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Environmental Risks of Nanotechnology: National Nanotechnology Initiative Funding, 2000−2004

KATHERINE A. DUNPHY GUZMÁN,*,†,‡ MARGARET R. TAYLOR,§ AND JILLIAN F. BANFIELD†,‡,||

Department of Earth & Planetary Science, University of California, Berkeley, California 94720-4767, Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, Goldman School of Public Policy, University of California, Berkeley, California 94720-7320 and Department of Environmental Science, Policy & Management, University of California, Berkeley, California 94720

By considering risk in the early stages of a technology, costs of identifying important health and environmental impacts *after* a technology has widely diffused can be avoided. Nanotechnology, involving materials and objects less than 100 nm in size, is an important case in point. In this paper we analyze the research priorities discussed by various interest groups concerned with the environmental risks of nanotechnology, evaluate the distribution of federal environmental nanotechnology R&D funding, and discuss research in this field. Overall federal environmental R&D funding to date is limited and focuses more on the positive environmental applications of nanotechnology than on basic knowledge/research, tools for nanoenvironmental research, or the potential risks of nanotechnology. The situation began to change in 2004 when a significant increase occurred in federal R&D funding for the environmental implications of engineered nanomaterials. Though literature exits on the exposure, transport, and toxicity of incidental nanoparticles, little work has been published on the environmental risks of engineered nanoparticles.

Introduction

Risk is an important issue to consider in the early stages of any new technology. Belatedly identified health and environmental risks have halted technologies of widespread societal usefulness, leaving society to scramble for functional substitutes; the cases of chlorofluorocarbons (CFCs) (*1*) and asbestos (*2*) are examples. Even risks not scientifically certain but broadly *perceived* can cause similar inefficiencies; despite heavy investments in genetically modified organisms (GMOs) and their potential benefits to society, public perception of risk has slowed GMO development.

By proactively studying the potential risks of an emerging technology, we can avoid having to react to problems caused by belatedly identified real and perceived risks. Nanotechnology, involving materials and objects on the scale of 100 nm and smaller with unique, size-related properties, could benefit from such proactive consideration of risk. Nanotechnology is forecast to revolutionize a diverse array of industries as scientists and engineers design devices and materials that are superior in terms of speed, efficiency, and strength. The nanoparticles being investigated for technology uses fall under the broader categories of carbons, semiconductors, metallics, oxides/hydroxides, phosphates, and zeolites. (See the Supporting Information for nanomaterials and applications.)

Simultaneously, recent publicity about nanotechnology highlights its potential risks to humans and ecosystems (*3*−*7*). Perceived environmental risks can prove to be nanotechnology's Achilles' heel. Whereas *natural* nanoparticles are a key component in our ecosystem, as "nanofossils" (*8*), products of chemical weathering (*9*), products of microbial and microbial-related processes (*10*−*13*), and components of aquatic sediments (*14*, *15*), the behavior of *manufactured* nanoparticles and new nanoproducts in the environment is largely unknown. *Incidental* nanoparticles, i.e., nanoparticles produced as byproducts of processes such as combustion and pollution, already are inadvertently released in the environment, where they have been linked with negative health effects and changes in cloud properties (*16*). Models developed to predict the fate, transport, and human impact of familiar environmental contaminants (e.g., organic compounds, micrometer-sized materials, radionuclides) will need to be modified for prediction of nanoparticle behavior. For example, the residence time of nanoparticles and their aggregates in air may be different from that of larger micrometer-scale dust particles (*17*). In addition, the oxidation and dissolution rates, which are highly dependent upon surface area, may increase dramatically as size decreases (*18*), possibly releasing constituent materials in a bioavailable form. Furthermore, nanoparticles can enter cells (*19*, *20*) and cross the blood−brain barrier (*21*−*23*) (a characteristic that has been harnessed for drug delivery), where they may have unexpected health effects. A thorough discussion of nanoparticles in the environment is presented by Biswas and Wu (*24*).

In this paper, we analyze the research priorities discussed by various interest groups concerned with the environmental risks of nanotechnology and review the extent to which government funding is currently distributed to assess and address these risks. We also discuss research needs in the field.

Research Priorities and the Risks of Nanotechnology

Organizations that have weighed in on the risks of nanotechnology include government agencies and committees, nongovernmental organizations, industry groups, and academic researchers.

Government Priorities. In 2001, the National Nanotechnology Initiative (NNI) was established under the supervision of Nanoscale Science, Engineering, and Technology (NSET) to serve as the coordinator of government funding for U.S. research in nanotechnology and to support the development of the burgeoning nanotechnology industry. A number of governmental agencies—under the particular leadership of the National Science Foundation (NSF)—have facilitated discussions of the risks of nanotechnology through workshops, reports, symposia, and publications, which are detailed in the Supporting Information.

Priorities of Environmental Organizations. The range of perspectives on future nanotechnology development can

* Corresponding author e-mail: kadunphy@berkeley.edu.
† Department of Earth & Planetary Science, University of California.
‡ Lawrence Berkeley National Laboratory.
§ Goldman School of Public Policy, University of California.
|| Department of Environmental Science, Policy & Management, University of California.

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TABLE 1. Common Research Priorities for Nanotechnology Environment and Safety Research

	government/ academia (*29*)	environmental organizations (*26*, *27*)	industry (*28*)
basic knowledge/research	x	x	x
assess current knowledge			x
identify model systems to perform in-depth analysis			x
nanomaterial identification and nomenclature	x	x	
tools for nanoenvironmental research	x	x	x
tools for monitoring nanomaterials	x	x	x
database of environmental monitoring information	x		
develop high-throughput/multianalyte toxicological methodologies	x		
environmental implications of nanoparticles	x	x	x
monitor nanomaterials			x
safe work practices development, documentation, and training		x	x
research exposure	x	x	x
research toxicology	x	x	x
research nanoparticle fate and transport	x	x	
perform life cycle analyses		x	

TABLE 2. Federal Agencies Reporting Nanotechnology Research Budgets to the National Nanotechnology Initiative and Reported Environment and Health Safety Research Funding

agency	estimated environment and health safety research funding, 2000–2004
Department of Commerce: National Institute of Standards and Technology	
Department of Justice	
Department of Defense	$5.5 million
Environmental Protection Agency	$16.5 million
Department of Energy: Office of Basic Energy Sciences, Office of Industrial Technologies	
National Aeronautics and Space Administration	
Department of Health and Human Services: National Institute for Occupational Safety and Health and the National Institute for Environmental Health Sciences	$2.3 million
National Science Foundation	$63.9 million
U.S. Department of Agriculture	
Department of Homeland Security: Transportation Security Administration	

be represented by two environmental groups with divergent views. The Action Group on Erosion, Technology, and Concentration (ETC Group) has put out a well-publicized call for a moratorium on the laboratory use and commercial development of synthetic nanoparticles. It justifies this moratorium under the precautionary principle, the lack of understanding of the risks of nanotechnology, and the lack of established best practices for the handling and use of nanoparticles (*25*).

In contrast, Environmental Defense (ED) does not call for a moratorium. Instead, they ask for a life cycle approach that includes proactive risk management involving premanufacturing hazard identification, exposure evaluation, and interim worker and environmental safety protocols (*26*). ED calls for a significant increase in funding—at least $100 million annually over the next several years—to identify nanomaterial risk (*27*).

Industry Priorities. The nanotechnology industry is comprised of a large number of start-up companies as well as some larger, established companies. Start-up companies have remained largely silent on the risks of nanotechnology, perhaps due to their size and resource constraints. The established chemical industry, however, has taken a lead in discussing research needs on the basis of the potential risks of nanotechnology. The Chemical Industry Vision2020 Technology Partnership established an R&D road map for nanomaterials (*28*) that prioritizes (i) assessing human health and environmental impact hazards, (ii) determining exposure potentials for nanosized materials, and (iii) establishing handling guidelines for operations involving nanomaterials.

Common Priorities. Table 1 shows the results of our analysis of the nanotechnology risk-related research priorities set out in documents representing these stakeholder groups: an NSF/NSET workshop that brought together government representatives and scientists (*29*), a presentation and statement by Environmental Defense (*26*, *27*), and the Chemical Industry Vision2020 Technology Partnership R&D road map (*28*). The documents from ED outlined more specific priorities than those of the ETC Group and were therefore chosen to represent the nongovernmental organization interests. We coded these documents, outlining categories of research needs. All three documents discuss the need for tools to monitor nanomaterials and the need to understand exposure pathways, toxicity, fate, and transport of nanomaterials. Two documents discuss the identification and nomenclature of nanomaterials.

Research Funding and the Risks of Nanotechnology

We analyzed the funding history of the NNI as an important indicator of the realized priorities of the federal government regarding research related to the risks of nanotechnology. The "history" considered here begins in 2000, the year before the official establishment of the NNI, and continues through 2004, the most recent year for which complete data are available.

NNI Agencies Conducting Environmental Research. The NNI is the main coordinating body for government funding of nanotechnology. Table 2 shows these reporting agencies and indicates the four that report environment and health safety research (*30*). The NNI does not report total funding amounts by department or agency, though our analysis provides an estimate of these amounts, as discussed below.

Methodology. Analysis of the research funding of the NNI agencies involved three main tasks: (1) defining the term

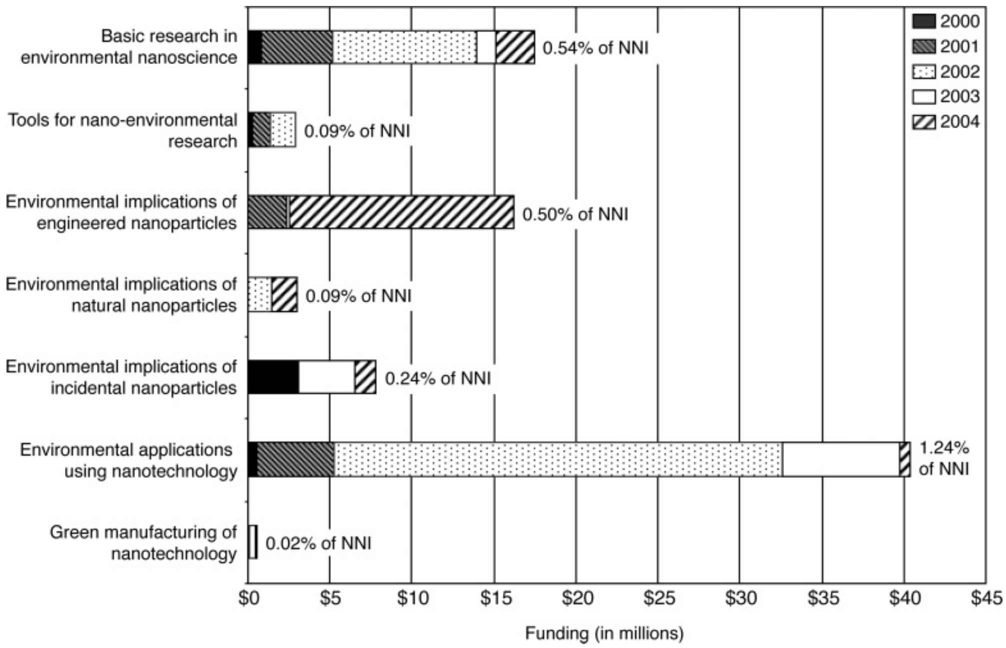

FIGURE 1. Estimated NNI environmental research, 2000−2004.

"environment" for this analysis, (2) obtaining data from the various relevant agencies, and (3) coding and analyzing these data. Our definition of the environment encompasses soil, sediment, air, water, plants, animals (including humans), and other organisms. We consider basic environmental research and tools development, the study of the environmental risks of nanotechnology, and positive environmental uses of nanotechnology (e.g., for remediation). We exclude from our analysis potential applications of nanotechnology for medical or biotechnological gains as well as social and educational grants.

We obtained data from several sources: the NSF Fastlane Web site (*31*) via its award search feature, examination of NSF-funded research proposals, the Environmental Protection Agency (EPA) National Center for Environmental Research Web site (*32*) via its search feature and the award lists specific to nanotechnology-related requests for proposals, a telephone interview with the NSET representative from the National Institute for Occupational Safety and Health (NIOSH) (*33*), and the NNI Web site (*34*), which provided data from other agencies.

We grounded our code scheme on the three research priorities established above. The main categories are (1) basic knowledge/research in environmental nanoscience, (2) tools for nanoenvironmental research, (3) the environmental implications of nanoparticles that are (a) engineered (and, thus, most commercially relevant), (b) incidental, or (c) natural, (4) environmental applications using nanotechnology, and (5) green manufacturing of nanotechnology. For methodological details and category definitions, see the Supporting Information.

General Results. Estimates of cumulative research funding in environment and health safety research were calculated for each agency from the years 2000−2004 (Table 2). The largest agency funding environment and health safety research is NSF, which contributed an estimated $63.9 million during 2000−2004 (approximately 6.9% of NSF's $926 million NNI contribution over this time period). Second highest is the EPA, which awarded its entire $16.5 million NNI contribution to this area. The number of agencies reporting environment and health safety research funding has increased over time; whereas in 2000−2003 only the NSF and EPA reported such funding, in 2004 the Department of Defense (DOD) and the Department of Health and Human Services also reported such funding. This appears to reflect agency response to the growing public concern over nanotechnology risk.

Figure 1 shows the result of coding NNI funding for nanotechnology and the environment from 2000 to 2004, assessing the coded data cumulatively, as well as by year. We estimate that funding to date in all environmental nanotechnology studies—$88.2 million—is only 2.7% of the $3.26 billion of federal grant money coordinated by the NNI in this period. Note that the bulk of environmental nanotechnology funding goes to "environmental applications using nanotechnology". The next most prominent category of funding through 2004 is "basic research in environmental nanoscience".

Further Results on Funding for the Environmental Implications of Engineered Nanoparticles. The "environmental implications of engineered nanoparticles" category most directly relevant to the environmental risks of nanotechnology received only 0.5% of NNI funding in 2000−2004. Table 3 shows the NNI-coordinated awards granted in "implications of engineered nanoparticles" during this time. Before 2003, only one award is seen in the entire funding category. This estimated amount is a portion of Rice University's NSF-funded Center for Biological and Environmental Nanotechnology (CBEN), where one of three themes is nanomaterials in the environment. Of this theme, a portion addresses the formation, fate, and transport of nanoparticles in natural systems.

2004 saw a surge of funding for the environmental implications of engineered nanoparticles, with 12 of these grants funded by the EPA's Impacts of Manufactured Nanomaterials on Human Health and the Environment program. DOD also funded a large center on nanotoxicology in 2004. Together, the CBEN and the DOD nanotoxicology center account for over half the award amounts in this category.

In the research priorities section above, discussions of the environmental implications of nanotechnologies encompassed four subareas: exposure pathways, toxicity, fate, and transport. Table 3 shows that funding for the implications of engineered nanoparticles focuses on the latter three subareas.

TABLE 3. NNI-Funded Studies of the Environmental Implications of Engineered Nanoparticles

year	NNI agency	award	principal investigator(s), institution	title of study
2001	NSF	$2 342 222, estimated (2/9 of total award)	Vicki Colvin, Richard Smalley, Rice University	CBEN: Center for Biological and Environmental Nanotechnology—Formation, Fate, and Transport of Nanoparticles in Natural Systems
2003	EPA	$100 000	Lester Lave, Carnegie Mellon University	A Life Cycle Analysis Approach for Evaluating Future Nanotechnology Applications
2003	EPA	$99 740	Earl R. Beaver, Beth Beloff, Dicksen Tanzil, Mark Wiesner, Rice University	Implications of Nanomaterials Manufacture and Use: Development of a Methodology for Screening Sustainability
2004	DOD	$5 500 000	Gunter Oberdorster, University of Rochester	Toxicology and Biokinetics of Engineered Nanoparticles
2004	NSF	$1 600 000	Ronald Turco, Timothy Filley, Purdue University	Response of Aquatic and Terrestrial Microorganisms to Carbon-Based Manufactured Nanoparticles
2004	NIOSH	$1 700 000	internal research	Understanding and Controlling Potential Health Impact of Nanoparticles
2004	NIEHS (NTP)	$600 000	internal research	Toxicology of Nanoparticles
2004	EPA	$455 000	Paul Westerhoff, David Capco, Yongsheng Chen, John C. Crittenden, Arizona State University	The Fate, Transport, Transformation and Toxicity of Manufactured Nanomaterials in Drinking Water
2004	EPA	$332 099	Patricia Holden, Jay L. Nadeau, University of California, Santa Barbara, McGill University	Transformations of Biologically-Conjugated CdSe Quantum Dots Released into Water and Biofilms
2004	EPA	$334 998	Kent E. Pinkerton, Ting Guo, University of California, Davis	Health Effects of Inhaled Nanomaterials
2004	EPA	$328 972	Nancy A. Monteiro-Riviere, Jim E. Riviere, North Carolina State University	Evaluating Nanoparticle Interactions with Skin
2004	EPA	$334 750	P. Lee Ferguson, G. Thomas Chandler, W. A. Scrivens, University of South Carolina at Columbia	Chemical and Biological Behavior of Carbon Nanotubes in Estuarine Sedimentary Systems
2004	EPA	$335 000	Vicki H. Grassian, Patrick O'Shaughnessy, Peter S. Thorne, University of Iowa	Impacts of Manufactured Nanomaterials on Human Health and the Environment—A Focus on Nanoparticulate Aerosol and Atmospherically Processed Nanoparticulate Aerosol
2004	EPA	$333 797	Mason B. Tomson, Rice University	Adsorption and Release of Contaminants onto Engineered Nanoparticles
2004	EPA	$335 000	Robert H. Hurt, Agnes B. Kane, Brown University	Physical and Chemical Determinants of Nanofiber/Nanotube Toxicity
2004	EPA	$335 000	Ronald F. Turco, Bruce M. Applegate, Timothy Filley, Purdue University	Repercussion of Carbon Based Manufactured Nanoparticles on Microbial Processes in Environmental Systems
2004	EPA	$334 881	C. P. Huang, Daniel K. Cha, Shah S. Ismat, University of Delaware	Short-Term Chronic Toxicity of Photocatalytic Nanoparticles to Bacteria, Algae, and Zooplankton
2004	EPA	$335 000	Alison C. P. Elder, Hong Yang, University of Rochester	Iron Oxide Nanoparticle-Induced Oxidative Stress and Inflammation
2004	EPA	$332 958	John Veranth, Christopher A. Reilly, Garold S. Yost, University of Utah	Responses of Lung Cells to Metals in Manufactured Nanoparticles
2004	NSF	$129 989	Jacqueline Isaacs, Richard Czerw, Northeastern University	Carbon Nanotube Synthesis: Assessing Economic and Environmental Tradeoffs in Process Design

Research Outcomes and the Risks of Nanotechnology

Research related to the fate, transport, exposure, and toxicity of nanoparticles established its foundations many years prior to the establishment of the NNI. For instance, atmospheric scientists have been studying nanoparticulate aerosols and toxicologists have been studying nanoparticles classified as ultrafine particles (UFP) for a number of years. More recently, engineered nanoparticles have been studied in these contexts, and we have only begun to see results from NNI-funded projects.

Exposure, Environmental Fate, and Transport. Nanotechnology exposure, environmental fate, and transport will be fundamental in determining overall environmental impact. Although concentrations of incidental nanoparticle aerosols have been shown to decay with distance from the source (*35*, *36*), it is unknown if engineered nanoparticles, especially those coated to reduce aggregation, will behave similarly. The exposure and release of carbon nanotubes in a manufacturing environment (*37*) results in low aerosol concentrations as a result of handling, but suggests that dermal exposure may be an issue. Exposure assessment studies of engineered nanoparticles have focused on worker exposure, but exposure of the ecosystem and the public to nanoparticles, from either manufacturing or the use and disposal of nanoparticle-based products, needs to be quantified.

Nanoparticles of CeO_2, a strong oxidant, have recently been shown to both decarboxylate and polymerize some small organic molecules (*38*). These nanoparticles have been tested for use as a gasoline additive to enhance combustion. The environmental release of CeO_2 may therefore potentially impact carbon chemistry in soils, water, and organisms. The overall environmental impact of these particles is dependent upon understanding how environmental conditions, such as solution chemistry, redox potential, heat, pressure, biochemical reactions over time, and presence or absence of coatings, may affect stability and behavior.

Transport studies to date have been limited to aerosol transport in the atmosphere and transport studies in porous media (*39*, *40*). However, each ecosystem component must be considered: soil, sediment, oceans, surface waters, groundwaters, and the atmosphere, with oxygen availability taken into consideration for these components.

Toxicity. Toxicity studies are the most prevalent type of nanomaterial impact study published. Oberdorster et al. recently published a comprehensive review of toxicology of nanoparticles and discussion of mechanisms, based on their years of expertise in UFP toxicology (*41*). UFP aerosol research suggests that some smaller nanoparticles show increased toxicity due to their increased surface area; however, particle structure and composition, not only particle size, may play a role in toxicity.

There may be significant reasons for concern regarding carbon-based nanomaterials, given predictions that they will strongly partition into cellular hydrophobic compounds such as lipids relative to water (*42*, *43*), potentially resulting in significant bioconcentration. In addition, researchers have found fullerene-related photoinduced damage to lipids, proteins, and cells (*44*−*48*), skin inflammation (*49*), alteration of biochemical functions (*50*, *51*), brain damage (*52*), severe organ damage (*53*, *54*), and distribution into cells and tissues (*55*−*58*). Carbon nanotubes are found to be cytotoxic (*59*−*61*) and to induce granulomas in lungs of laboratory animals (*62*, *63*).

Other nanoparticles such as metals and metal oxides (Cu, Co, TiO_2, and SiO_2) have also been shown to have inflammatory (*64*, *65*) and toxic (*66*) effects on cells, and TiO_2 nanoparticulates have also been shown to induce DNA damage and chromosomal aberrations (*67*). Hydroxyapatite nanoparticles, a substance closely related to the mineral component of bones and teeth, were found to induce cell death (*68*).

Surface derivatization and light exposure are known to greatly affect the toxicity of semiconductor nanoparticles (*20*, *69*, *70*), TiO_2 nanoparticles (*71*, *72*), and fullerenes (*45*, *48*, *73*−*76*). Many believe that surface coatings have the potential to greatly alter the toxicity, solubility, reactivity, bioavailability, and catalytic properties of underlying nanoparticles, thus minimizing their health and environmental impacts. Unfortunately, these coatings may not persist indefinitely after release of the underlying nanoparticle into the environment: prolonged exposure to light and oxygen may cause oxidation of either the surface ions to which coatings are bound or the coating itself, the coating may preferentially partition into the local environment, and microbes may utilize the coating in chemical reaction activity.

For example, a study of CdSe quantum dots with a surface coating (*77*) found a lack of cytotoxicity, likely a consequence of its surface coating. In the event that the surface coating does not persist, CdSe (like CdTe and CdS) is known to be toxic in bulk form and may be particularly reactive and bioavailable in nanoparticulate form. Meanwhile, water-soluble CdSe quantum dots without surface coatings can cause DNA damage (*78*) and can be toxic to cells (*20*, *69*, *70*, *79*), although the mechanism for toxicity is still being debated in the literature.

Other factors affect toxicity, such as concentrations of nanoparticles. The concentrations likely to be seen in environmental contexts are intrinsically linked to the exposure studies, which, unfortunately, are incomplete. Studies should also encompass toxicity to microorganisms, larger animals, and plants.

Global Impact and Life Cycles. Global-scale impact of nanoparticles should also be considered, as small particles have been shown to have atmospheric impact (cloud properties). Nanoparticulate oxides such as TiO_2, used to degrade pollutants and for disinfection (*80*−*82*), may have the potential to induce other organic transformations and impact photochemical reactions in the atmosphere. Nanoparticles are key components in many biogeochemical processes (*8*−*13*); any global-scale impact of engineered nanoparticles on elemental cycles should be considered.

Finally, life cycle analyses of nanoparticles, incorporating results of the studies discussed above to determine the overall impact of these particles, will be critical to discussing the risks involved with each new nanoproduct as it is developed.

Research Outlook

Government-funded solicitations for research proposals in the area of environmental impact of nanotechnology increased in 2005. As funding in this area increases, it is important to consider the many broad areas that "environmental impact" encompasses.

Important strides are clearly being made to advance knowledge regarding the environmental risks of nanotechnology in the early stages of its development as an emerging technology. Continuing, strengthening, and systematizing these efforts will allow this revolutionary technical area to develop in a sustainable, responsible fashion. This will ensure that, in the case of nanotechnology, the public will avoid the costs associated with identifying important health and environmental impacts *after* a technology has widely diffused.

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Supporting Information Available

Nanomaterials and their current or potential applications (Table S1) and further details on government discussions on environmental risks of nanotechnology as well as methodological details and category definitions of the funding analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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