechnology is advancing so rapidly, activities that encourage self-learning and life-long learning should be given the highest priority. Environmental engineers need to constantly be aware of contemporary environmental issues pertinent to nanotechnology. Therefore, it is essential that in teaching this module, students develop a culture of reading newspapers, journals and government/industry reports and journal publications on regular basis to become aware of the contemporary environmental issues and be prepared to discuss these issues in the classroom. Each student should be required to report on four articles (closely related to each unit of the

module) that he or she read from a variety of sources such as newspapers, internet, environmental journals, etc. Students need to submit a brief summary of the article along with the source to the instructor and other students in the class. Students may also be required to give a five minute in class presentation and lead a classroom discussion on the topic. These activities can be used to assess student's learning outcome in this module. Learning outcome of this module can also be assessed by developing an evaluation rubric based on the stated learning objectives in all four units of the module. Instructors can develop a quiz, exam or assign a term paper to assess the outcomes of the learning objectives.

Conclusion

The teaching/learning module on environmental impact of nanotechnology will provide students a broad background on nanotechnology, and an understanding of the health, safety and environmental risks associated with the exposure of engineered nanoparticles. Through this module students will also gain knowledge on the current technologies for nanoparticle pollution control and regulatory issues. The developed module can easily be integrated with an existing sophomore/Junior level environmental engineering course.

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