Approaches to Safe Nanotechnology

An Information Exchange with NIOSH

National Institute for Occupational Safety and Health
Centers for Disease Control and Prevention

October 1, 2005

Director’s Message

The field of nanotechnology is advancing rapidly and will likely revolutionize the global industry. As with any new technology, we are faced with many unknowns; all of which raise questions concerning occupational safety and health. The National Institute for Occupational Safety and Health (NIOSH) is committed to ensuring worker protection as nanotechnology develops.

NIOSH has developed the document *Approaches to Safe Nanotechnology: An Information Exchange with NIOSH* to raise awareness of potential safety and health concerns from exposure to nanomaterials. The document also addresses current and future research needs essential to understanding the potential risks that nanotechnology may have to workers.

It is imperative that the scientific community come together to advance our understanding of nanotechnology and its implications in the workplace. I invite you to participate in this process and encourage you to provide feedback, comments, or suggestions regarding the *Approaches to Safe Nanotechnology* document. I also encourage you to share any relevant information or experience pertaining to the field of nanotechnology.

As our knowledge grows, NIOSH plans to provide valuable guidance to the safe handling of nanoparticles and other safe approaches to nanotechnology. This will be an effort that evolves as the technology advances and our knowledge and experience grows.

Thank you.

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DRAFT (9-30-05)

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Summary

Safety and health practitioners recognize a lack of consistent guidance for the safe handling of nanomaterials. This information gap is critical because of the unknown risk that nanomaterials pose to workers. Experimental studies in rats have shown that at equivalent mass doses, insoluble ultrafine particles (smaller than 100 nm) are more potent than large particles of similar composition in causing pulmonary inflammation and lung tumors. Whether these effects would occur in exposed workers is not known. **If engineered nanoparticles involve the same characteristics that seem to be associated with ultrafine particles, they may raise the same concerns.** The greater hazard may relate to the larger number and total surface area of nanoparticles compared with that of the larger particles at the same mass concentration. **Until these preliminary findings and hypotheses are confirmed, we can have no firm knowledge about the health risks that nanoparticles pose to exposed workers.** However, to increase the likelihood of safe work with nanomaterials, we should consider using control measures that are known to work for larger particles. In terms of control measures, nanoparticles appear to have no major physical features that would make them behave differently from larger particles in a control system. Therefore, it may be useful for those working with nanomaterials to employ the range of control technologies, work practices, and personal protective equipment demonstrated to be effective with other fine and ultrafine particles.

This document reviews what is currently known about nanoparticle toxicity and control, but it is only a starting point. The document serves as a request from NIOSH to occupational safety and health practitioners, researchers, product innovators and manufacturers, employers, workers, interest group members, and the general public to exchange information that will ensure that no worker suffers material impairment of safety or health as nanotechnology develops. Opportunities to provide feedback and information are available throughout this document.

Introduction

Nanotechnology is the manipulation of matter on a near-atomic scale to produce new structures, materials, and devices. This technology has the ability to transform many industries and to be applied in many ways to areas ranging from medicine to manufacturing. Research in nanoscale technologies is growing rapidly worldwide. By 2015, the National Science Foundation estimates that nanotechnology will have a $1 trillion impact on the global economy and will employ 2 million workers, 1 million of which may be in the United States [Roco and Bainbridge 2001].

Nanomaterials present new challenges to understanding, predicting, and managing potential health risks to workers. As with any new material being developed, scientific data on the health effects in exposed workers are largely unavailable. **In the case of nanomaterials, the uncertainties are great because the characteristics of nanomaterials may be different from those of the larger particles with the same chemical composition.** Safety and health practitioners recognize the critical lack of guidance on the safe handling of nanomaterials—especially now, when the degree of risk to exposed workers is unknown.

The National Institute for Occupational Safety and Health (NIOSH) is working in parallel with the development and implementation of commercial nanotechnology through (1) conducting strategic planning and research, (2) partnering with public- and private-sector colleagues from the United States and abroad, and (3) making information widely available. The NIOSH goal is to provide national and world leadership for incorporating research findings about the applications and implications of nanotechnology into good occupational safety and health practice for the benefit of all nanotechnology workers.

Intent and Purpose

With the launch of the *Approaches to Safe Nanotechnology* Web page, NIOSH hopes to do the following:

- **Raise awareness** of the occupational safety and health issues being identified in the rapidly moving and changing science and applications and implications of nanotechnology.
- Use the best information available to **make interim recommendations** on occupational safety and health practices in the production and use of nanomaterials. These interim recommendations will be updated as appropriate to reflect new information. They will address key components of occupational safety and health, including monitoring, engineering controls, personal protective equipment, occupational exposure limits, and administrative controls. They will draw from the ongoing NIOSH assessment of current best practices, technical knowledge, and professional judgment. Throughout the development of these guidelines, the utility of a hazard-based approach to risk assessment and control will be evaluated and, where appropriate, recommended.
- **Facilitate an exchange of information** between NIOSH and its external partners from ongoing research, including success stories, applications, and case studies.

- **Respond to requests** from industry, labor, academia, and other partners who are seeking science-based, authoritative guidelines.
- **Identify information gaps** where few or no data exist and where research is needed.

The NIOSH Web site will serve as a starting point for developing good work practices and will set a foundation for developing proactive strategies for responsible development of nanotechnologies in the U.S. workplace. This site will be dynamic in soliciting stakeholder input and featuring regular updates.

Scope

This document has been developed to provide a resource for stakeholders who wish to understand more about the safety and health applications and implications of nanotechnology in the workplace. The information and guidelines presented here are intended to aid in risk assessments for engineered nanomaterials and to set the stage for the development of more comprehensive guidelines for reducing potential workplace exposures in the wide range of tasks and processes that use nanomaterials. The information in this document will be of specific interest to the following:

- Occupational safety and health professionals who must (1) understand how nanotechnology may affect occupational health and (2) devise strategies for working safely with nanomaterials
- Researchers working with or planning to work with engineered nanomaterials and studying the potential occupational safety and health impacts of nanomaterials
- Policy and decision-makers in government agencies and industry
- Risk evaluation professionals
- People working with or potentially exposed to engineered nanomaterials in the workplace

In addition to presenting this document, NIOSH is requesting data and information from key stakeholders that is relevant to the development of occupational safety and health guidelines. The purpose will be to develop a complete resource of occupational safety and health information and recommendations for working safely with nanomaterials based on the best available science. Particular attention will be given to questions about the potential health risks associated with exposure to nanoparticles and to the steps that can be taken to protect worker health. The information provided in this document has been abstracted from peer-reviewed literature currently available. **This document and resulting guidelines will be systematically updated by NIOSH as new information becomes available from NIOSH research or others in the scientific community.**

Established safe work practices are generally based on an understanding of the hazards associated with the chemical composition of a material. Engineered nanomaterials exhibit unique properties that are related to their physical size and structure as well as chemical composition. Considerable uncertainty still exists as to whether these unique properties involve occupational health risks. However, the large body of scientific literature that exists on exposures and responses to ultrafine and other airborne particles in animals and humans will be useful. Current information about the potential health effects of nanomaterials, exposure assessment, and exposure control is limited. **Until further information is available, interim safe working practices should be developed based on the best available information.** The information and guidelines in this document are intended to aid in risk assessments for engineered nanomaterials and to set the stage for development of more comprehensive guidelines for reducing potential workplace exposures in the wide range of tasks and processes using nanomaterials.

Descriptions and Definitions

Nanotechnology involves the manipulation of matter at nanometer-length* scales to produce new materials, structures, and devices. The U.S. National Nanotechnology Initiative (NNI) (see nano.gov/html/facts/whatIsNano.html) defines a technology as nanotechnology only if it involves all of the following:

1. Research and technology development involving structures with at least one dimension in the range of 1 to100 nanometers (nm), frequently with atomic/molecular precision

2. Creating and using structures, devices, and systems that have unique properties and functions because of their nanometer-scale dimensions

3. The ability to control or manipulate on the atomic scale

Nanotechnology is an enabling technology that offers the potential for unprecedented advances in many diverse fields. The ability to manipulate matter at the atomic or molecular scale makes it possible to form new materials, structures, and devices that exploit the unique physical and chemical properties associated with nanometer-scale structures. The promise of nanotechnology goes far beyond extending the use of current materials. New materials and devices with intricate and closely engineered structures will allow for (1) new directions in optics, electronics, and optoelectronics; (2) development of new medical imaging and treatment technologies; and (3) production of advanced materials with unique properties and high-efficiency energy storage and generation.

Although nanotechnology-based products are generally thought to be at the pre-competitive stage, an increasing number of products and materials are becoming commercially available. These include nanoscale powders, solutions, and suspensions of nanoscale materials as well as composite materials and devices having a nanostructure.

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*1 nanometer (nm) = 1 billionth of a meter (10^{-9}).

Nanoscale titanium dioxide, for instance, is finding uses in cosmetics, sun-block creams, and self-cleaning windows. And nanoscale silica is being used as filler in a range of products, including dental fillings. Recently, a number of new or “improved” consumer products using nanotechnology have entered the market—for example, stain and wrinkle-free fabrics incorporating “nanowhiskers,” and longer-lasting tennis balls using butyl-rubber/nanoclay composites. Further details on anticipated products can be found at www.nano.gov/html/facts/appsprod.html.

A. Nanoparticles

Nanoparticles are particles with diameters between 1 and 100 nm. Nanoparticles may be suspended in a gas (as a nanoaerosol), suspended in a liquid (as a colloid or nano-hydrosol),or embedded in a matrix (as a nanocomposite). Nanoparticles are commonly incorporated in a larger matrix or substrate referred to as a nanomaterial. The precise definition of “particle diameter” depends on particle shape as well as how the diameter is measured. Particle morphologies may vary widely at the nanoscale. For instance, carbon fullerenes represent nanoparticles with identical lengths in all directions, whereas single-walled carbon nanotubes (SWCNTs) typically form convoluted, fiber-like nanoparticles with only two dimensions below 100 nm. Many regular but nonspherical particle morphologies can be engineered at the nanoscale, including “flower” and “belt”-like structures. For examples of some nanoscale structures, see www.nanoscience.gatech.edu/zlwang/research.html

B. Ultrafine particles

The term “ultrafine particle” has traditionally been used by the aerosol research and occupational and environmental health communities to describe airborne particles typically smaller than 100 nm in diameter. Although no formal distinction exists between ultrafine particles and nanoparticles, **the term “ultrafine” is frequently used in the context of nanometer-diameter particles that have not been intentionally produced but are the incidental products of processes involving combustion, welding fume, or diesel exhaust.** Likewise, the term “nanoparticle” is frequently used with respect to particles demonstrating size-dependent physicochemical properties, particularly from a materials science perspective, although no formal definition exists. As a result, the two terms are sometimes used to differentiate between engineered (nanoparticle) and incidental (ultrafine) nanometer-scale particles.

It is currently unclear whether the use of source-based definitions of nanoparticles and ultrafine particles is justified from a safety and health perspective. This is particularly the case where data on nonengineered, nanometer-diameter particles are of direct relevance to the impact of engineered particles. An attempt has been made in this document to preferentially use the term “nanoparticle” where the material or data pertaining to it has some relevance to understanding a particular issue associated with nanotechnology

C. Engineered nanoparticles

Engineered nanoparticles are intentionally produced, whereas incidental nanoparticles or ultrafine particles are byproducts of processes such as combustion and vaporization. Engineered nanoparticles are designed with very specific properties (including shape, size, surface properties, and chemistry), and collections of the particles in an aerosol, colloid, or powder will reflect these properties. Incidental nanoparticles are generated in a relatively uncontrolled manner and are usually physically and chemically heterogeneous compared with engineered nanoparticles.

D. Nanoaerosol

A nanoaerosol is a collection of nanoparticles suspended in a gas. The particles may be present as discrete nanoparticles, or as agglomerates of nanoparticles. These agglomerates may have diameters larger than 100 nm. In the case of an aerosol consisting of micrometer-diameter particles formed as agglomerates of nanoparticles, the definition of nanoaerosol is open to interpretation. It is generally accepted that if the nanostructure associated with the nanoparticles is accessible (through the component nanoparticles being available for either physical, chemical, or biological interactions), then the aerosol may be considered a nanoaerosol. However, if the nanostructure within individual micrometer-diameter particles does not directly influence particle behavior (for instance, if the nanoparticles were inaccessibly embedded in a solid matrix), the aerosol would not be described as a nanoaerosol.

Potential Health Concerns

Nanotechnology is an emerging field. As such, there are many uncertainties as to whether the unique properties of engineered nanomaterials (which underpin their commercial potential) also pose occupational health risks. These uncertainties arise because of gaps in knowledge about the factors that are essential for predicting health risks—factors such as routes of exposure, movement of materials once they enter the body, and interaction of the materials with the body's biological systems. The potential health risk following exposure to a substance is generally associated with the magnitude and duration of the exposure, the persistence of the material in the body, the inherent toxicity of the material, and the susceptibility or health status of the person. More data are needed on the health risks associated with exposure to engineered nanomaterials. Results of existing studies in animals or humans on exposure and response to ultrafine or other respirable particles may provide a basis for preliminary estimates of the possible adverse health effects from exposures to similar materials on the nanoscale. **It must be recognized that the influence of particle properties, including size and surface area, are not fully understood.** Existing toxicity information about a given material can provide a baseline for anticipating the possible adverse health effects that may occur from exposure to that same material on the nano-scale (see www.cdc.gov/niosh/homepage.html for listing).

A. Exposure routes

The most common route of exposure to airborne particles in the workplace is by inhalation. Like deposition of other types of airborne particles, discrete nanoparticle deposition in the respiratory tract is determined by particle diameter. Agglomerates of nanoparticles will deposit according to the diameter of the agglomerate, not constituent nanoparticles. Research is still ongoing to determine the physical factors that contribute to the agglomeration and de-agglomeration of nanoparticles, and the role of these structures in the toxicity of inhaled nanoparticles.

Discrete nanoparticles are deposited in the lungs to a greater extent than larger respirable particles [ICRP 1994], and deposition may increase during strenuous physical activity [Jaques and Kim 2000; Daigle et al. 2003] and among persons with existing lung diseases or conditions [Brown et al. 2002]. On the basis of studies reported from animal model studies, discrete nanoparticles may enter the bloodstream and translocate to other organs. [Nemmar et al. 2002; Oberdörster et al. 2002].

Discrete nanoparticles that deposit in the nasal region may be able to enter the brain by translocation along the olfactory nerve, as was recently observed in rats [Oberdörster et al. 2004]. The axonol transport of insoluble particles of 50, 200, and possibly 500 nm was also reported in the same research. This exposure route has not been studied in humans, and research is continuing to evaluate its relevance.

Ingestion is another route whereby nanoparticles 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 also could happen during handling of materials that contain nanoparticles. Ingestion may also accompany inhalation exposure because particles that are cleared from the respiratory tract via the mucociliary escalator may be swallowed [ICRP 1994]. Little is known about possible adverse effects from the ingestion of nanoparticles.

Some studies suggest that nanoparticles also could enter the body through the skin during occupational exposure. The U.K. Royal Society and Royal Academy of Engineers have reported that unpublished studies indicate nanoparticles of titanium dioxide used in sunscreens do not penetrate beyond the epidermis [The Royal Society and The Royal Academy of Engineering 2004]. However, the report also makes a number of recommendations addressing the need for further and more transparent information in the area of nanoparticle dermal penetration. Tinkle et al. [2003] have shown that particles smaller than 1 μm in diameter may penetrate into mechanically flexed skin samples. Research is ongoing to determine whether this is a viable exposure route for nanoparticles [www.uni-leipzig.de/~nanoderm/]; Some laboratory studies conducted in vitro using cultured cells have suggested that carbon nanotubes can be absorbed and deposited in skin cells and potentially induce cellular toxicity [Monteiro-Riviere et al. 2005; Shvedova et al. 2003]. It remains unclear, however, how these findings may be extrapolated to a potential occupational risk, given that additional data are not yet available for comparing the cell model studies with actual conditions of occupational exposure.

B. Effects Seen in Animal Studies

Experimental studies in rats have shown that at equivalent mass doses, tested insoluble ultrafine particles are more potent than larger particles of similar composition in causing pulmonary inflammation, tissue damage, and lung tumors [Lee et al. 1985; Oberdörster and Yu 1990; Oberdörster et al. 1994; Heinrich et al. 1995; Driscoll 1996; Renwick et al. 2004] .

Specialized forms of engineered nanoparticles may differ in their toxicity from other nanoparticles. SWCNTs have been evaluated in recent studies of mice and rats exposed via intratracheal instillation. SWCNTs instilled into the lungs of mice and rats produced increased early fibrosis, granulomas, and toxicity in the pulmonary interstitium of the lungs compared with carbon black and quartz [Lam et al. 2004; Warheit et al. 2004]. One study suggested that the SWCNTs may act through a different mechanism than other inhaled contaminants because of the absence of pulmonary inflammation or cellular proliferation [Warheit et al. 2004].

NIOSH researchers recently reported adverse lung effects in mice following exposure to SWCNTs using a dosing technique that correlated with the OSHA Permissible Exposure Limit (PEL) for graphite (5 mg/m^3) [Shvedova et al. 2005]. The study included a dose that was correlated with the dose that would be deposited in a person exposed at the graphite PEL for approximately twenty 8-hour work days. The findings suggest that exposure to SWCNTs in mice leads to pulmonary inflammation, oxidative stress, development of multifocal granulomatous pneumonia and fibrosis.

C. Observations from Epidemiological Studies Involving Fine and Ultrafine Particles

Epidemiological studies in workers exposed to aerosols including fine and ultrafine particles have reported lung function decrements, adverse respiratory symptoms, chronic obstructive pulmonary disease, and fibrosis [Kreiss et al. 1997; Gardiner et al. 2001; Antonini 2003]. In addition, some studies have found elevated lung cancer among workers exposed to certain ultrafine particles, e.g., diesel exhaust particulate [Steenland et al. 1998; Garshick et al. 2004] or welding fumes [Antonini 2003]. The implications of these studies, however, are uncertain because other studies have not found elevated lung cancer, and the precise contribution of the ultrafine particle fraction in workplace aerosols to the observed adverse health effects is still open to question and a matter of active research.

Epidemiological studies in the general population have shown associations between particulate air pollution and increased morbidity and mortality from respiratory and cardiovascular diseases [Dockery et al. 1993; HEI 2000; Pope et al. 2002; Pope et al.

2004] . Although some epidemiological studies have shown adverse health effects associated with exposure to the ultrafine particulate fraction of air pollution [Peters et al. 1997; Penttinen et al. 2001; Ibald-Mulli et al. 2002], uncertainty exists about the role of ultrafine particles relative to the other air pollutants in causing the observed adverse health effects.

D. Hypotheses from Animal and Epidemiological Studies

Research reported from laboratory animal studies and from human epidemiological studies lead to several hypotheses regarding the potential health effects of engineered nanoparticles. As this research continues, more data will become available to support or refute these hypotheses.

1. Engineered nanoparticles are likely to have health effects similar to well-characterized ultrafine particles with similar physical and chemical characteristics.

Studies in rodents and humans support the hypothesis that incidental ultrafine particles nanoparticles may pose a greater respiratory hazard than the same mass of larger particles with similar chemical composition. Studies of existing particles have shown adverse health effects in workers exposed to ultrafine particles (e.g., diesel exhaust particulate, welding fumes); and animal studies have shown that ultrafine particles are more inflammogenic and tumorigenic in the lungs of rats than an equal mass of larger particles of similar composition [Oberdörster and Yu 1990; Driscoll 1996; Tran et al. 1999, 2000]. **If engineered nanoparticles involve the same characteristics that seem to be associated with reported effects from ultrafine particles, they may also involve the same concerns.**

Although the characteristics of existing ultrafine particles and engineered nanoparticles may differ substantially, the toxicological and dosimetric principles derived from these studies may be relevant to engineered particles. The biological mechanisms of particle-related lung diseases (e.g., oxidative stress, inflammation, and production of cytokines, chemokines, and cell growth factors) [Mossman and Churg 1998; Castranova 2000] also appear to be involved in the lung responses to ultrafine or nanoparticles [Donaldson et al. 1998; Donaldson and Stone 2003; Oberdörster et al. 2005]. Toxicological studies have shown that the chemical and physical properties that are important factors influencing the fate and toxicity of ultrafine particles may also be significant for nanoparticles [Duffin et al. 2002; Kreyling et al. 2002; Oberdörster et al. 2002].

2. **Surface area and activity, particle number, and solubility may be better predictors of potential hazard than mass.**

The greater potential hazard may relate to the greater number or surface area of nanoparticles compared with that for the same mass concentration of larger particles [Oberdörster et al. 1992; Oberdörster et al. 1994; Peters et al. 1997; Moshammer and Neuberger 2003]. This hypothesis is based primarily on the pulmonary effects observed in studies of rodents exposed to various types of ultrafine or fine particles (e.g., titanium dioxide, carbon black, barium sulfate, carbon black, diesel soot, coal fly ash, and toner) and in humans exposed to aerosols including nanoparticles (e.g., diesel exhaust and welding fumes). These studies indicate that for a given mass of particles, relatively insoluble nanoparticles are more toxic than larger particles of similar chemical composition and surface properties. Studies of fine and ultrafine particles have shown that particles with less reactive surfaces are less toxic [Tran et al. 1999; Duffin et al. 2002]. However, even particles with low inherent toxicity (e.g., titanium dioxide) have been shown to cause pulmonary inflammation, tissue damage, and fibrosis at sufficiently high particle surface area doses [Oberdörster et al. 1992, 1994; Tran et al. 1999, 2000].

Through engineering, nanomaterials can be generated with specific properties. For example, a recent study has shown the cytotoxicity of water-soluble fullerenes can be reduced by several orders of magnitude by modifying the structure of the fullerene molecules (e.g., by hydroxylation) [Sayes et al. 2004]. These structural modifications were shown to reduce the cytotoxicity by reducing the generation of oxygen radicals – which is the probable mechanism by which the cell membrane damage and cell death occurred in laboratory animals.

The studies of ultrafine particles may provide useful data to develop preliminary hazard or risk assessments and to generate hypotheses for further testing. More research is needed of the specific particle properties and other factors that influence the toxicity and disease development associated with airborne particles, including those characteristics that may be most predictive of the potential safety or toxicity of new engineered nanoparticles.

Potential Safety Hazards

Very little is known about the safety risks that engineered nanomaterials might pose, beyond some data indicating that they possess certain properties associated with safety hazards in traditional materials. From currently available information, the potential safety concerns most likely would involve catalytic effects or fire and explosion hazards if nanomaterials are found to behave similarly to traditional materials in key respects.

A. Fire and explosion

Although insufficient information exists to predict the fire and explosion risk associated with nanoscale powders, **nanoscale combustible material could present a higher risk than a similar quantity of coarser material, given its unique properties** [HSE 2004]. Decreasing the particle size of combustible materials can increase combustion potential and combustion rate, leading to the possibility of relatively inert materials becoming as highly reactive as nanomaterials. Dispersions of combustible nanomaterial in 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 engineered nanomaterials. In the case of some metals, explosion risk can increase significantly as particle size decreases.

The greater activity of nanoscale materials forms a basis for research into nanoenergetics. For instance, nanoscale Al/MoO_3 thermites ignite more than 300 times faster than corresponding micrometer-scale material [Granier and Pantoya 2004].

B. Catalytic reaction

Nanometer-diameter particles and nanostructured porous materials 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 that would not otherwise be anticipated from their chemical composition alone [Pritchard 2004].

Working with Engineered Nanomaterials

Engineered nanomaterials are diverse in their physical, chemical, and biological nature. The processes used in research, material development, production, and use or introduction of nanomaterials have the potential to vary greatly. **Until further information on the possible health risks and extent of occupational exposure to nanomaterials becomes available, interim precautionary measures should be developed and implemented.** These measures should focus on the development of safe working practices tailored to specific processes and materials where workers might be exposed. Hazard information that is available about common materials that are being manufactured in the nanometer range (for example, TiO_2) should be considered as a starting point in developing any work practices. The following guidelines are designed to aid in risk assessments for engineered nanomaterials, and for reducing the risk of exposure in the workplace. Using a risk-based approach to assess a given process and develop precautionary measures is consistent with good professional occupational safety and health practice and with those recommended by the UK Royal Society and Royal Academy of Engineers [The Royal Society and The Royal Academy of Engineering 2004].

A. Potential for occupational exposure

Very few studies have been measured exposure to nanoparticles that are purposely produced and not incidental to an industrial process. In general, it is likely that processes generating nanomaterials in the gas phase, or using or producing nanomaterials as powders or slurries/suspensions/solutions (i.e. in liquid media) pose the greatest risk for releasing nanoparticles. In addition, maintenance on production systems (including cleaning and disposal of materials from dust collection systems) is likely to result in exposure to nanoparticles if it involves disturbing deposited nanomaterial. Exposures associated with waste streams containing nanomaterials may also occur.

The magnitude of exposure to nanoparticles when working with nanopowders depends on the likelihood of particles being released from the powders during handling. Studies on exposure to SWCNTs have indicated that although the raw material may release visible particles a few millimeters in diameter into the air when handled, the release rate of inhalable and respirable particles is relatively low (on a mass or number basis) compared with other nanopowders [Maynard et al. 2004]. Since data are generally lacking with regard to the generation of inhalable/respirable particles during the production and use of engineered nanomaterials, further research is required to determine exposures under various conditions.

Devices comprised of nanostructures, such as integrated circuits, pose a minimal risk of exposure to nanoparticles during handling. However, some of the processes used in their production may lead to exposure to nanoparticles (for example, exposure to commercial polishing compounds that contain nanoscale particles, or exposure to nanoscale particles that are inadvertently dispersed or created during the manufacturing and handling processes). Likewise, large-scale components formed from nanocomposites will most likely not present significant exposure potential. However, if such materials are used or handled in such a manner that can generate nanostructured particles (e.g., cutting, grinding), or undergo degradation processes that lead to the release of nanostructured material, then a potential exposure may occur by the inhalation, ingestion, and/or dermal penetration of these particles.

B. Factors affecting exposure to nanoparticles

Factors affecting exposure to engineered nanoparticles will include the amount of material being used and whether the material can be easily dispersed (in the case of a powder) or form airborne sprays or droplets (in the case of suspensions). 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 to and being deposited in the gas exchange (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 [Lippmann 1977; ICRP 1994; ISO 1995]. Particles that are capable of being deposited in the gas exchange region of the lungs are considered respirable particles. **The mass deposition fraction of discrete nanoparticles (i..e, <100 nm) is greater in the human respiratory tract than that for larger respirable particles.** Up to 50% of inhaled nanoparticles may deposit in the gas-exchange region [ICRP 1994]. For inhaled nanoparticles smaller than approximately 30 nm, an increasing mass fraction of particles is predicted to deposit in the upper airways of the human respiratory tract [ICRP 1994]. At present there is insufficient information to predict situations and scenarios that are likely to lead to exposure to nanomaterials. However, some of those workplace factors that can increase the potential for exposure include the following:

- 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 nanoparticles in the gas phase in nonenclosed systems will increase the chances of aerosol release to the workplace.
- Handling nanostructured powders will lead to the possibility of aerosolization.
- Maintenance on equipment and processes used to produce or fabricate nanomaterials will pose a potential for exposure to workers performing these tasks.
- Cleaning of dust collection systems used to capture nanoparticles can pose a potential for both skin and inhalation exposure

Exposure Assessment and Characterization

Until more information is available on the mechanisms underlying nanoparticle toxicity, it is uncertain as to what measurement technique should be used to monitor exposures in the workplace. If the qualitative assessment of a process has identified potential exposure points and leads to the decision to measure nanoparticles, several factors must be kept in mind. Current research indicates that mass and bulk chemistry may be less important than particle size, surface area, and surface chemistry (or activity) for nanostructured materials [Oberdörster et al. 1992, 1994]. Research is still ongoing into the relative importance of these different exposure metrics, and how to best characterize exposures against them. Once the decision has been made to measure exposure, the metric to be used will depend on availability of sampling equipment or instruments and experience with those methods or instruments. **Regardless of the metric and method selected, it is critical that measurements be conducted before production or processing of a nanoparticle to obtain background data.** Measurements made during production or processing can then be evaluated to determine if there has been an increase in the metric selected. NIOSH intends to release the results of its research on this site and invites additional information and comments to be submitted.

A. Monitoring workplace exposures

Although research continues to address questions of nanoparticle toxicity, a number of exposure assessment approaches can be instituted to determine worker exposures. These assessments can often be performed using traditional industrial hygiene sampling methods that include the use of samplers placed at static locations (area sampling), samples collected in the breathing zone of the worker (personal sampling), or real-time measurements of exposure that can be personal or static. In general, personal sampling is preferred to ensure an accurate representation of the worker’s exposure, whereas area samples (e.g., size-fractionated aerosol samples) and real-time (direct-reading) exposure measurements may be more useful for evaluating the need for improvement of engineering controls and work practices.

Many of the sampling techniques that are available for measuring airborne nanoaerosols vary in complexity but can provide useful information for evaluating occupational exposures with respect to particle size, mass, surface area, number concentration, composition, and surface chemistry. Unfortunately, relatively few of these techniques are readily applicable to routine exposure monitoring. These measurement techniques are described below along with their applicability for monitoring nanometer aerosols.

For each measurement technique used, it is vital that the key parameters associated with the technique and sampling methodology be recorded when measuring exposure to nanoaerosols. This should include the response range of the instrumentation, whether personal or static measurements are made, and the location of all potential aerosol sources. Comprehensive documentation will facilitate comparison of exposure measurements and aid the re-interpretation of historic data as further information is developed on appropriate exposure metrics.

Size-fractionated aerosol sampling

Studies have indicated that particle size plays an important role in determining the potential effects of nanoparticles in the respiratory system, either by influencing the physical, chemical, and biological nature of the material, affecting the surface area of deposited particles, or enabling deposited particles to move to other parts of the body. Animal studies indicate that the toxicity of nanometer aerosols is more closely associated with aerosol surface area and particle number than the mass concentrations of the aerosol. However, mass concentration measurements may be applicable for evaluating occupational exposure to nanometer aerosols where a good correlation between the surface area of the aerosol and mass concentration can be determined.

Aerosol samples can be collected using inhalable, thoracic, or respirable samplers, depending on the region of the respiratory system most susceptible to the inhaled particles. **Current information suggests that the gas-exchange region of the lungs is particularly susceptible to nanomaterials [ICRP 1994], suggesting the use of respirable samplers.** Respirable fraction samplers will also collect a nominal amount of nanometer-diameter particles that can deposit in the upper airways and ultimately cleared or transported to other parts of the body.

Respirable fraction samplers allow mass-based exposure measurements to be made using gravimetric and/or chemical analysis [NIOSH 1994a]. However, they do not provide information on aerosol number, size, or surface area concentration, unless the relationship between different exposure metrics for the aerosol (e.g., density, particle shape) has been previously characterized. Currently, no commercially available personal samplers are designed to measure the particle number, surface area, or mass concentration of nanometer aerosols. However, several methods are available that can be used to estimate surface area, number, or mass concentration for particles smaller than 100 nm.

In the absence of specific exposure limits or guidelines for engineered nanoparticles, exposure data gathered from the use of respirable samplers [NIOSH 1994b] can be used to determine the need for engineering controls or work practices and for routine exposure monitoring of processes and job tasks. When chemical components of the sample need to be identified, chemical analysis of the filter samples can permit smaller quantities of material to be quantified, with the limits of quantification depending on the technique selected [NIOSH 1994a]. The use of conventional impactor designs to assess nanoparticle exposure is limited, since practical impaction limits are 200 to 300 nm. Low-pressure cascade impactors that can measure particles to ≥ 50 nm may be used for static sampling, since their size and complexity preclude their use as personal samplers [Marple et al. 2001, Hinds 1999]. A personal cascade impactor is available with a lower aerosol cut point of 250 nm [Misra et al. 2002], allowing an approximation of nanometer particle mass concentration in the worker's breathing zone. For each method, the detection limits are of the order of a few micrograms of material on a filter or collection substrate [Vaughan et al. 1989]. Cascade impactor exposure data gathered from worksites where nanomaterials are being processed or handled can be used to make assessments as to the efficacy of exposure control measures.

Real-time aerosol sampling

The real-time (direct-reading) measurement of nanometer aerosol concentrations is limited by the sensitivity of the instrument to detect small particles. Many real-time aerosol mass monitors used in the workplace rely on light scattering from groups of particles (photometers). This methodology is generally insensitive to particles smaller than 300 nm [Hinds 1999]. Optical instruments that size individual particles and convert the measured distribution to a mass concentration are similarly limited to particles larger than 100 to 300 nm.

The Scanning Mobility Particle Sizer (SMPS) is widely used as a research tool for characterizing nanometer aerosols, although its applicability for use in the workplace may be limited because of its size, cost, and the inclusion of a radioactive source. The Electrical Low Pressure Impactor (ELPI) is an alternative instrument that combines a cascade impactor with real-time aerosol charge measurements to measure size distributions [Keskinen et al. 1992].

Surface area measurements

Relatively few techniques exist to monitor exposures with respect to aerosol surface area. Isothermal adsorption is a standard off-line technique used to measure the specific surface area of powders that could be adapted to measure the specific surface area of collected aerosol samples. For example, the surface area of particulate material (e.g., using either a bulk or an aerosol sample) can be measured in the laboratory using a gas adsorption method (e.g., Brunauer, Emmett, and Teller, BET) [Brunauer et al. 1938]. However, the BET method requires relatively large quantities of material, and measurements are influenced by particle porosity and adsorption gas characteristics.

The first instrument designed to measure aerosol surface-area was the epiphaniometer [Baltensperger et al. 1988]. This device measures the Fuchs or active surface-area of the aerosols by measuring the attachment rate of radioactive ions. For aerosols less than approximately 100 nm in size, measurement of the Fuchs surface area is probably a good indicator of external surface-area (or geometric surface area). However, for aerosols greater than approximately 1 µm the relationship with geometric particle surface-area is lost [Fuchs 1964]. Measurements of active surface-area are generally insensitive to particle porosity. The epiphaniometer is not well suited to widespread use in the workplace because of the inclusion of a radioactive source and the lack of effective temporal resolution.

This same measurement principle can be applied with the use of a portable aerosol diffusion charger. Studies have shown that these devices provide a good estimate of aerosol surface area when the airborne particles are smaller than 100 nm in diameter. For larger particles, diffusion chargers underestimate aerosol surface area. However, further research is needed to evaluate the degree of underestimation. Extensive field evaluations of commercial instruments are yet to be reported. However, laboratory evaluations with monodisperse silver particles have shown that 2 commercially available diffusion chargers can provide good measurement data on aerosol surface area for particles smaller than 100 nm in diameter but underestimate the aerosol surface area for particles larger than 100 nm in diameter [Ku and Maynard (in press)].

Particle number concentration measurement

The importance of a particle number concentration as an exposure metric is not clear from the toxicity data. In many cases, health end points appear to be more closely related with particle surface area rather than particle number. However, the number of particles depositing in the respiratory tract or other organ systems may play an important role.

Aerosol particle number concentration can be measured relatively easily using Condensation Particle Counters (CPCs). These are available as hand-held static instruments, and they are generally sensitive to particles greater than 10 to 20 nm in diameter. CPCs designed for the workplace do not have discrete size-selective inputs, and so they are typically sensitive to particles up to micrometers in diameter. Commercial size-selective inlets are not available to restrict CPCs to the nanoparticle size range; however, the technology exists to construct size-selective inlets based on particle mobility, or possibly inertial pre-separation. An alternative approach to estimating nanoparticle concentrations using a CPC is to use the instrument in parallel with an optical particle counter. The difference in particle count between the instruments will provide an indication of particle number concentration between the lower CPC detectable particle diameter and the lower optical particle diameter detectable (typically 300 to 500 nm).

A critical issue when characterizing exposure using particle number concentration is selectivity. **Nanoparticles are ubiquitous in many workplaces**, from sources such as combustion, vehicle emissions, and infiltration of outside air. Particle counters are generally insensitive to particle source or composition **making it difficult to differentiate between incidental and process-related nanoparticles using number concentration alone.** In a study of aerosol exposures while bagging carbon black, Kuhlbusch et al. [2004] found that peaks in number concentration measurements were associated with emissions from fork lift trucks and gas burners in the vicinity, rather than the process under investigation. Although this issue is not unique to particle number concentration measurements, orders of magnitude difference can exist in aerosol number concentrations depending on concomitant sources of particle emissions.

Although using nanoparticle number concentration as an exposure measurement may not be consistent with exposure metrics being used in animal toxicity studies, **such measurements may be a useful indicator for identifying nanoparticle emissions and determining the efficacy of control measures.** Portable CPCs are capable of measuring localized aerosol concentrations, allowing the assessment of particle releases occurring at various processes and job tasks [Brouwer et al. 2004].

Surface Area Estimation

Information about the relationship between different measurement metrics can be used for estimating aerosol surface area. If the size distribution of an aerosol remains consistent, the relationship between number, surface area, and mass metrics will be constant. In particular, mass concentration measurements can be used for deriving surface area concentrations, assuming the constant of proportionality is known. This constant is the specific surface area (surface to mass ratio).

Size distribution measurements obtained through sample analysis by transmission electron microscopy may also be used to estimate aerosol surface area. If the measurements are weighted by particle number, information about particle geometry will be needed to estimate the surface area of particles with a given diameter. If the measurements are weighted by mass, additional information about particle density will be required.

If the airborne aerosol has a lognormal size distribution, the surface-area concentration can be derived using three independent measurements. An approach has been proposed using three simultaneous measurements of aerosol that included mass concentration, number concentration, and charge [Woo et al. 2001]. With knowledge of the response function of each instrument, minimization techniques can be used to estimate the parameters of the lognormal distribution leading to the three measurements used in estimating the aerosol surface area.

An alternative approach has been proposed whereby independent measurements of aerosol number and mass concentration are made, and the surface area is estimated by assuming the geometric standard deviation of the (assumed) lognormal distribution [Maynard 2003]. This method has the advantage of simplicity by relying on portable instruments that are finding increasing application in the workplace. Theoretical calculations have shown that estimates may be up to a factor of ten different from the actual aerosol surface-area, particularly when the aerosol has a bimodal distribution. Field measurements indicate that estimates are within a factor of three of the active surface-area, particularly at higher concentrations. In workplace environments, aerosol surface-area concentrations can be expected to span up to 5 orders of magnitude; thus, surface-area estimates may be suited to initial or preliminary appraisals of occupational exposure concentrations.

Although such estimation methods are unlikely to become a long-term alternative to more accurate methods, they may provide a viable interim approach to estimating the surface area of nanometer aerosols in the absence of precise measurement data. Additional research is needed on comparing methods used for estimating aerosol surface area with a more accurate aerosol surface area measurement method. NIOSH is conducting research in this area and will communicate results as they become available. In the interim, NIOSH welcomes additional information and input on this topic.

B. Proposed Sampling Strategy

Currently, there is not one sampling method that can be used to characterize exposure to nanosized aerosols. Therefore, any attempt to characterize workplace exposure to nanoparticles must involve a multifaceted approach incorporating many of the sampling techniques mentioned above. Brouwer et al. [2004] recommend that all relevant characteristics of nanoparticle exposure be measured and a sampling strategy similar to theirs would provide a reasonable approach to characterizing workplace exposure.

The first step would involve identifying the source of nanoparticle emissions. A CPC provides acceptable capability for this purpose. **It is critical to determine ambient or background particle counts before measuring particle counts during the manufacture or processing of the nanoparticles** involved. If a specific nanoparticle is of interest (e.g. TiO_2), then area sampling with a filter suitable for analysis by electron microscopy should also be employed. Transmission electron microscopy (TEM) can identify specific particles and can estimate the size distribution of the particles.

Once the source of emissions is identified, aerosol surface area measurements should be conducted with a portable diffusion charger and aerosol size distributions should be determined with an SMPS or ELPI using static (area) monitoring. A small portable surface area instrument could be adapted to be worn by a worker, although depending on the nature of the work, this may be cumbersome. Further, losses of aerosol with the addition of a sampling tube would need to be calculated. The location of these instruments should be considered carefully. Ideally they would be placed close to the work areas of the workers of interest, but other factors such as size of the instrumentation, power source etc. should be considered.

Lastly, personal sampling using filters suitable for analysis by electron microscopy should be employed, particularly if measuring exposures to specific nanoparticles is of interest. Electron microscopy can be used to identify the particles, and can provide an estimate of the size distribution of the particle of interest. The use of a personal cascade impactor or a respirable cyclone sampler with a filter, though limited, will help to remove larger particles that are not of interest and allowing for a more definitive determination of particle size.

Using a combination of these techniques, an assessment of worker exposure to nanoparticles can be conducted. This approach will allow a determination of the presence and identification of nanoparticles, and the characterization of the important aerosol metrics, providing a reasonable estimate of exposure can be achieved. This approach is not without limitations, however. It largely relies on static or area sampling, which will hamper interpretation and increase the inaccuracy of the exposure estimate.

Exposure Control Procedures

Given the limited information about the health risks associated with occupational exposure to engineered nanoparticles, precautionary work practices should be tailored to the processes and job tasks in which exposure might occur. **For most processes and job tasks, the control of airborne exposure to nanoparticles can most likely be accomplished using a wide variety of engineering control techniques similar to those used in reducing exposures to general aerosols** [Ratherman 1996; Burton 1997]. To ensure that the appropriate steps are taken to minimize the risk of exposure, a risk management program should be implemented. Elements of such a program should include the education and training of workers in the proper handling of nanomaterials, the criteria and procedures for installing engineering controls (e.g., exhaust ventilation) at process locations where exposure might occur, and the development of procedures describing the types of personal protective equipment (e.g., clothing, respirators) that should be used and when it should be worn.

A. Engineering controls

In general, control techniques such as source enclosure (i.e., isolating the generation source from the worker) and local exhaust ventilation systems should be effective for capturing airborne nanoparticles, based on what is known of nanoparticle motion and behavior in air. Ventilation systems should be designed, tested, and maintained using approaches recommended by the American Conference of Governmental Industrial Hygienists [ACGIH 2001]. In light of current scientific knowledge regarding the generation, transport, and capture of aerosols, these control techniques should be effective for controlling airborne exposures to nanometer-scale particles [Seinfeld and Pandis 1998; Hinds 1999].

Dust collection efficiency of filters

Current knowledge indicates that a well-designed exhaust ventilation system with a high-efficiency particulate air (HEPA) filter should effectively remove nanoparticles [Hinds 1999]. NIOSH is conducting research to validate the efficiency of HEPA filter media used in environmental control systems and in respirators in removing nanoparticles. As results of this research become available, they will be posted on the NIOSH Web site. Filters are tested using particles that have the lowest probability of being captured (typically around 300 nm in diameter). Collection efficiencies for smaller particles should exceed the measured collection efficiency at this particle diameter [Lee and Liu 1982]. The use of a HEPA filter must also be coupled to well-designed filter housing. For example, if the filter is improperly seated, nanoparticles have the potential to bypass the filter, leading to filter efficiencies much less than predicted [NIOSH 2003]. An unventilated process enclosure that is effective in controlling the emission of larger particles may not be effective in controlling nanoparticles because of their greater ability to penetrate small gaps and the nontraditional measurements needed to evaluate effectiveness of control.

B. Work Practices

The incorporation of good work practices in a risk management program can help to minimize worker exposure to nanomaterials. Examples of good practices include the following:

- Cleaning work areas at the end of each work shift (at a minimum) using HEPA vacuum pickup and wet wiping methods. Dry sweeping or air hoses should not be used to clean work areas. Cleanup and disposal should be conducted in a manner that prevents worker contact with wastes and complies with all applicable Federal and State, and local regulations.
- Preventing the storage and consumption of food or beverages in workplaces where nanomaterials are handled.
- Providing hand-washing facilities and encouraging workers to use them before eating, smoking, or leaving the worksite.
- Providing facilities for showering and changing clothes to prevent the inadvertent contamination of other areas (including take-home) caused by the transfer of nanoparticles on clothing and skin.

C. Personal protective clothing

Currently, no guidelines are available on the selection of clothing or other apparel for the prevention of dermal exposure to nanoparticles. Published research has shown that penetration efficiencies for 8 widely different fabrics (including woven, non-woven, and laminated fabrics) against 0.477 µm particles range from 0.0 % to 31%, with an average of 12% [Shalev et al. 2000]. Penetration efficiencies for nanoparticles have not been studied. However, even for powders in the macro scale, it is recognized that skin protective equipment (i.e. suits, gloves and other items of protective clothing) is very limited in its effectiveness to reduce or control dermal exposure [Schneider et al. 2000]. In any case, although nanoparticles may penetrate the epidermis, there has been little work to suggest that penetration leads to disease; and no dermal exposure standards have been generated.

Existing clothing standards already incorporate testing with nanometer-sized particles and therefore provide some indication of the effectiveness of protective clothing with regard to nanoparticles. For instance, ASTM standard F1671–03 specifies the use of a 27-nm bacteriophage to evaluate the resistance of materials used in protective clothing to penetration by bloodborne pathogens [ASTM Subcommittee F23.40 2003].

D. Respirators

In the hierarchy of controls, respirators may be necessary when engineering and administrative controls do not adequately keep worker exposures to an airborne contaminant below a regulatory limit or an internal control target. Currently, there are no specific exposure limits for airborne exposures to engineered nanoparticles although occupational exposure limits (e.g., OSHA, NIOSH, ACGIH) exist for larger particles of similar chemical composition. Preliminary scientific evidence indicates that nanoparticles may be more biologically reactive than larger particles of similar chemical composition and thus may pose a greater health risk when inhaled.

The decision to institute respiratory protection recommended in this document should be based on a combination of professional judgment and the results of the risk assessment and risk management approach recommended in the document. The effectiveness of administrative, work practice, and engineering controls can be evaluated using the measurement techniques described in Exposure Assessment and Characterization. If worker exposure to nanoparticles remains a concern after instituting measures to control exposure, the use of respirators can further reduce worker exposures. Several classes of respirators exist that can provide different levels of protection when properly fit tested on the worker. Table 1 lists various types of particulate respirators that can be used along with information on the level of exposure reduction that can be expected from each and the advantages and disadvantages of each respirator type. To assist respirator users, NIOSH has published the document *NIOSH Respirator Selection Logic (RSL)* that provides a process that respirator program administrators can use to select appropriate respirators for agents with exposure limits (see www.cdc.gov/niosh/docs/2005-100/default.html). As new toxicity data for individual nanomaterials become available, NIOSH will review the data and make recommendations for respirator protection.

When respirators are required to be used in the workplace, the Occupational Safety and Health Administration (OSHA) respiratory protection standard (29 CFR 1910.134) requires that a respiratory program be established that includes the following program elements: (1) an evaluation of the worker's ability to perform the work while wearing a respirator, (2) regular training of personnel, (3) periodic environmental monitoring, (4) respirator fit testing, and (5) respirator maintenance, inspection, cleaning, and storage. The standard also requires that the selection of respirators be made by a person knowledgeable about the workplace and the limitations associated with each type of respirator. OSHA has also issued guidelines for employers who choose to establish the voluntary use of respirators [29 CFR 1910.134 Appendix D].

NIOSH tests and certifies respirator filters using solid (NaCl) or liquid (DOP) particles that are nominally 0.3 µm in diameter to determine the filter's collection efficiency at 95% to at least 99.97%. Particles of this size are considered to be the most penetrating particle size [TSI 2005; NIOSH 1996]. Particles larger than 0.3 µm are collected most efficiently by impaction, interception, and settling. Particles smaller than 0.3 µm are collected most efficiently by diffusion or electrostatic attraction. Current data indicate that the penetration of approximately 0.3-µm particles represents the worst case [Martin and Moyer 2000]. Since nanoparticles are typically smaller than 100 nanometers they are theoretically collected more efficiently than the 0.3-µm test aerosols [Hinds 1999]. NIOSH is conducting research to validate the efficiency of HEPA filter media used in environmental control systems and in respirators in removing nanoparticles. As results from this research become available, they will be posted on the NIOSH Web site.

Table1. Air-Purifying Particulate Respirators

Respirator type	NIOSH assigned protection factor (106)	Advantages	Disadvantages	Cost (2004 dollars)
Filtering facepiece (disposable)	10	– Lightweight – No maintenance or cleaning needed – No effect on mobility	– Provides no eye protection – Can add to heat burden – Inward leakage at gaps in face seal – Some do not have adjustable head straps – Difficult for a user to do a seal check – Level of protection varies greatly among models – Communication may be difficult – Fit testing required to select proper facepiece size – Some eyewear may interfere with the fit	$0.70 to $10

Elastomeric half-facepiece	10	– Low maintenance – Reusable facepiece and replaceable filters and cartridges – No effect on mobility	– Provides no eye protection – Can add to heat burden – Inward leakage at gaps in face seal – Communication may be difficult – Fit testing required to select proper facepiece size – Some eyewear may interfere with the fit	Facepiece: $12 to $35 filters: $4 to $8 each
Powered with loose-fitting facepiece	25	– Provides eye protection – Protection for people with beards, missing dentures or facial scars – Low breathing resistance – Flowing air creates cooling effect – Face seal leakage is generally outward – Fit testing is not required – Prescription glasses can be worn – Communication less difficult than with elastomeric half-facepiece or full-facepiece respirators – Reusable components and replaceable filters	– Added weight of battery and blower – Awkward for some tasks – Battery requires charging – Air flow must be tested with flow device before use	Unit: $400 to $1,000 Filters: $10 to $30
Elastomeric full-facepiece with N-100, R-100, or P-100 filters	50	– Provides eye protection – Low maintenance – Reusable facepiece and replaceable filters and cartridges – No effect on mobility – More effective face seal than that of filtering facepiece or elastomeric half-facepiece respirators	– Can add to heat burden – Diminished field-of-vision compared to half-facepiece –Inward leakage at gaps in face seal –Fit testing required to select proper facepiece size –Facepiece lens can fog without nose cup or lens treatment –Spectacle kit needed for people who wear corrective glasses	Facepiece: $90 to $240 Filters: $4 to $8 each Nose cup: $30
Powered with tight-fitting half-facepiece or full-facepiece	50	–Provides eye protection with full-facepiece –Low breathing resistance –Face seal leakage is generally outward –Flowing air creates cooling effect	–Added weight of battery and blower –Awkward for some tasks –No eye protection with half-facepiece –Fit testing required to select proper facepiece	Unit: $500 to $1,000 Filters: $10 to $30

		–Reusable components and replaceable filters	size –Battery requires charging –Communication may be difficult –Spectacle kit needed for people who wear corrective glasses with full face-piece respirators –Air flow must be tested with flow device before use	
Note: The assigned protection factors in this table are from the NIOSH Respirator Selection Logic.(106) When the table was prepared, OSHA had proposed amending the respiratory protection standard to incorporate assigned protection factors.(107) The Internet sites of NIOSH (www.cdc.gov/niosh) and OSHA (www.osha.gov) should be periodically checked for the current assigned protection factor values.				

E. Cleanup of nanomaterial spills

No specific guidance is currently available on cleaning up nanomaterial spills. Until relevant information is available, it would be prudent to base strategies for dealing with spills on current good practices, together with available information on exposure risks and the relative importance of different exposure routes. Standard approaches to cleaning up 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/liquid traps. As in the case of any material spill, handling and disposal of the waste material should follow any exiting Federal, State, or local regulations.

When developing procedures for cleaning up nanomaterial spills, consideration should be given to the potential for exposure during cleanup. Inhalation exposure and dermal exposure will likely present the greatest risks. Consideration will therefore need to be given to appropriate levels of personal protective equipment. Inhalation exposure in particular will be influenced by the likelihood of material re-aerosolization. In this context, it is likely that a hierarchy of potential exposures will exist, with dusts presenting a greater inhalation exposure potential than liquids, and liquids in turn presenting a greater potential risk than encapsulated or immobilized nanomaterials and structures.

Research

NIOSH has developed a strategic plan for research on several occupational safety and health aspects of nanotechnology. The plan is available at www.cdc.gov/niosh/topics/nanotech/strat_plan.html. Review and feedback on the plan is welcomed.

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*_Code of Federal Regulations_. See CFR in references.

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