UNIVERSITY of NEW HAMPSHIRE

NANOMATERIALS SAFETY PROGRAM

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The most current version of this document can be found online at:
http://www.unh.edu/ehs/

TABLE OF CONTENTS

I. Purpose

This document has been written to offer health and safety guidance to faculty, staff, students, and visitors working with nanotechnology at the University of New Hampshire. The purpose of this **Nanomaterials Safety Program** is to provide a framework for recognizing, evaluating and controlling hazards associated with nanotechnology operations and operations. **Note:** Most nanotechnology hazards are related to either dermal exposure or inhalation of nanoparticles or nanomaterials.

The Nanomaterials Safety Program should be used in conjunction with the UNH Laboratory Safety Plan and the Office of Environmental Health and Safety (OEHS) should be consulted to review all activities involving nanotechnology before beginning work with these materials. A site-specific risk assessment should be conducted by OEHS to determine the potential hazards of working with the materials. In addition, an individual safety plan should be developed for the laboratory.

II. Introduction

Nanotechnology involves the manipulation of matter at nanometer scales to produce new materials, structures, and devices. Nanoparticles are materials that have at least one dimension (e.g., length, width, height, diameter) that is less than 100 nanometers. A nanometer, or nm, is 1×10^{-9} meters or one millionth of a millimeter (see Appendix A for a comparison of different-sized objects).

Nanoparticles may be suspended in a gas (e.g., nanoaerosol), suspended in a liquid (e.g., nanocolloid or nanohydrosol), or embedded in a matrix (e.g., nanocomposite). In this document, the term “nanomaterials” is used to refer to the various different forms of nanoparticles that are created in the laboratory.

Nanomaterials are used in electronic, magnetic, optoelectronic, biomedical, cosmetic, pharmaceutical, catalytic and materials applications and processes. Examples of products benefiting from the unique properties of nanomaterials include:

- Automobile catalytic converters;
- Bumpers on cars;
- Burn and wound dressings;
- Dental-bonding agents;
- Electroconductive coatings;
- Inks;
- Light-weight, stronger tennis racquets;
- Longer-lasting tennis balls;
- Metal cutting tools;
- Optical fibers;
- Paints and coatings to protect against corrosion;
- Protective and glare-reducing coatings for eyeglasses and cars;
- Stain-free clothing and mattresses;
- Step assists on vans; and
- Sunscreens and cosmetics.

There are many industrial processes that produce particles in the nanometer size range. These unintentionally produced nanomaterials are often referred to as ultra-fine particles or ultra-fine aerosols. Ultra-fine particles are defined as “particles with aerodynamic diameters less than 100 nm.” Ultra-fine particles tend to be formed through nucleation, gas-to-particle reactions, or evaporation. An example in which ultra-fine particles are created is the synthesis of carbon black by flame pyrolysis, which produces a powdered form of carbon with a very high surface-to-mass ratio. This material is usually highly agglomerated but has a primary particle size in the order of 100 nm. Other common materials produced by flame pyrolysis or similar thermal processes include fumed silica (i.e., silicon dioxide), ultra-fine titanium dioxide (TiO_2) and ultra-fine metals such as nickel. Additional industrial processes, such as thermal spraying and coating, create and use nanomaterials as part of the process. Welding can also generate ultra-fine particles in a plume of aggregated nanomaterials.

Ultra-fine particles are produced in large quantities from diesel engines and from domestic activities such as gas cooking. Ultra-fine particles are also found in the atmosphere where they originate from combustion sources (e.g., traffic, forest fires), volcanic activity, and from atmospheric gas-to-particle conversion processes such as photo-chemically driven nucleation.

Research with nanomaterials has shown that the physiochemical characteristics of particles can influence their effects in biological systems. Some of these characteristics include:

- Charge;
- Chemical reactivity;
- Degree of agglomeration;
- Shape;
- Size;
- Solubility;
- Surface area; and
- Surface composition.

There are many unknowns as to whether the unique properties of engineered nanomaterials pose health concerns. The potential health risk following exposure to a substance is generally associated with the following:

- Magnitude and duration of the exposure;
- Persistence of the material in the body;
- Inherent toxicity of the material; and
- Susceptibility or health status of the person.

Unfortunately, there are limited data in this area with regard to nanomaterials so prudent health and safety practices are required.

III. Regulations

At this time, there are no federal regulations that specifically address the health and safety implications of nanotechnology. Further, there are no national or international consensus standards on measurement techniques for nanomaterials in the workplace. However, as with conventional chemicals, research with nanomaterials must be conducted in a manner that is safe and responsible. All chemicals, including nanomaterials, must be transported, stored, used, and disposed in accordance with all federal, state, and local requirements.

The Occupational Safety and Health Administration (OSHA) requires employers to maintain a safe and healthful workplace, "free from recognized hazards likely to cause death or serious physical harm." In order to comply with OSHA, laboratory personnel must be informed of the risks associated with workplace hazards. This is generally accomplished through training programs, material safety data sheets, labeling and signage, and other methods.

The Resource Conservation and Recovery Act (RCRA) regulates the transportation, treatment, disposal, and cleanup of hazardous waste. Nanomaterials that meet the definition of a "hazardous waste" in RCRA are subject to this rule.

Nanomaterials that are defined as "chemical substances" under the Toxic Substances Control Act (TSCA) and which are not on the TSCA Inventory must be reported to U.S. Environmental Protection Agency (EPA). A Pre-manufacture Notice must be submitted to the EPA by anyone intending to manufacture or import a chemical substance that is not on the TSCA Inventory of Chemical Substances.

The Federal Insecticide, Fungicide, and Rodenticide Act requires that the EPA approve all new pesticide products, as well as new uses and changes in the composition of existing pesticide products, before the products may be sold or distributed in commerce. In order to evaluate an application for registration, the EPA requires the applicant to provide a complete characterization of the composition of the product, proposed labeling which describes the intended use of the product, and the results of extensive health and safety testing.

It should be also noted that the U.S. Food and Drug Administration currently regulates a wide range of products including those that utilize nanotechnology or contain nanomaterials (e.g., a drug delivery device).

IV. Nanoscience at UNH

The University of New Hampshire (UNH) is home to at least three entrepreneurial groups that research nanosized applications and processes, including:

- **Center for High-Rate Nanomanufacturing (CHN):** The CHN was created to bridge the gap between nanoscale science research and the creation of commercial products. The CHN develops processes and tools that will enable high-rate/high-volume, bottom-up, nanoscale directed assembly of nanoelements and polymer nanostructures. The CHN is currently composed of faculty, staff, and students from the Chemistry, Physics, Mechanical Engineering, and Materials Science Departments.

- **Nano Group:** The Nano Group is a core group of scientists and engineers at the UNH working on a range of nanotechnology projects that are designed to make, move, model and characterize nanoscale structures, surfaces and features.

- **Nanostructured Polymers Research Center (NPRC):** The NPRC was created to actively foster the development of complex polymeric materials based on multiple phases with significant structure at the nanometer scale.

Figure 1. Polystyrene particles packed in an array (Courtesy Don Sundberg, University of New Hampshire, Nanostructured Polymers Research Center).

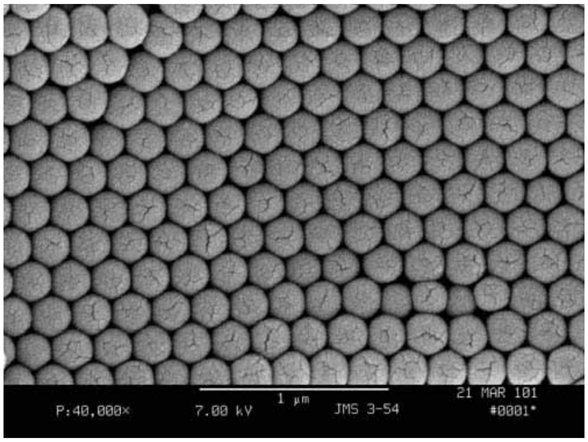

Figure 2. Multi-lobed latex particles (Courtesy Don Sundberg, University of New Hampshire, Nanostructured Polymers Research Center).

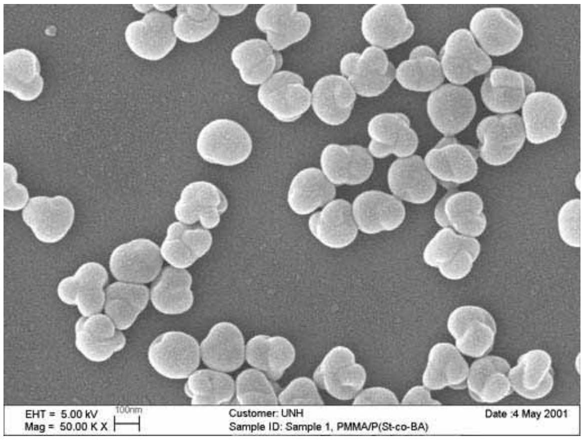

Figure 3. Debundled Carbon Nanotubes (Courtesy Glen Miller, University of New Hampshire, Center for High-Rate Nanomanufacturing).

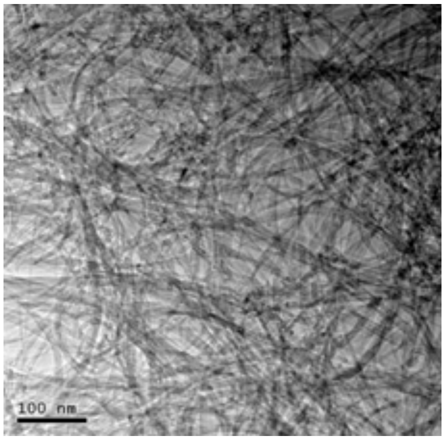

Figure 4. Nano-lithography using C_{60} molecules. (Courtesy Glen Miller, University of New Hampshire, Center for High-Rate Nanomanufacturing).

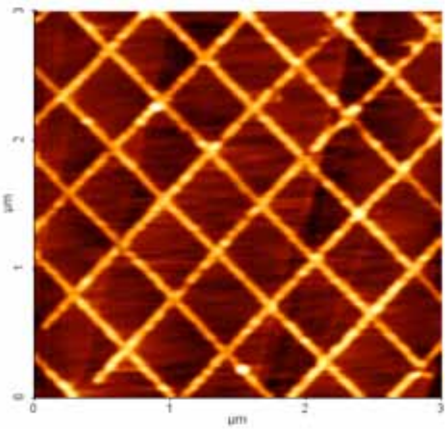

Figure 5. Nano-Whiskers using C_{60} molecules. The distance from one red point to the next is 1 nm (Courtesy Glen Miller, University of New Hampshire, Center for High-Rate Nanomanufacturing).

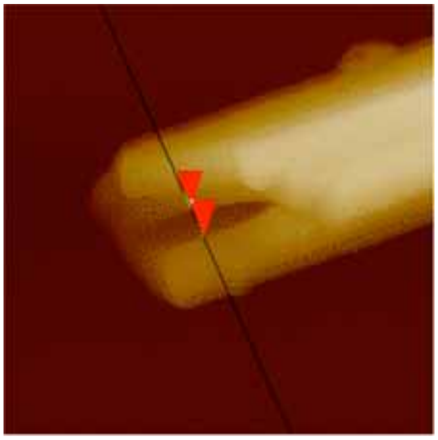

Figure 6. Computer model of fullerene crystals. (Courtesy Glen Miller, University of New Hampshire, Center for High-Rate Nanomanufacturing).

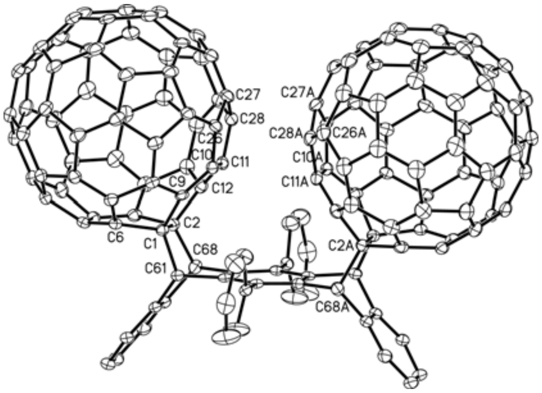

Table 1. Potential Sources of Occupational Exposure to Nanomaterials for Various Synthesis Methods*

Process Synthesis	Particle Formation	Exposure Source or Worker Activity	Primary Exposure Route**
Gas Phase	In air	Direct leakage from reactor, especially if the reactor is operated at positive pressure.	Inhalation
		Product recovery from bag filters in reactors.	Inhalation / Dermal
		Processing and packaging of dry powder.	Inhalation / Dermal
		Equipment cleaning/maintenance (including reactor evacuation and spent filters).	Dermal (and inhalation during reactor evacuation)
Vapor Deposition	On substrate	Product recovery from reactor / dry contamination of workplace.	Inhalation
		Processing and packaging of dry powder.	Inhalation / Dermal
		Equipment cleaning/maintenance (including reactor evacuation).	Dermal (and inhalation during reactor evacuation)
Colloidal	Liquid suspension	If liquid suspension is processed into a powder, potential exposure during spray drying to create a powder, and the processing and packaging of the dry powder.	Inhalation / Dermal
		Equipment cleaning/maintenance.	Dermal
Attrition	Liquid suspension	If liquid suspension is processed into a powder, potential exposure during spray drying to create a powder, and the processing and packaging of the dry powder.	Dermal
		Equipment cleaning/maintenance.	Dermal

* Adapted from Aitken, R.J., Creely, K.S., Tran, C.L. 2004. Nanoparticles: An Occupational Hygiene Review. Research Report 274. Prepared by the Institute of Occupational Medicine for the Health and Safety Executive, North Riccarton, Edinburgh, England.

** **Note:** Ingestion would be a secondary route of exposure from all sources/activities from deposition of nanomaterials on food or mucous that is subsequently swallowed (primary exposure route inhalation) and from hand-to-mouth contact (primary exposure route dermal).

V. Exposure Routes

The most common route of exposure to a nanomaterial is through inhalation (see Table 1). The deposition of discrete nanomaterials in the respiratory tract is determined by the particle's aerodynamic or thermodynamic diameter. Particles that are capable of being deposited in the gas exchange region of the lungs are considered respirable particles.

Discrete nanomaterials are deposited in the lungs to a greater extent than larger respirable particles. Deposition increases with exertion (due to an increase in breathing rate and change from nasal to mouth breathing). It also increases among persons with existing lung diseases or conditions. Based on animal studies, discrete nanomaterials may enter the bloodstream from the lungs and translocate to other organs.

Ingestion is another route whereby nanomaterials may enter the body. Ingestion can occur from unintentional hand-to-mouth transfer of materials. This can occur with traditional materials and it is scientifically reasonable to assume that it could happen during handling of materials that contain nanomaterials. Ingestion may also accompany inhalation exposure because particles that are cleared from the respiratory tract via the mucociliary escalator may be swallowed.

A few studies suggest that nanomaterials may enter the body through the skin during exposure. At this time, it is not known if skin penetration of nanomaterials would result in adverse health effects. There is also little information about the health effects of injecting nanomaterials into living organisms.

VI. Factors Affecting Exposure

Every attempt should be made to prevent or minimize exposure to nanomaterials. Factors affecting exposure to nanomaterials include the amount of material being used and whether it can be easily dispersed or form airborne sprays or droplets. The degree of containment and duration of use will also influence exposure. In the case of airborne material, particle or droplet size will determine whether the material can enter the respiratory tract and where it is most likely to deposit. Inhaled particles smaller than 10 μm in diameter have some probability of penetrating and being deposited in the gas-exchange (i.e., alveolar) region of the lungs, but there is at least a 50% probability that particles smaller than 4 μm in diameter will reach the gas-exchange region.

At present there is insufficient information to predict all of the situations and workplace scenarios that are likely to lead to exposure to nanomaterials. However, there are some workplace factors that will increase the potential for exposure, including:

- Working with nanomaterials in liquid media without adequate protection (e.g., gloves) will increase the risk of skin exposure.
- Working with nanomaterials in liquid media during pouring or mixing operations, or where a high degree of agitation is involved, will lead to an increased likelihood of inhalable and respirable droplets being formed.
- Generating nanomaterials in the gas phase in non-enclosed systems will increase the chances of aerosol release in the workplace.
- Handling nanopowders will lead to the possibility of aerosolization.
- Maintenance on equipment and processes used to produce or fabricate nanomaterials will pose a potential exposure risk to workers performing these tasks.
- Cleaning of dust collection systems used to capture nanomaterials will pose a potential for both skin and inhalation exposure.

VII. Engineering Controls

In order to provide a safe work environment for faculty, staff, students and visitors, engineering controls must be maintained wherever nanomaterials are used or stored. These controls may include local exhaust ventilation, localized filtration, and personal protective equipment. Respiratory protection is required when working with nanomaterials when local exhaust ventilation and filtration is not available. However, the preferred method for manipulating nanomaterials is in solution.

The following engineering controls should be used when handling nanomaterials:

- Use of a chemical fume hood is recommended for all tasks with potential of aerosolizing nanomaterials. In all cases where engineering controls alone do not sufficiently reduce exposure potential, provision of appropriate personal protective equipment will be required.
- A well-designed local exhaust ventilation system with a local high-efficiency particulate air (HEPA) filter should be used to effectively remove nanomaterials.
- Syringes used for nanomaterial injection must be safety engineered (i.e., self-sheathing syringes, luer-lock syringes). OEHS will consider exceptions on a case-by-case basis.
- Animals should be appropriately restrained and/or sedated prior to administering injections and other dosing methods.
- Laboratories and other spaces where nanomaterials are used or stored must be equipped with an eyewash station that meets American National Standards Institute (ANSI) and Occupational Safety and Health Administration (OSHA) requirements.

VIII. Administrative Controls

Although traditional permissible exposure limits (PEL) exist for many of the substances that nanomaterials are made from, the PEL for a nanomaterial of these substances is not yet clear. Thus, it is important to incorporate the following administrative controls into all laboratory operations:

- The laboratory's safety plan should be modified to include health and safety considerations of nanomaterials used in the laboratory.
- Principal investigators should develop and implement standard operating procedures (SOPs) in the preparation and administration of nanomaterials (with minimal exposure).
- Protocols involving the *in vivo* use of nanomaterials in vertebrate animals must be reviewed and approved by the Institutional Animal Care and Use Committee (IACUC) and the Institutional Biosafety Committee (IBC). Research with human subjects would require pre-approval from the Institutional Review Board (IRB) and the IBC.
- Laboratory personnel must receive the appropriate training, including specific nanomaterial-related health and safety risks, standard operating procedures, and steps to be taken in event of an exposure incident, prior to working with nanomaterials.
- Laboratory personnel must be instructed to use extreme caution when performing injections involving nanomaterials since accidental needle stick presents a potential exposure.

- Exposures involving nanomaterials or any other acutely hazardous material must be reported to OEHS as soon as possible.

IX. Work Practices

The incorporation of good work practices can help to minimize exposure to nanomaterials. Examples of good work practices include the following:

- Projects or applications with the potential for producing nanomaterial aerosols must be conducted within an approved chemical fume hood or biological safety cabinet.
- Needles used for nanomaterial injection must be disposed in an approved sharps containers immediately following use. Needles used for nanomaterial injection should never be bent, sheared, or recapped.
- Bench paper utilized during preparation of nanomaterial stock should be lined with an impervious backing to limit potential for contamination of work surfaces in the event of a minor spill.
- Work areas should be cleaned at the end of each work shift (at a minimum) using either a HEPA-filtered vacuum cleaner or wet wiping methods. Dry sweeping or air hoses should not be used to clean work areas. Bench tops, chemical fume hood interiors, biological safety cabinet interiors, equipment, and laboratory surfaces with potential for nanomaterial contamination should be routinely cleaned. Cleanup should be conducted in a manner that prevents worker contact with wastes. The disposal of all waste material should comply with all applicable federal, state, and local regulations.
- The storage and consumption of food or beverages in workplaces must be prohibited where nanomaterials are handled, processed, or stored, since exposure may occur via ingestion. Laboratory personnel should wash their hands carefully after working with nanomaterials and before eating, drinking, applying cosmetics, smoking, or using the restroom.
- Facilities for showering and changing clothes should be provided to prevent the inadvertent contamination of other areas (including take-home) caused by the transfer of nanomaterials on clothing and skin.

X. Personal Protective Equipment

Typical chemistry laboratory apparel should be worn when working with nanomaterials. Always wear appropriate clothing (e.g., long pants, shirts, shoes) and personal protective equipment, including safety glasses, laboratory coats, and gloves, when working with nanomaterials. Open sandals, shorts, and skirts are prohibited. Laboratory personnel involved in any task with a potential exposure to nanomaterials must wear the following personal protective equipment:

- **Protective gloves:** Glove selection is best determined by a risk assessment and the chemicals used for the procedure. Nitrile or rubber gloves, which cover hands and wrists completely through overlapping sleeve of lab coat when working with nanomaterials, may provide adequate protection. Wearing of two sets of gloves ("double gloving") is advised whenever performing tasks involving nanomaterials and other hazardous substances. Laboratory personnel should thoroughly wash hands with soap and water before and immediately upon removal of examination gloves.

- **Eye protection**: Safety glasses or goggles are considered to be the appropriate level of eye protection for working with nanomaterials. OEHS recommends wearing a full-face shield when conducting tasks posing potential for any generation of aerosol or droplets.

- **Protective clothing:** Laboratory coats or disposable gowns that provide complete coverage of skin must be worn when working with nanomaterials. Clothing contaminated with nanomaterials should be removed immediately. Do not take contaminated work clothes home – contaminated clothing should be disposed of as hazardous waste.

- **Respiratory protection:** If engineering controls are not adequate or are not available, and a potential aerosol exposure exists, respiratory protection is required. When working with nanomaterials, one of the following types of respirators must be worn:

    - Elastomeric half- or full-facepiece with N-100, R-100, or P-100 filters; or
    - Powered air-purifying respirator with N-100, R-100, or P-100 filters.

XI. Spill Cleanup

Anyone attempting to manage any spill involving hazardous agents must be wearing the appropriate personal protective equipment. Standard approaches to cleaning nanomaterial powder and liquid spills include the use of HEPA-filtered vacuum cleaners, wetting powders down, using dampened cloths to wipe up powders, and applying absorbent materials or liquid traps. Energetic cleaning methods such as dry sweeping or the use of compressed air should be avoided, or only be used with precautions that assure that particles suspended by the cleaning action are trapped by HEPA filters. If vacuum cleaning is employed, care should be taken that HEPA filters are installed properly, and bags and filters changed according to manufacturer's recommendations. At a minimum, the following procedures must be followed when managing an accidental spill of nanomaterials:

- Small spills (typically involving less than 5 mg of material) of nanomaterial-containing powder should be wet-wiped with cloth/gauze that is dampened with soapy water. Affected surfaces should be thoroughly wet-wiped three times over with appropriate cleaning agent and with a clean, damp cloth used for each wipe down. Following completion, all cloth and other spill clean-up materials with a potential for nanomaterial contamination must be disposed of as hazardous waste.

- Small spills (typically involving less 5 ml of material) of nanomaterial-containing solutions should be covered and absorbed with absorbent material. Areas affected by liquid spills should be triple cleaned with soap and water following removal of absorbent paper.

- For larger spills of nanomaterials, contact the OEHS at 862-4041.

As with any spill or clean-up of contaminated surfaces, handling and disposal of the waste material should follow existing Federal, State, or local regulations.

XII. Waste Disposal

Nanomaterials are potentially hazardous materials. Surplus stocks and other waste materials containing greater than trace contamination must be disposed of through the UNH Hazardous Waste Management Program. Due to the fact that certain nanomaterials may be unaltered during metabolism, all potential contaminated carcasses, bedding, and other materials must be disposed through incineration. In addition, all contaminated sharps waste materials must be placed in proper sharps container and disposed as biohazardous waste.

XIII. Hazard Assessments

Prior to beginning work with nanomaterials, a hazard assessment should be performed by a qualified industrial hygienist. The purpose of the assessment will be to identify appropriate work procedures, controls, and personal protective equipment to ensure worker safety. The assessment will evaluate several factors, including but not limited to the physical and chemical properties of the nanomaterial, the process by which the material will be generated and/or used, and existing engineering controls (e.g., fume hood, glove box). In some instances, the industrial hygienist may recommend collecting occupational exposure measurements (e.g., sampling). This will be performed to further understand potential hazards or to identify specific processes or equipment requiring additional engineering controls.

XIV. Catalytic Reactions

Nanomaterials have been used for many years as effective catalysts for increasing the rate of reactions or decreasing the necessary temperature for reactions to occur in liquids and gases. Depending on their composition and structure, some nanomaterials may initiate catalytic reactions and increase their fire and explosion potential that would not otherwise be anticipated from their chemical composition alone.

XV. Fires and Explosions

Although insufficient information exists to predict the fire and explosion risk associated with nanomaterials, nanoscale combustible material could present a higher risk than coarser material of similar quantity. Decreasing the particle size of combustible materials can reduce minimum ignition energy and increase combustion potential and combustion rate, leading to the possibility of relatively inert materials becoming highly combustible. Dispersions of combustible nanomaterials in the air may present a greater safety risk than dispersions of non-nanomaterials with similar compositions. Some nanomaterials are designed to generate heat through the progression of reactions at the nanoscale. Such materials may present a fire hazard that is unique to nanomaterials. In the case of some metals, explosion risk can increase significantly as particle size decreases. For example, nanoscale Al/MoO_3 thermites ignite more than 300 times faster than corresponding micrometer-scale material.

XVI. Glossary

Agglomerate – A group of particles held together by relatively weak forces, including van der Waals forces, electrostatic forces and surface tension.

Aggregate – A heterogeneous particle in which the various components are held together by relatively strong forces, and thus not easily broken apart.

Buckyballs - Spherical fullerenes composed entirely of carbon (C_{60}).

Fullerenes - Molecules composed entirely of carbon, usually in the form of a hollow sphere, ellipsoid, or tube.

Graphene - A one-atom thick sheet of graphite.

Nanoscience – The study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

Nanoaerosol – A collection of nanomaterials suspended in a gas.

Nanocolloid – A nanomaterial suspended in a gel or other semi-solid substance.

Nanocomposite – A solid material composed of two or more nanomaterials having different physical characteristics.

Nanoparticle – A substance with dimensions less than 100 nanometers in size.

Nanohydrosol – A nanomaterial suspended in a solution.

Nanotechnology – The understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications.

Nanotubes - A one-atom thick sheet of graphite (called graphene) rolled up into a seamless cylinder with diameter of the order of a nanometer.

Nanowires - A wire of dimensions of the order of a nanometer.

Nucleation - The first step in the process by which gases are converted to small liquid droplets.

Physiochemical – The underlying molecular organization of life that is manifested as chemical and energy transformations.

Pyrolysis - Chemical change brought about by the action of heat.

Quantum Dots – A nanomaterial that confines the motion of conduction band electrons, valence band holes, or excitons (pairs of conduction band electrons and valence band holes) in all three spatial directions.

Single Walled Carbon Nanotube – A single sheet of graphite (graphene), wrapped into a tube approximately 1.5 nanometers in diameter.

Thermites – A mixture of aluminum powder and a metal oxide (as iron oxide) that when ignited evolves a great deal of heat and is used in welding and in incendiary bombs.

Translocation – The act, process, or an instance of changing location or position.

Transmission Electron Microscopy (TEM) – An imaging technique whereby a beam of electrons is focused onto a specimen causing an enlarged version to appear on a fluorescent screen or layer of photographic film.

Ultra-Fine Particles - Airborne particles with an aerodynamic diameter of 0.1 μm (100 nm) or less.

XVII. References

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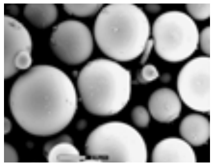
Appendix A: The Scale of Things – Nanometers and More

Things Natural

Dust mite
↔
200 µm

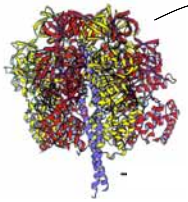
Ant
~ 5 mm

Human hair
~ 60-120 µm wide

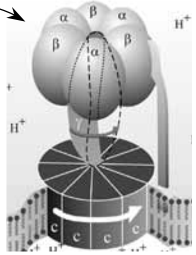


Fly ash
~ 10-20 µm

Red blood cells
(~7-8 µm)

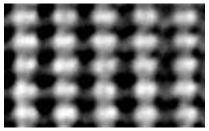


~10 nm diameter

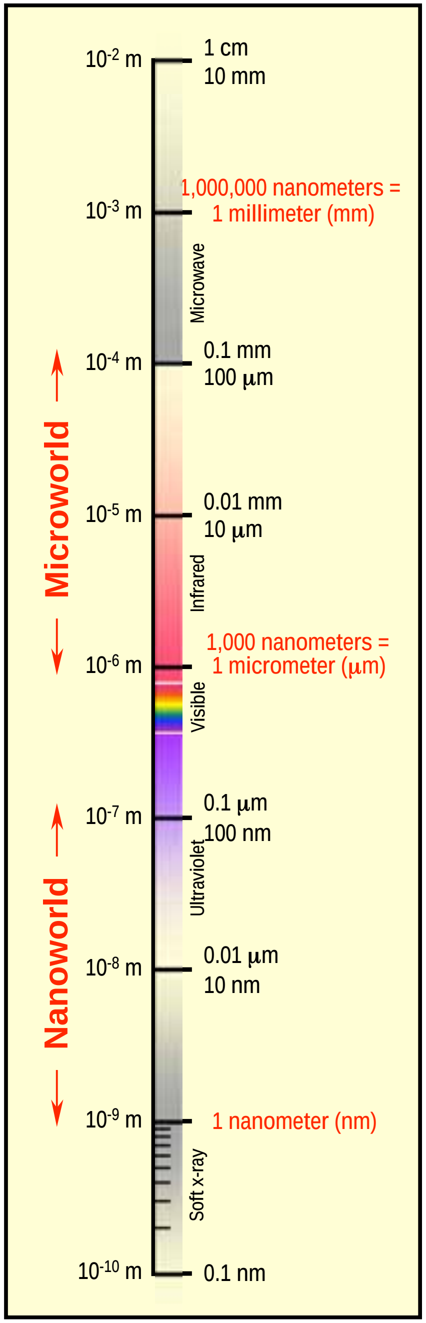


ATP synthase

DNA
~2-1/2 nm diameter



Atoms of silicon
spacing 0.078 nm



Microworld

Nanoworld

10^{-2} m — 1 cm
10 mm

10^{-3} m — 1,000,000 nanometers =
1 millimeter (mm)

Microwave

10^{-4} m — 0.1 mm
100 µm

10^{-5} m — 0.01 mm
10 µm

Infrared

10^{-6} m — 1,000 nanometers =
1 micrometer (µm)

Visible

10^{-7} m — 0.1 µm
100 nm

Ultraviolet

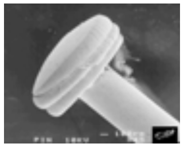
10^{-8} m — 0.01 µm
10 nm

10^{-9} m — 1 nanometer (nm)

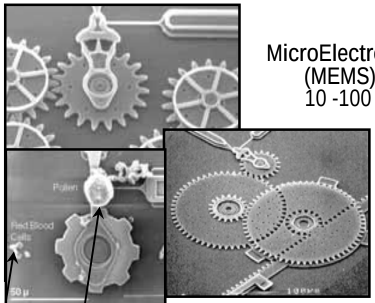
Soft x-ray

10^{-10} m — 0.1 nm

Things Manmade

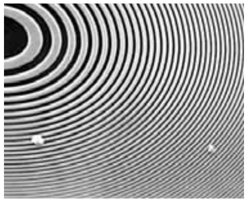


Head of a pin
1-2 mm

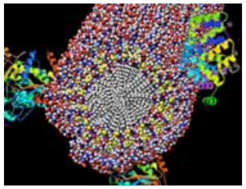


MicroElectroMechanical
(MEMS) devices
10 -100 µm wide

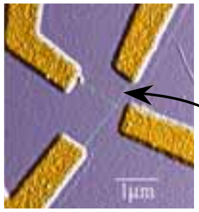
Pollen grain
Red blood cells



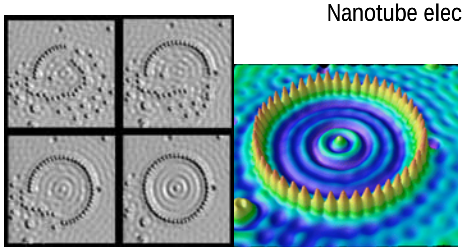
Zone plate x-ray “lens”
Outer ring spacing ~35 nm



Self-assembled,
Nature-inspired structure
Many 10s of nm

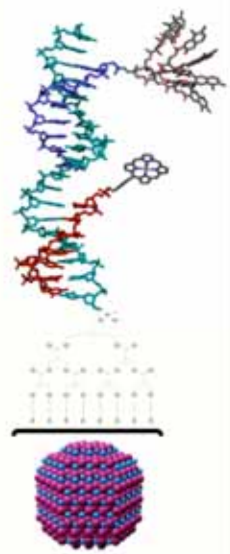


Nanotube electrode

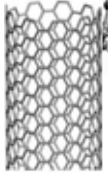


Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm

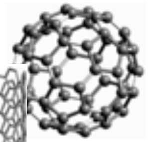
The Challenge



Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.



Carbon nanotube
~1.3 nm diameter



Carbon buckyball
~1 nm diameter

Office of Basic Energy Sciences
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