Green Nanotechnology: Straddling Promise and Uncertainty

Barbara P. Karn and Lynn L. Bergeson

Nanotechnology has been called the second Industrial Revolution. Its seemingly limitless potential will continue to inspire innovations in a dizzying array of beneficial applications and briskly transform society. Despite the hope and promise nanotechnology brings, engineered nanoparticles, the tiny engines driving this new transformative technology, also generate a palpable apprehension due to their largely unknown implications on human health and the environment. Enter green nanotechnology, an approach to managing the potential environmental, health, and safety (EHS) risks associated with the manufacture and use of nano-enabled products while fostering their responsible development and application.

This article describes green nanotechnology and discusses the reasons why traditional chemicals-assessment and management approaches may not be adequate in all cases in the near term when applied to nanomaterials. It outlines the reasons why green nanotechnology may serve as an alternative approach to chemicals assessment when applied to nanomaterials and suggests some measures to advance the goals of green nanotechnology.

Nanotechnology encompasses the science of nanomaterials, forms of matter in a particular size range, roughly between 1 and 100 nanometers (nm). Nanomaterials are bigger than most molecules and smaller than bacteria cells. They can consist of groups of single elements such as metals, groups of compounds such as metal oxides, tubes or wires of elements, soccer ball structures, branching structures, and infinite combinations of these. Nanomaterials can be regular and geometric like crystals or irregular like foam.

While nanomaterials are intentionally designed to be unique, what is common to all is their super small size, which imparts properties that are surprising and special. For example, gold is gold when we wear it or spend it. A 25 nm nano-sized clump of gold atoms is red; a 50 nm clump of gold atoms is green. The optical properties, i.e., color, change merely because of the size. The gold we wear is not active. At the nanoscale, gold becomes an active catalyst, helping turn chemicals X and Y into product Z.

Dr. Karn is a scientist with the U.S. Environmental Protection Agency's Office of Research and Development in Washington, D.C. Ms. Bergeson is managing director of Bergeson & Campbell, P.C., in Washington, D.C., and president of The Acta Group, L.L.C. and The Acta Group EU, Ltd with offices in Washington, D.C., and Manchester, UK. They may be reached at karn.barbara@epa.gov and lbergeson@lawbc.com.

Electrical properties also can change at the nanoscale. The rolled-up carbon chicken-wire structure of carbon nanotubes (CNT) is a conductor when the chicken wire falls in a straight line. The nanotube is a semiconductor if the chicken wire is slightly twisted. Semiconductors form the basis of the microprocessor chips and transistors in our computers and communication devices. The giant magnetoresistance effect occurs at the nanoscale and enables computer hard drive storage and cell phone memory. Its inventors, Peter Grünberg and Albert Fert, won the Nobel Prize in Physics in 2007.

Because of the special properties of materials at the nanoscale, nanotechnology has permeated all sectors of our economy. Semiconductor technologies, memory and storage technologies, display technologies, optic/photonic technologies, energy technologies, bio/health technologies, and consumer products such as textiles and cosmetics all make use of nanoscale materials.

Government and marketing sources predict a $3 trillion market for nanotechnology-related products by 2014. Is there a chance that this huge industry will be green and sustainable? What, after all, is "green" when applied to nanomaterials and their making?

Green Nanotechnology

There are two key aspects to green nanotechnology. The first involves nano products that provide solutions to environmental challenges. These green nano products are used to prevent harm from known pollutants and are incorporated into environmental technologies to remediate hazardous waste sites, clean up polluted streams, and desalinate water, among other applications. Nanomaterials enable clean drinking water through membrane technologies or nano-based procedures that destroy pathogens and toxic chemicals. Green nano products also enable sophisticated sensing and monitoring devices to detect hazardous pollutants, plant pathogens, and related toxins.

Nano products also further sustainability. New forms of energy generation, such as fuel cells, thermoelectric devices, solar cells, and improved batteries, reflect the application of nanoscale materials. Green nanotechnology miniaturizing products, which uses less material, are lighter to transport, and thereby save energy and fuel.

The second aspect of green nanotechnology involves producing nanomaterials and products containing nanomaterials with a view toward minimizing harm to human health or the environment. Most nanomaterials are made by chemical processes, and these processes may or may not generate pollutants, waste energy, or waste materials. New nanomaterials can be made using older, well-established principles of green chemistry, thus avoiding dependence on current processes that might result in pollutants. One green chemistry principle is to use safer solvents and reaction conditions. There are many examples where different kinds of nanomaterials can be made in water or supercritical carbon dioxide, thus avoiding use of risky solvents.

> Nano products further sustainability . . . Green nanotechnology miniaturizes products, which use less material, are lighter to transport, and thereby save energy and fuel.

A corollary principle that is very much a part of green nanotechnology is waste prevention. Because many nanomaterials are or will be made by self-assembly or solid-state processes, there are fewer opportunities to generate waste resulting from chemicals trying to find each other in the reaction "soup."

Green engineering principles are also applicable as nanomaterials increasingly are incorporated into larger, more conventionally scaled products. Green engineering "embraces the concept that decisions to protect human health and the environment can have the greatest impact and cost effectiveness when applied early to the design and development phase of a process or product." U.S. Environmental Protection Agency (EPA), Other Sustainability Resources, Green Engineering, http://epa.gov/ncer/p3/other/index.html (last updated June 16, 2009). The most relevant timeframe in the green-engineering life cycle of a nanomaterial is the early stages of the technology, the design stage. Green engineering requires that we consider the full life cycle of a product, from the extraction of the materials from the ground through manufacturing, product use, and its end of life. Green nanotechnology's focus on the full life cycle can help us better prepare for recycling, reuse, or remanufacture of nanomaterials and nano-enabled products, thus minimizing the generation of new hazards through unplanned disposal.

Nanomaterials can be engineered to be greener, thus minimizing potential risks through product design and the use of safer materials. For example, nanomaterials can be coated so that they do not dissolve in water or enter biological cells. Some nanomaterials can be made from renewable ingredients or biological waste products that are nontoxic.

A subset of greener production includes using nanomaterials to "green up" current processes. Catalysts are the most important nanomaterials for this use. As a spherical particle gets smaller and smaller, it has more surface area proportional to its total volume. Catalyst reactions take place on the surface, so the more surface area and less volume, the better. In other words, nanomaterials used as catalysts have very high surface areas enabling them to implement more efficient, less wasteful, and less-polluting chemical reactions.

Nanoscale membranes are another illustration of nano applications for making current processes greener. In many chemical reactions, useful products must be separated from waste. These separations can be energy intensive and wasteful or by themselves can cause pollution. Nanoscale membranes can minimize separation steps and lower energy use.

The examples above are merely illustrative of the broad range of green nano products and processes. While there is much reason to be optimistic about nanotechnology's place in the environment, there is also, as discussed below, reason to be cautious when creating and managing these unique forms of matter. If approached responsibly, risk mitigation and management of nanotechnology can help ensure that this new technology's development is more sustainable.

Key Nano Uncertainties

The world's fascination with the science of the teeny-tiny is tempered by a disconcerting fear of the uncertainties surrounding nanomaterials. The image conjured up in Eric Drexler's groundbreaking book *Engines of Creation: The Coming Era of Nanotechnology* (Anchor 1986) of "unruly herds" of atoms gone awry is not the source of the concern as much as the fear of the unknown. In this case, the unknown is the lack of knowledge in key areas regarding the human health and environmental implications of nanoparticles. Complete data sets for the most commercially common nanoscale materials—CNTs, metal oxides, carbon fullerenes, and related materials—do not yet exist. The recent data that have emerged are, in some instances, troubling. For example, research indicates that multiwalled CNTs can penetrate the lining of the lung. These data supplement earlier studies that show multiwalled CNTs injected into the lining of the abdominal cavity of mice cause inflammation and granulomas suggestive of the onset of mesothelioma of the abdominal lining, a reaction similar to that of other durable fibers, including asbestos.

Scientific uncertainty, however, should not dampen our collective drive to innovate. Rather, any such uncertainty should be properly reflected in governance and regulatory policies that protect human health and the environment and recognize the fragility of this evolving technology as it matures commercially. At the core of this uncertainty is the fact that nanoparticles and nanomaterials are unique, and their highly variable physical-chemical nature contributes significantly not only to the commercial value of the nanoparticles but also to their hazard profile. As a result, grouping nanomaterials to assess efficiently their hazard characteristics, as is currently done with larger-scale chemicals, and extrapolating from data pertinent to a nanoscale substance's larger, conventionally sized counterpart is not currently possible due to the size differences and the inherently different nature of materials where quantum interactions take place.

Additionally, conventional analytical tools and protocols may not accurately capture the hazard potential of nanoscale materials. Standard chemical analytical and monitoring tools and detection equipment are not typically calibrated or engineered to apply readily or at all to nanoscale materials. Even if such tools were readily available, there is little consensus on how to test nanomaterials and which materials to test first. To the extent there is broad agreement among nano stakeholders, it is rooted in the belief that much more EHS testing needs to be done to identify, characterize, and manage potential risks effectively to ensure that the commercialization of nanotechnology occurs responsibly and sustainably.

In this regard, there are many nano EHS data development initiatives underway globally, too numerous to summarize here. While each is essential, taken as a whole they are unlikely to address any time soon the large need for additional EHS data. One recent estimate for U.S. costs alone for toxicity testing of existing nanoparticles ranges from $249 million for optimistic assumptions about nanoparticle hazards (that the nanoparticles are relatively safe and require only screening assays) to $1.8 billion for more extensive, long-term *in vivo* testing.

Emerging Regulatory/Governance Frameworks

The paucity of toxicological and ecological effects data and information on engineered nanoparticles and nanomaterials has challenged the ability of regulatory agencies to provide effective oversight of nanotechnology's development and commercialization. Over the past several years, governmental bodies and nano stakeholders alike have initiated a broad range of actions intended to manage nanotechnology prudently and communicate as much to nano detractors. The activities include a diverse mix of regulatory initiatives, government-initiated voluntary/mandatory data-gathering initiatives, and various private-sector product stewardship/codes of conduct initiatives.

A fundamental issue that has been debated for years is whether the range of existing legal authorities and governance tools are adequate to address the potential risks posed by nanotechnology. The American Bar Association Section of Environment, Energy, and Resources Nanotechnology Papers (www.abanet.org/environ/nanotech) early and comprehensively provided much-needed legal analyses of the core environmental statutes and the authority each conveys to EPA in mitigating and preventing potential nanotechnology risks. Although the debate continues, many believe that, on the whole, current laws are adequate and that no news laws are needed. While the government's statutory authorities may be sufficiently broad to address nano, the government's expertise, resources, or political will may not be sufficient to deploy these legal authorities in a way that will manage nanotechnology risks effectively in the near future.

There is no oversight mechanism currently in place to rationalize disparate policy and regulatory initiatives underway throughout the federal government. This fact inspired one prolific author, Dr. J. Clarence Davies, to call for the creation of the Department of Environment and Consumer Protection. In his 2009 report *Oversight of Next Generation Nanotechnology* (www.nanotechproject.org/publications/archive/pen18/), Davies notes that this new agency would foster more integrated approaches to governance and use "sustainability plans" developed by product manufacturers to summarize known information about the product's components, its adverse effects, a product life-cycle analysis, and an explanation of why the product would not cause any undue risk.

To some, the lack of broad federal integration has hampered effective regulatory oversight initiatives across agencies. Within EPA, regulatory programs implementing the core environmental laws likely need revision to address emerging technologies like nanotechnology. Many federal environmental laws that address chemicals, and their implementing programs, offer volume-based exemptions of one form or another. For example, the Toxic Substances Control Act (TSCA) low-volume exemption from notification for chemical production is limited to less than 10,000 kilograms per year. Resource Conservation and Recovery Act small-quantity generator and the Clean Air Act standards are mass-based. For the small production amounts of most nanomaterials, volume/mass-based exemptions make little sense, excluding nanomaterials from our current regulatory system premised on a metric that simply does not apply.

EPA's Office of Pollution Prevention and Toxics (OPPT) is farthest along in developing a body of work under TSCA pertinent to nanoscale materials. Because TSCA is the principal federal law that authorizes EPA to regulate chemical substances, EPA has focused extensively on deploying its TSCA authority to regulate nanoscale substances, materials that are characterized as TSCA "chemical substances." On the regulatory front, EPA has prepared a policy statement dated January 2008, *TSCA Inventory Status of Nanoscale Substances—General Approach*, to assist manufacturers in determining whether TSCA Inventory requirements apply to nanoscale chemical substances. EPA has received and reviewed several new chemical notices under TSCA Section 5 for nanoscale materials, including CNTs. On October 31, 2008, EPA published a notice outlining the TSCA requirements potentially applicable to CNTs and advised CNT manufacturers of EPA's position that CNTs must be listed on the TSCA Inventory. On November 5, 2008, EPA issued a final significant new use rule (SNUR) for fifty-six substances, two of which included nanoscale substances. After March 1, 2009, CNTs that are manufactured for commercial purposes and that are not listed on the TSCA Inventory or otherwise exempt could be subject to compliance monitoring.

These focused EPA OPPT efforts are laudable. They do not, however, reflect a systematic, comprehensive, or concerted effort within the federal government to make domestic environmental regulatory programs nano-ready. Nanotechnology research, development, and policy activities are coordinated through the twenty-five federal agencies and departments of the National Nanotechnology Initiative (NNI). Each of these entities, however, has separate regulatory and governance frameworks for addressing nanotechnology pursuant to the legal authorities granted to each under various enabling statutes. The level of effort among federal entities on nano-specific initiatives regarding governance is disparate. For example, within EPA, OPPT and the Office of Pesticide Programs are much further along than EPA's air, water, and waste offices. Other agencies such as the Consumer Product Safety Commission appear to be at relatively early stages of nano-development, while others such as the National Institute for Occupational Safety and Health are quite expert in areas involving nano workplace practices and controls.

Governmental bodies have, not surprisingly, responded differently to the key challenge they each face in regulating nanoscale materials, the paucity of information on nanoscale materials. The absence of information on nanotechnology hazard and exposure has frustrated the government's ability to provide meaningful oversight of these materials and the manufacturing operations that generate and/or process them.

To obtain such information, governments have solicited information either on a voluntary or mandatory basis. The UK Department for Environment, Food, and Rural Affairs (DEFRA) initiated a voluntary nanoscale materials reporting program in 2006. Under it, DEFRA sought basic information on nanoscale materials, toxicological and eco-toxicological information, and information on risk-management practices. By most accounts, the program was unsuccessful.

EPA launched a voluntary Nanoscale Materials Stewardship Program (NMSP) in January 2008. Under the NMSP's "Basic Program," participants were invited to voluntarily report available information on the engineered nanoscale materials they manufacture, import, process, or use. Under the "In-Depth Program," participants were asked to voluntarily develop data over a longer period of time, alone or in consortia, for a particular nanomaterial. Both program components have garnered little participation from manufacturers and other nano stakeholders.

In contrast to the voluntary reporting programs launched by EPA and DEFRA, Environment Canada reportedly intends to launch a mandatory reporting/data-gathering program in 2009 under Section 71 of the Canadian Environmental Protection Act, 1999. Other countries, such as Australia and Germany, are developing data call-ins for nanomaterials.

In addition, several domestic local authorities have used or have attempted to use existing legal authorities to compel the submission of information pertinent to nanoscale materials. Late in 2006, the Berkeley, California, City Council approved a proposal to require businesses to report nanoparticles being used, provide available toxicological information, and outline measures for safe handling of the materials. A similar measure was considered in Cambridge, Massachusetts, but ultimately failed. More recently, in January 2009, the California Department of Toxic Substances Control (DTSC) announced that it is requiring the submission of data "regarding analytical test methods, fate and transport in the environment, and other relevant information from manufacturers of carbon nanotubes." DTSC states that the term "manufacturers" includes persons and businesses that produce CNTs in California or import CNTs into California for sale.

Private-Sector Governance Strategies

Based on the perception that traditional governance mechanisms, including statutory measures and notice-and-comment rulemakings, are ill-suited tools for nanotechnology governance, the private sector, in concert with governmental entities in some instances, is pursuing an unprecedented number of innovative governance initiatives to address nanotechnology. These initiatives, which are global in nature, fall loosely into two broad categories: (1) EHS research, nomenclature/terminology, and standard-setting initiatives, and (2) product-stewardship measures.

EHS research, nomenclature and terminology, and standard-setting measures are underway globally at a frantic pace. No effort is made here to discuss each with precision in detail. The work has been undertaken by a wide range of government organizations; international organizations, including the International Organization for Standardization (ISO), ASTM International, and the Organization for Economic Cooperation and Development (OECD); public-interest/research organizations, including Environmental Defense Fund, Meridian Institute, Consumers Union, and ETC; and private-sector entities, including DuPont, the American Chemistry Council Nanotechnology Panel, the NanoBusiness Alliance, and the Business and Industry Advisory Committee.

OECD, in particular, has been extremely energetic in the area of nanotechnology. Two OECD Committees are relevant: (1) the Chemicals Committee and its Working Party on Manufactured Nanomaterials (WPMN) and (2) the Committee on Science and Technological Policy's Working Party on Nanotechnology (WPN), which focuses on creating supportive frameworks for innovation on nanotechnologies. Both committees are active, but the Chemicals Committee's WPMN has been particularly busy.

The WPMN is engaged in work on eight projects, each managed by a Steering Group (SG). The projects are: SG1 "Development of an OECD Database on EHS Research"; SG2 "EHS Research Strategies on Manufactured Nanomaterials"; SG3 "Safety Testing of Representative Set of Manufactured Nanomaterials"; SG4 "Manufactured Nanomaterials and Test Guidelines"; SG5 "Cooperation on Voluntary Schemes and Regulatory Programmes"; SG6 "Cooperation on Risk Assessment and Exposure Assessment"; SG7 "Alternative Test Methods"; and SG8 "Exposure Measurement and Mitigation." These projects have commanded the international cooperation of an unprecedented number of OECD participants and others and are advancing the goals of each SG at a rapid pace. The output is expected to be historic at several levels, not the least of which is the international cooperation exhibited to complete the six projects. Much more could be written about these OECD projects. The point is these activities reflect an internationalization of effort focused on advancing the responsible development of nanotechnology that has commanded the time, attention, and commitment of global stakeholders unlike any other transnational challenge.

Other global initiatives are underway in the standard-setting arena. The ISO Technical Committee 229 on Nanotechnologies created three working groups: terminology and nomenclature, measurement and characterization, and health, safety, and environment. ASTM International Committee E56 on nanomaterials is also working on nanotechnology standards, and its Subcommittee E56.01 approved a standard on nanotechnology terminology, E2456-06, in 2007. Importantly, green nanotechnology may be promoted through a new WPMN project on the environmental benefits of nanotechnology, which will convene at a conference on "Potential Environmental Benefits of Nanotechnology: Fostering Safe, Innovation-led Growth."

Nanotechnology has inspired unprecedented collaboration on the development of best-practice standards. In 2007, Environmental Defense Fund and DuPont formally announced the release of their joint effort, the Nano Risk Framework. The Framework is rapidly becoming the standard for measuring best-management practice in the nano industry. The Framework defines "a systematic and disciplined process for identifying, managing, and reducing potential environmental, health, and safety risks of engineered nanomaterials across all stages of a product's 'lifecycle'—its full life from initial sourcing through manufacture, use, disposal or recycling, and ultimate fate." http://nanoriskframework.com/page.cfm?tagID=1095. The Framework consists of six distinct steps and is intended to be used iteratively as stages of development advance and new information becomes available.

Another key initiative is the Responsible NanoCode. Britain's Royal Society, the Nanotechnology Industries Association, Insight Investment, and the U.K. government-sponsored Nanotechnology Knowledge Transfer Network collaborated on the proposed code. The objective of this "principles-based" voluntary code of conduct is to encourage industries, retailers, universities, research institutes, and other public or privately funded bodies involved in developing, manufacturing, and selling products of nanotechnology to adhere to seven principles to demonstrate responsible governance. Code proponents launched a consultation period in the United States, and in May of 2008, the Working Group of the Responsible Nano Code signed off on the code.

This brief discussion does not address directly green nanotechnology principles. It does, however, help explain why the design of nanomaterials according to the principles of green nanotechnology would complement and support current regulatory and other governance measures intended to address risk while fostering the sustainable development of nanotechnology.

Steps to Facilitate Green Nanotechnology

Emerging governance strategies and mechanisms such as those described above demonstrate a concerted effort to ensure effective oversight mechanisms are in place to foster the responsible development of nanotechnology. Many of the EHS concerns associated with nanotechnology could be addressed through more extensive application of green nanotechnology practices. By ensuring nanoscale materials are engineered with human health and the environment in mind, their deployment in applications to further sustainability are unlikely to invite the kinds of EHS concerns that have been the subject of much discussion over the past several years. To foster the development of green nanotechnology, stakeholders should consider undertaking the following steps:

> The absence of information on nanotechnology hazard and exposure has frustrated the government's ability to provide meaningful oversight of these materials and their manufacture.

Develop a Life-Cycle Assessment Appropriate for Green Nano Products—Before a nano product or production process can be considered green, its EHS implications must be assessed using an appropriately tailored life-cycle assessment that is capable of identifying and quantifying nanotechnology EHS implications and gauging the trade-offs that arise in the context of their applications. For example, life-cycle assessment could compare the energy savings brought about by a nano-enabled product with the same product's larger-scaled counterpart.

Establish Performance and Branding Standards for Green Nanotechnology—Too little is known about green nanotechnology, and the term itself is not well understood. Stakeholders should consider establishing specific standards that products would need to meet to be considered green. If these standards are met, stakeholders should use the criteria in branding products as "green nano."

Provide Tax and Related Business Incentives to Innovators to Encourage Application of Green Nanotechnology—Among the many challenges nano innovators face is the cost of commercializing a product and the shortage of investment capital to do so. To the extent government funding is available, it should be made available first to nano innovators who embrace green nanotechnology. Similarly, private funding should be incentivized by the availability of greater tax benefits and other forms of tax relief for those who embrace green nanotechnology.

Increase Patent Term Protection for Green Nano Products—Innovators whose products reflect the principles of green nano should be rewarded by extended patent term protection.

Establish a DfE Green Nano Category—EPA's Design for the Environment (DfE) recognizes and rewards innovative product design that reflects sustainability. The program should develop a "Green Nano" category that promotes nano products that are the result of green nanotechnology processes.

Provide More Resources for Green Nano Research—Research dollars are always in short supply in the nano area. Enhanced research funding should be made available to green nano research. On the promising but speculative front, it is worth noting that pending legislation to reauthorize the NNI could provide greater funding for nano, and perhaps green nano, research. H.R. 554, the National Nanotechnology Initiative Amendments Act of 2009, passed the U.S. House of Representatives in Feb. 2009. Companion legislation has been introduced in the Senate. H.R. 554 would strengthen research of EHS implications of nanotechnology, improve public-private partnership opportunities, require NNI agencies to develop a plan for EHS research, and specifically note near-term and long-term goals. The bill would assign responsibility to an official in the Office of Science and Technology Policy for overseeing planning and implementation processes to help ensure federal agencies' nano research programs are conducted efficiently. If enacted, these measures would go a long way to ensuring the responsible development of green nanotechnology.

Convene a Forum to Develop and Implement Green Nano Principles in a Systematic Way—Although there are many ongoing dialogues focusing on controlling risks from nanomaterials, there remains a paucity of fora that address risk prevention through the design of safer and more environmentally benign nanomaterials and the processes that make them. The creation of a forum intended chiefly to address green nano principles would provide great value.

Green nanotechnology offers great promise as a sustainable tool that may well address the EHS concerns that have arisen in connection with nanotechnology. There are considerable upsides to seizing the moment and approaching policy, regulatory, and governance issues proactively to ensure green nanotechnology is given every opportunity to succeed. In the long run, if approached responsibly, green nanotechnology will enable more sustainable products and processes for the next industrial revolution.