

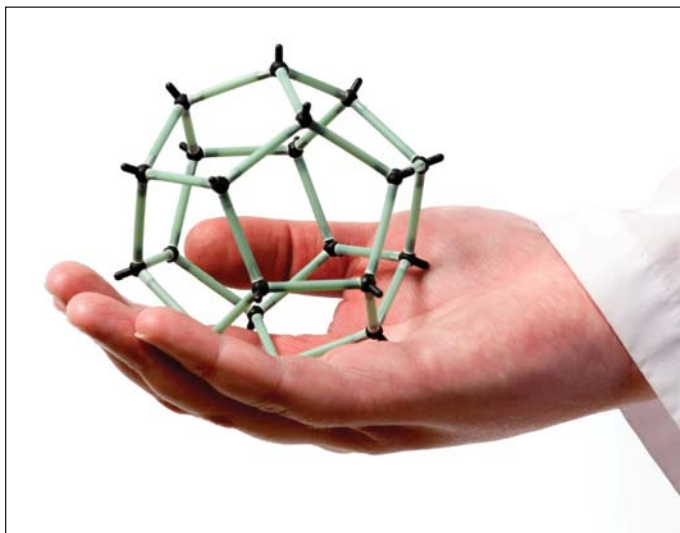
Nanomaterials: What are the Environmental and Health Impacts?

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More than 500 consumer products containing nanomaterials are on the market today, and that number is steadily increasing (1). It is, therefore, not unreasonable to assume that human and environmental exposure to nanomaterials is already occurring.

As with previous emerging technologies, such as pesticides and genetically modified foods, there have been uncertainties and concerns about the health risks associated with nanotechnology. After the establishment of the National Nanotechnology Initiative (NNI) in 2001, the rapid development of new nanomaterial applications has outpaced the research on related environmental, health and safety (EHS) issues (2). The NNI Amendments Act of 2008, (sidebar, p.38) which is intended to strengthen research efforts toward understanding the EHS implications of nanotechnology, calls for the establishment of standard nanotechnology nomenclature, standard reference materials for EHS testing, and standard methods and procedures for evaluating nanomaterials' EHS impacts.

Some people argue that society's perception of nanotechnology is skewed by unwarranted fears that are based on poor scientific justification and statements from various environmental groups. Although there may be unnecessary hype when it comes to nanotechnology safety, experiences with materials such as



chlorofluorocarbons (CFCs), polychlorinated biphenols (PCBs), and asbestos suggest it would be wise to discover and address any potential negative health and environmental effects before the use of nanomaterials becomes widespread. In order to accurately inform the public about the impact of nanotechnology, the technical community must understand and clearly communicate the potential environmental and health implications of nanomaterials.

Media attention regarding the presence of zinc oxide and titanium dioxide nanoparticles in sunscreens is a good example of the need for more information and clear communication. Sunscreens have long used zinc oxide and titanium dioxide. The advantages of the nanoscale versions of these chemicals include enhanced scattering and absorption (their UV-protective capability is optimal at particle sizes less than 100 nm) as well as clear appearance (because nanoparticles are smaller than the wavelength of visible light, the char-

acteristic white color is not seen by the naked eye after application). However, because nanoscale materials have unique properties, concerns about whether these nanomaterial-containing products could have negative health effects have been raised.

Some interest groups warn against using sunscreens containing nanoparticles. For example, to inform consumers, Friends of the Earth (www.foe.org) publishes a catalog (3) that categorizes sunscreens as either nano-

containing or nano-free. Others, such as the Environmental Working Group (www.ewg.org), recommend zinc oxide and titanium dioxide nanoparticle-based sunscreens because they are more effective at blocking UVA radiation than the alternatives (4). Despite the increased research into the penetration, photostability and cytotoxicity of these oxide nanoparticles, no unanimous conclusion has been reached by the technical community, leaving consumers to speculate about the safety of nanoparticle-containing sunscreen products.

Researchers face several challenges in providing sound risk-assessment data for nanomaterials. Obtaining physiologically or environmentally relevant information on which to base risk assessments is difficult. Laboratory experiments are the primary means of generating toxicity data, but in many circumstances, such experiments lack realism and do not accurately reflect actual exposure conditions. Thus,

despite increased attention to nanomaterial EHS by the research community, uncertainty remains.

The progress in carbon-nanotube toxicology research illustrates some of the obstacles. Carbon nanotubes are manufactured under the same Chemical Abstracts Service (CAS) Registry number as graphite, which has little to no known toxicity. In 1998, concerns were raised about whether nanotubes could become “the next asbestos” with respect to health effects due to their physical similarities (5). Now, ten years later, researchers have published evidence that nanotubes can elicit inflammatory effects similar to those seen after asbestos exposure (6).

Although data now corroborate the notion that carbon nanotubes can exhibit asbestos-like qualities, it is important to relate the levels and method of exposure that elicit such effects to what people and the environment would typically encounter. Some argue that nanomaterials are not yet developed to the point where significant exposure is occurring. Others argue that production of nanomaterials is projected to increase from the estimated 2,300 tons/yr produced today to 58,000 tons/yr by 2020, and that exposures will continue to increase (7, 8).

Whether nanomaterial-specific regulations will be implemented to control the extent of incidental, occupational and environmental exposure is unknown at this time. For now, nanomaterials may be regulated under existing legislation. Several U.S. government agencies, such as the Consumer Product Safety Commission (CPSC), Food and Drug Administration (FDA), Occupational Safety and Health Administration (OSHA), and Environmental Protection Agency (EPA), are considering how to apply current regulations to nanotechnology.

Existing environmental laws

Several environmental acts may already apply to nanomaterials, particularly their production and “end-of-life” environmental consequences.

The EPA is examining the interpretation of these laws as they pertain to nanomaterials, as well as the technological challenges in the enforcement of nanomaterial regulations. Some of the issues surrounding the interpretation of these statutes to include nanotechnology are discussed here. [The American Bar Association’s Section of Environment, Energy, and Resources has reviewed the legal applicability of existing EPA statutes to nanotechnology, and has published briefing documents (9) on its website (www.abanet.org/enviro/nanotech).]

The Toxic Substances Control Act (TSCA) authorizes the EPA to review and establish limits on the manufacture, processing, distribution, use and/or disposal of new chemical substances that the EPA determines pose “an unreasonable risk of injury to human health or the environment.” The Clean Air Act (CAA) and Clean Water Act (CWA) give the EPA authority to establish technology-based limitations on and treatment standards for air emissions and liquid effluents generated during the manufacture, use and disposal of nanomaterials. Wastes from commercial-

scale nanotechnology facilities may be regulated under the Resource Conservation and Recovery Act (RCRA) if they meet the RCRA definition of hazardous waste; the extent of regulation depends on the quantity of hazardous wastes generated and whether the wastes are treated, stored or disposed of onsite. The Comprehensive Environmental Response Compensation and Liability Act (CERCLA), more commonly known as the Superfund law, provides the EPA with broad authority to require parties that release hazardous substances to clean up contaminated sites.

TSCA has received the most attention to date, because it is considered the primary law relevant to the environmental implications of chemicals. However, determining whether nanomaterials are “new” or “existing” chemical substances is a key issue that must be clarified before TSCA rules can be applied.

On Jan. 28, 2008, the EPA launched the Nanoscale Materials Stewardship Program (NMSP) and released the “TSCA Inventory Status of Nanoscale Substances — General

NNI AMENDMENTS ACT OF 2008

The National Nanotechnology Initiative (NNI) Amendments Act of 2008 (H.R. 5940) passed the House of Representatives on June 5, 2008, by a vote of 407 to 6. Currently, the Act (S. 3274) is still under review by the Senate Committee on Commerce, Science, and Transportation.

Briefly, the Act reauthorizes the NNI while increasing emphasis on environmental and safety research as well as education and commercialization.

More specifically, H.R. 5940 calls for:

- a publicly accessible EHS research database of the projects supported under the NNI to be developed and maintained by the National Nanotechnology Coordination Office
- interdisciplinary research centers focused on green nanotechnology
- an NNI external advisory panel
- a Coordinator for Social Dimensions of Nanotechnology, to be filled by an associate director of the White House Office of Science and Technology Policy (OSTP), who will develop an annual research plan to coordinate federal EHS research activities
- triennial review of the NNI by the National Research Council.

The Senate version (S.3274) adds the following provisions:

- Government Accountability Office (GAO) review of the regulatory authority of all of the federal agencies that oversee nanotechnology to identify any gaps in current codes, standards and regulations and to recommend changes to close those gaps
- national discussion to increase the awareness of U.S. citizens of nanotechnology, with authorization of \$2 million for at least two large-scale forums.

For more information, see the Congressional Research Service Report entitled “Nanotechnology and Environmental, Health, and Safety: Issues for Consideration,” available at <http://fas.org/sgp/crs/misc/RL34614.pdf>.

Approach,” which outlines how the EPA currently determines whether nanomaterials fall under TSCA (10). In that document, the EPA stresses that the “molecular identity” of the chemical substance will be the deciding factor. TSCA (Section 3(2)(A)) states that “‘chemical substance’ means any organic or inorganic substance of a particular molecular identity, including (i) any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature, and (ii) any element or uncombined radical.” Therefore, if a nanomaterial’s molecular identity is the same as that of a chemical already listed in the TSCA inventory, its manufacturer will not be required to submit a Premanufacture Notice (PMN) for that nanomaterial.

Interestingly, the EPA has said that it will not consider different physical forms of nanomaterials, such as size, shape or dispersion (aggregates), when determining whether nanomaterials have different molecular identities from existing TSCA chemicals. Chemical substances already in the TSCA inventory represent both nanoscale and larger forms. Thus, producers of nanomaterials composed of chemicals listed on the TSCA inventory do not necessarily need to report that they are manufacturing nanoscale forms of the chemicals.

The reasoning behind this interpretation seems to go against the fundamental thrust behind the nanotechnology boom. The benefits of using nanomaterials over their bulk counterparts are primarily due to their size. In his famous lecture, physicist Richard Feynman commented, “at the atomic level, we have new kinds of forces and new kinds of possibilities, new kinds of effects” (11).

Moving from the microscale to the nanoscale leads to two major changes: an increase in the surface-area-to-volume ratio, and the appearance of quantum size effects. Larger surface-area-to-volume ratios make nanoparticles more reactive because

more of their atoms reside on the surface of the particle. Quantum size effects arise when the size of the particles falls below the Bohr radius of the material. For example, due to quantum confinement of the electron-hole pair, the optical properties of quantum dots are size-dependent and their absorption peak can be tuned by controlling the size of the synthesized particles (12). In addition, for biomedical applications, nanoparticles exhibit improved delivery and transport properties, because they are orders of magnitude smaller than cells (which measure approximately 10 μm in diameter).

These “new kinds of effects” have given rise to the strongest, stiffest and darkest-color materials yet to be seen. However, these effects could have unforeseen consequences as well. Thus, regardless of whether a nanomaterial has a bulk counterpart in the TSCA inventory, it is important to fully characterize nanomaterials and understand the human-health and environmental implications of their properties and uses. If the bulk form of a nanomaterial is on any of the hazardous-chemicals lists, an acceptable maximum threshold level of exposure to the nanomaterial form should be determined. The EPA could then consider specifying nanomaterial-specific levels of acceptable release.

Currently, the CERCLA hazardous substances list (13) does not include any specific nanomaterials, but it does list some chemical components of nanomaterials (*e.g.*, arsenic, cadmium, lead, selenium, tellurium) and bulk forms of nanomaterials (*e.g.*, lead sulfide or silver) along with reportable quantity thresholds. Because these levels are based on mass, they may not be suitable for nanomaterials. In addition, the size of nanomaterials affects their transport capabilities, allowing them to reach areas inaccessible to their bulk counterparts. As a result, the effects elicited at the mass threshold for the bulk form may arise at lower concentrations of their nanoscale form.

Sufficient research has not been conducted to determine the extent to which different nanomaterials may be hazardous, and more studies into the concentrations and exposure conditions that cause toxicity for each nanomaterial need to be pursued.

Although the EPA has full authority to regulate chemicals that pose an unreasonable risk to human health or the environment, it must first conduct a risk assessment. Risk assessment involves identifying and defining the hazard, assessing the effects of exposure, characterizing and analyzing the risk of exposure, and communicating and evaluating the risk estimates to improve risk management and mitigation (14).

Data generated from basic research and routine testing need to be available to serve as a basis for predictive models. To date, the main focus of nanomaterial toxicology research has been the determination of lethal concentration (LC_{50}) exposure levels for different nanomaterials using *in vitro* human, mammalian and bacterial cell cultures, as well as *in vivo* vertebrate and invertebrate model systems. Although the results of several nanoparticle toxicity studies are now available, a systematic approach to testing had not been established, and many of the early experiments were not designed to isolate the source of the toxicity (15).

Consistency in reporting is crucial to allow reexamination and cross-comparison of nanoparticle toxicity data. Establishing standardized reporting criteria for nanotoxicology studies would facilitate future risk assessment. It is important to fully characterize the physiochemical characteristics (hydrodynamic size, shape, charge, surface coatings, dispersity) of the nanoparticles being tested. Under the NMSP’s basic program, the EPA has collected initial information on nanomaterials from 25 manufacturers, but because participation is voluntary, the information reported varies in detail. As a result, the EPA has obtained an incomplete inventory of what nano-

materials are currently in production and use, and only a partial database of the current findings on the impact and nature of exposures to those nanomaterials.

A precautionary approach

The EPA's current practice of categorizing nanomaterials based on their bulk counterparts for the purposes of TSCA assumes that nanomaterials are just smaller entities of their corresponding bulk materials and that they should exhibit similar properties. However, since the nanotechnology boom is based on the unique properties that nanomaterials possess and that bulk materials lack, this is a poor assumption. The point of contention ultimately comes down to whether nanomaterials are believed to be significantly different from their bulk counterparts. Different philosophies on nanomaterial safety have evolved from this.

Some argue that nanotechnology development should be guided by the Precautionary Principle, which states "when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically ... The proponent of the activity, rather than the public, should bear the burden of proof" (16). In practice, this would

require manufacturers to prove that their products are not hazardous before being sold.

Others believe that this risk aversion could bring nanotechnology progress to a standstill. Invoking the precautionary principle should promote research to protect public health and the environment. However, it is possible that these efforts could turn out to be unnecessary. Therefore, it is important to track and collect information as it becomes available to allow evaluation of the precautionary efforts being taken. It should be possible to concurrently foster the drive for progress while continuing efforts to identify and respond to any unintended consequences that may arise.

Nanomaterials may not be inherently safe, but it is premature to

say that they are inherently dangerous. This uncertainty is a significant factor influencing the decisions of industry and government leaders. Without sufficient data to conduct thorough evaluations of nanomaterial safety, this uncertainty will remain.

Despite the arguments discounting the importance of research into the human health and environmental impact of nanomaterials, such research is necessary. Regardless of the possibility that the risks associated with nanomaterial exposure may prove to be minor, it is the obligation of engineers and scientists to understand the interactions of these new materials being introduced into society and determine if any adverse health and environmental impacts could arise.

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