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Discussion

Safety aspects of nanotechnology based activity

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ABSTRACT

Nanoscience has emerged rapidly in terms of interdisciplinary research, technological applications, and consumer products. The unique properties of engineered nanomaterials may be accompanied by undesired health hazards, leading to a concurrent interest in the safety of nanotechnology related work, application and disposal environment. However, the field of nano-environmental safety has fallen behind commercial development due to the lack of resources and, in some cases, motivation in researching this field. In order to encourage nano-environmental safety and determine if work is needed to answer research questions in this area NSF organized a workshop with participants from universities, national laboratories and industry. The purpose of the workshop was to share information across organizations, discuss the current state of nano-safety, and identify research challenges and solutions. This article presents the significant outcomes from the study.

1. Introduction

Nanoscience has influenced a wide range of fields including biotechnology (Pelaz et al., 2012), energy (Ji et al., 2011), structural materials (Ostrikov et al., 2011), electronics (Wang et al., 2009), sensors (Kumar et al., 2011), etc. In the immediate past decade, significant research advances have been made in the synthesis and characterization of nanostructures to engineer nanoparticles with varying size, shape, functional properties, and surface potential, which have revolutionized the scientific community as well as industry (Reddy et al., 2012; Ruiz-Hitzky et al., 2010; Vasilescu et al., 2012). Particularly for high-technology applications, the processing of nanostructures into useful objects such as monoliths, films, devices and bulk nanomaterials has started to attract attention in various sectors (Cao et al., 2010; Reddy et al., 2012). The increasing nanoscience and nanotechnology activity has led to increasing demand for safety protocols and procedures for researchers and other workers. In the next decade, nanotechnology will be translated from research labs to consumer use, motivated by responsiveness to societal needs for better quality of lifestyle and environment. Nanosafety is of prime importance to creating a sustainable nanotechnology environment.

While most nanotechnology environmental concerns have focused on toxicology (Nowack and Bucheli, 2007), very few have addressed creating safer environments for nanotechnology research, development, and commercialization. With escalated research in nanotechnology and transformational commercial products, more and more nanoparticles find their way to the environment. Particular importance needs to be given to laboratory working conditions involved in nanomaterials research because these environments represent a first line of exposure. Care must be taken to avoid nanoparticle inhalation, dermal contact, ingestion, etc. The objective should be to minimize the direct as well as indirect exposure of researchers and workers to nanoparticles.

The unique physico-chemical properties of nanoparticles differ largely from their bulk counterparts, and the well-established environmental health and safety methods may or may not be suitable for nanoparticle environments. For example, well-designed ventilation systems with high-efficiency particular air (HEPA) filter should be effective in capturing airborne nanoparticles. However, this may not be the case for surface active nanoparticles. Thus to conduct nanotechnology research responsibly, accurate assessment of workplace conditions is required, and precautions must be taken for mitigating adverse effects caused by the nanoparticle working environment. The safety aspect of nanotechnology facilities should include good laboratory practices and proper infrastructure development.

The safety concerns for any nanotechnology facility could be very complicated and is a broad topic of discussion for the experts in the field. Thus to discuss the safety aspects of nanotechnology facility, participants from universities, research institutes and

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industry must be included in the dialog that contributes to the current understanding, challenges and possible solutions regarding nano-safety. Recently, a workshop titled: "*Safety aspects of nanosystems and infrastructure for Sustainability*" was organized at University of Central Florida, Orlando, FL. The findings from this workshop can lead to further discussion of important safety research activities in nanoscience through the workshop lectures, discussions, and future directions to create a safe, sustainable nanotechnology environment. In order to facilitate the current understanding of nano-related safety practices and further the endeavors in developing safe nanoscience work environments, NSF encouraged the participation of researchers, industrialists, and policy makers in this workshop. The study aimed at the exchange of technical information of mutual interest and provided opportunities to move ahead in developing nanosafety. The attendees consisted of a diversified group of scientists (from academia, national laboratories, industries, and national agencies) who discussed the importance of safety aspects of nanosystems.

"Nanosafety" is a broad term and a lack of specific objectives can lead to ineffective use of resources. Thus to maintain diversity and cover the main spectrum of "Nano-Safety", the following topics were covered:

1. Personal protection from nano exposure.
2. Instrumentation for nanosafety monitoring.
3. Nano storage safety and handling and disposal.
4. Lab (hood, sink, storage, etc.) and infrastructure design for nano-research.
5. Information sharing to keep a safe environment for nano-research.

The challenges associated with nanosafety and possible measures to overcome the issues are presented here.

2. Results and discussions

For each topic of discussion, we first identified the current state of the art in laboratory safety associated with nanoscience and technology. Following the discussion on current measures, we further identified the challenges in nanosafety. Finally, feasible solutions were suggested to overcome the challenges associated with nanosafety. The discussions from each topic are detailed in the following sections.

2.1. Personal protection for nanomaterial exposure

The technological advancements to meet specialized applications have led to the production of novel nanomaterials with unique properties. The toxicological studies on various nanomaterials suggest some may be harmful on exposure to living systems (Casals et al., 2008; Colvin, 2003; Oberdorster, 2010; Papp et al., 2008; Radad et al., 2012; Tian et al., 2006; Xia et al., 2009; Yang et al., 2009; Zhao et al., 2011; Zhu et al., 2009). Personal protection becomes necessary when other control measures do not meet safe exposure limits. Personal protective equipment (PPE) includes respirators, protective clothing, gloves, etc. In order to produce nanomaterials with high throughput and precise control, gas phase methods are preferred over liquid phase synthesis (Biskos et al., 2008). The waste formation associated with such gas phase production of nanomaterials and nanotechnology based consumer products results in airborne nanoparticles which stay suspended in air for a long time and form the most predominant path for entering human body through inhalation (Kuhlbusch et al., 2011; Nazarenko et al., 2012; Yang et al., 2008). Nanomaterials also are known to deposit on the skin of workers. Nanoparticle deposition on skin causes exposure primarily in the stratum cornea of normal skin. However, skin with damage or abrasion allows nanoparticles to penetrate deeper into the epidermis. Although direct penetration is limited, skin exposure to nanoparticles may have significant effects (Monteiro-Riviere and Riviere, 2009; Ryman-Rasmussen et al., 2006; Saathoff et al., 2011).

2.1.1. Current state of the art

The Occupational Safety & Health Administration (OSHA) requires a respiratory program in workplaces. The standard requires that National Institute of Occupational Health and Safety (NIOSH)-approved particulate respirators be selected based on an expert knowledgeable of the limitations of respirators and workplaces (Shaffer and Rengasamy, 2009). NIOSH recommends the use of NIOSH respirator selection logic (RSL) (NIOSH, February 26, 2013). NIOSH-approved respirators have been shown to provide expected levels of protection when properly used. A recent study (Rengasamy et al., 2009) showed that respirators effectively capture smaller size nanoparticles as predicted by the single fiber theory. Particle penetration, however, exceeded NIOSH allowable penetration levels when number-based methods were employed as opposed to the photometric methods (Rengasamy et al., 2009, 2011). Particles below 200 nm size showed a decrease in leakage through face seal area of respirators. However, the high mobility of nanoparticles indicated otherwise, and the results obtained from mannequin studies showed a twofold higher concentration of nanoparticles than larger size particles inside the breathing zone (Rengasamy and Eimer, 2012). It was also observed that among the particles that enter inside the respirator, a higher concentration of nanoparticles inside the respirator can be expected in workplaces producing high concentration of nanoparticles (Rengasamy and Eimer, 2012).

The use of nitrile gloves provides sufficient protection against nanoparticles produced in many laboratory operations. Only a few studies have reported the penetration of nanomaterials through protective clothing and gloves (Faccini et al., 2012; Gao et al., 2011). Some studies also showed no significant penetration of smaller size particles such as a bacteriophage through nitrile gloves (Edlich et al., 1999).

2.1.2. What are the challenges?

The fast growth of the nanotechnology industry presents potential challenges with the use of Personal Protective Equipment (PPE). Nanomaterial-producing industries and users should be aware of the health and environmental effects of engineered nanomaterials. The use of appropriate PPE to reduce worker exposure to harmful nanomaterials is important. This could be achieved by industries collaborating with research institutions, although not many industries are interested in working with researchers to reduce nanomaterial exposures. In the case of respirators, the selection process becomes difficult with limited information on the toxicity, a lack of available occupational exposure limits (OELs) for most nanomaterials, and limited exposure measurements in the workplace (van Broekhuizen, 2011). Portable high precision instruments for workplace measurements are not readily available in the market. Another challenge is the availability of PPE standards and recommendation/guidance documents. Government agencies have only developed limited or no regulations for the use of PPE (e.g. gloves and protective clothing) for nanomaterials.

2.1.3. Needs to be addressed

The effectiveness of existing PPE needs to be evaluated for a variety of nanoparticle workplace exposures. Currently available PPE may be sufficient for protection against nanomaterials in many cases, but a thorough evaluation of PPE for nanomaterials is required to ascertain their effectiveness in a variety of settings. This