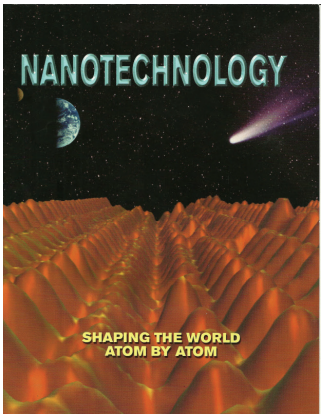
The National Nanotechnology Initiative Approach to Environment, Health, and Safety: A Model for Future Science Investments

Brandi L. Schottel and Barbara Karn

President Bill Clinton requested a competition in early spring 1999 to identify and sponsor a defining scientific initiative as part of his legacy. Presidential assistants Tom Kalil and Neal Lane contacted Mihail (Mike) Roco to make a presentation. Roco was program director of the National Science Foundation's (NSF) Particulate and Multiphase Processes in the Chemical and Transport Systems Division and had formed an informal committee of interested parties in NSF and other federal agencies, industry, and academia to discuss promotion of basic research in an emerging interdisciplinary field, later to become the National Nanotechnology Initiative (NNI). The new technology could potentially create "molecular factories" for breakthroughs in fields from environmental conservation to medicine. On March 11, 1999, Roco presented the National Nanotechnology Initiative at the White House Office of Science and Technology Policy (OSTP) to an audience with little knowledge of the topic, requesting $500 million for nanotechnology research. Nanoscience out-shone two other scientific initiative finalists: tissue engineering and electronic communications. Within weeks, the President's Council of Advisors



A 1999 Nanotechnology public brochure, *Nanotechnology: Shaping the World Atom by Atom*

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on Science and Technology (PCAST) endorsed nanotechnology as Clinton's science initiative. The council recognized the revolutionary promise of the new technology.

The history of new technology is littered with cases of the widespread introduction and application of new materials and processes without sufficient testing for their adverse environmental and health consequences. The problems with asbestos and DDT are examples wherein insufficient concern and foresight led to health and environmental disasters. Roco, along with colleagues at the Environmental Protection Agency (EPA), pushed for inclusion of environment, health, and safety (EHS) considerations in the reports and legislation as they proceeded through Congress until final passage of the 21st Century Nanotechnology Research and Development Act on December 3, 2003. As a result of the efforts of several key persons, working through government agencies, nanotechnology represents the first revolutionary scientific breakthrough that included federal oversight of environmental, health, and safety aspects concurrent with the technology's development—a model to be considered for all future science investments. This article traces their successful efforts to incorporate EHS safety procedures at every stage of development.

The Promise of Nanotechnology

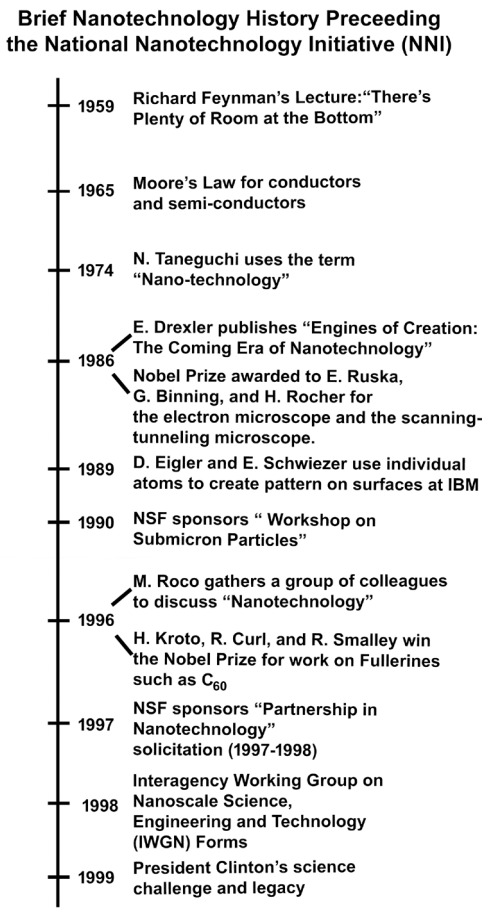
Nanotechnology is the understanding and control of matter with at least one dimension between 1 and 100 nanometers (100 nm is about 1/10 the size of a bacterium) in which unique chemical and physical phenomena enable novel applications.[1] The small size of these materials causes increased reactivity of common substances such as iron, gold, and silver, simply because of their increased surface area to mass ratio (chemical reactions must take place at surfaces). Nanotechnology is characterized as an enabling technology because it can permeate all industries in a variety of ways. For example, nanoparticles make coatings more durable and colorful; electronic circuits become smaller as the "wires" reach nanoscale dimensions; nanocatalysts for chemical processes are more efficient and selective due to their increased and more complex surfaces; materials like plastics become lighter as fillers are nanoscaled; medicines can be delivered on the backs of nanomaterials for specific cell penetration; energy materials for batteries, wind turbines, and thermoelectrics (to name a few) become more efficient and cheaper; environmental remediation and water/

[1] "Nanotechnology Definition," National Nanotechnology Coordination Office (NNCO), *http://www.nano.gov/nanotech-101/what/definition*, (accessed Apr. 30, 2014).

wastewater treatment are enhanced; food production is made safer with targeted nanopesticides and nutrients. The list of benefits and product improvement from nanotechnology stretches the imagination.

The Origin of Nanotechnology

Quantum theory predicted the special properties that result from materials confined to dimensions less than 100 nm well before scientists could synthesize such nanoscaled materials. The first mention of "nanotechnology," rather than miniaturization, appears in the 1959 lecture by Nobel Laureate Richard P. Feynman, "There's Plenty of Room at the Bottom."[2] In 1965 Intel's Gordon E. Moore correctly predicted that the number of transistors on an integrated circuit would double approximately every year, as methods to make these smaller devices advanced.[3] The first use of the word "nanotechnology" can be traced to a presentation by Norio Taniguchi in 1974: "'Nanotechnology' mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or one molecule."[4] This does not comply



A brief timeline of pre-NNI nanotechnology history

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[2] Richard P. Feynman, "There's Plenty of Room at the Bottom," *Journal of Microelectromechanical Systems* 1, No. 1 (1992): 60–66.

[3] Gordon E. Moore, "*Cramming More Components on to Integrated Circuits*," *Proceedings of the IEEE* 86, no. 1, (1998): 82–85.

[4] Norio Taniguchi, "*On the Basic Concept of 'Nano-Technology,'*" Proceedings of the International Conference Production Engineers, Tokyo, Part II, Japan Society of Precision Engineering, (1974).

with the NNI's definition of nanotechnology, but rather with chemistry techniques on a small scale.

Other important examples in the development of the foundation of nanotechnology include Nobel Prizes awarded for work on instruments and synthesis directly leading to nanotechnology. In the 1986 book *Engines of Creation: The Coming Era of Nanotechnology,* Eric Drexler presented a different definition of nanotechnology as "molecular factories."[5] Toward the end of the 1980s, Dr. Mihail (Mike) Roco observed that "nano-technology-like" research appeared in many different NSF programs. His ensuing efforts marked the beginning of the National Nanotechnology Initiative.

NSF: Birthplace of the NNI

At the time, the language to define nanotechnology appeared in grant submissions, workshop results, and academic publications, but it took the efforts of Roco, Dr. Jim Murday, and others to build a cohesive field of research in nanotechnology. Roco, a mechanical engineering professor at the University of Kentucky, came to NSF in 1990 to serve as a program director for the Particulate and Multiphase Processes in the Chemical and Transport Systems Division. During his early years at NSF, he arranged and attended many workshops regarding particulates, submicron particles, and other materials on a "small" scale. In response to a growing trend of "nanotechnology-related topics," he formed an informal committee of interested parties in NSF and other federal agencies, industry, and academia to discuss promotion of basic research in this emerging interdisciplinary field. This committee, which included Murday of the Naval Research Laboratory, Dr. Paul Alivisatos from the University of California, Berkeley, and Dr. Stan Williams of Hewlett Packard,[6] developed a workable definition of nanotechnology for the research community by examining existing documents on the topic. For example, a 1990 NSF Submicron Particles Workshop report stated, "the aerosols are generally understood as condensed-phase particles whose chemical and physical properties [are] different from those of bulk materials only to the extent that their dimensions impose special characteristics. Size-dependent physical and chemical properties that have been clearly identified in studies of nanometer-sized clusters have not

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[5] K. Eric Drexler, *Engines of Creation: The Coming Era of Nanotechnology* (New York: Doubleday, 1986).

[6] Mihail C. Roco, "The US National Nanotechnology Initiative after 3 years (2001–2003)," *Journal of Nanoparticle Research* 6 (2004): 1–10.

yet been taken into account in studies of the particulate ensembles that compose aerosols or colloids."[7] This particular section concerned fundamental properties, but later, this "concern" was extended to possibilities that these materials might affect the surrounding environment in an unknown, negative way. Interest in nanomaterial properties was clearly present, but not focused to promote targeted research programs.

In 1997 Roco and NSF colleagues requested research proposals in the solicitation "Partnership in Nanotechnology."[8] This solicitation, open to all NSF scientific disciplines, ran for two years and resulted in 24 awards totaling about $13 million. Intended as an experiment to judge the response of the academic community, the solicitation promoted the formation of a new, interdisciplinary scientific field in nanotechnology. As a result of this successful solicitation, Tom Kalil, Economic Assistant to President Clinton, contacted Mike Roco regarding the formation of a nanotechnology working group under the National Science and Technology Council's (NSTC) Committee on Technology.[9] In 1999, this Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN) produced a report on nanotechnology research. Ten agencies and offices compiled a 362-page report to compare nanotechnology advances and programs in the United States with those of Europe and Asia.[10] The report specifically highlighted the government funds allocated in 1997 for nano-research in three regions: $120 million in Japan and $128 million in the European Union, compared to $116 million in the United States. While the United States appeared to either lead or be on par with Japan and Europe in four research categories (assembly and synthesis, biological approaches and applications, nanoscale dispersions and coatings, and high surface area materials), it trailed both Japan and Europe in nanodevices and consolidated materials.

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[7] The National Science Foundation, Division of Fluid, Particulate, and Hydraulic Systems, *Report: Workshop on Submicron Particles held November 19–20, 1990*, (Arlington, VA: the National Science Foundation, Division of Fluid, Particulate, and Hydraulic Systems, 1990).

[8] "Partnership in Nanotechnology," NSF program announcement (1997), The National Science Foundation, *http://www.nsf.gov/pubs/1998/nsf9820/nsf9820.htm* (accessed June 1, 2014).

[9] Roco, "The US National Nanotechnology Initiative after 3 years (2001–2003)," 1–10.

[10] R. W. Siegle and Mihail C. Roco, Editors, *Nanostructure Science and Technology: A Worldwide Study* (Loyola College, MD: National Science and Technology Council (NSTC), Committee on Technology, Interagency Working Group on NanoScience, Engineering and Technology (IWGN), and International Technology Research Institute, World Technology (WTEC) Division, 1999).

In early spring 1999, Tom Kalil and Dr. Neal Lane (then serving as Assistant to the President for Science and Technology following his tenure as NSF director) requested Roco to enter a competition requested by President Clinton. The president wished to leave behind a defining scientific initiative with the national budget surplus. His Council of Advisors on Science and Technology (PCAST) and Office of Science and Technology Policy (OSTP) asked Roco to represent the nanotechnology efforts of the IWGN. On March 11, 1999, he had 10 minutes to present the initiative. The presentation went extremely well, and the IWGN was encouraged to compile a long-term national strategy for U.S. nanotechnology research.[11]

The *Nanotechnology Research Directions: IWGN Workshop Report*, published in September 1999, presented an idealized vision for U.S. nanotechnology research and development.[12] The plan had far-reaching goals, including an environment, health, and safety strategy. Future research directions specified the use of nanotechnology to fix environmental problems. Even more important, this document included a section addressing potential implications and societal problems that could result from nanotechnology. In a section devoted to the environmental strategy, the authors speculated that there would be some adverse effects attributed to nanomaterials, and that these effects should be investigated alongside advances in the technology in order to counter future problems: "An increased knowledge of the dynamics of processes specific to nanoscale structures in natural systems can improve the understanding of complex processes occurring in the environment and lead to the development of approaches for mitigating environmental harm."[13] The *Nanotechnology Research Directions* report detailed the plan for what would become the President's National Nanotechnology Initiative. By September 1999, PCAST and OSTP had narrowed the competition pool to three "finalists," and Mike Roco was asked again to present the NNI. Nanoscience was the most impressive initiative among the finalists, and within weeks, PCAST adopted nanotechnology as Clinton's science initiative.

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[11] Roco requested $500 million for nanotechnology research, while other presenters for different topics only requested $20–$30 million.

[12] Interagency Working Group on Nanoscience, Engineering and Technology (IWGN), *Nanotechnology Research Directions: IWGN Workshop Report – Vision for Nanotechnology R&D in the Next Decade*, Edited by Mihail C. Roco, R. S. Williams, and Paul Alivisatos, (Norwell, MA: Kluwer Academic Publishers, Sept. 1999), 211.

[13] Ibid.

The Initiative is Announced

In December 1999 Neal Lane and John Young, the PCAST co-chairs, endorsed the establishment of the NNI in a letter to President Clinton. They stated that nanotechnology was of paramount importance to advance technology in the United States and to continue U.S. dominance in scientific advancements.[14] They omitted potential EHS implications. Convinced by the evidence, President Clinton announced the NNI as a presidential initiative on January 21, 2000, in a speech at Caltech.[15] The proposed budget of $464 million was matched almost immediately by Japan.[16] A formal press release issued on January 21, 2000, indicated that the NNI was a high priority, and the IWGN composed an abbreviated report for Congress.[17]

This second IWGN report, *National Nanotechnology Initiative: Leading to the Next Industrial Revolution*, streamlined the larger original report and focused on persuading Congress to fund the initiative.[18] In particular, it stressed that the United States was in danger of falling behind the international community in nanotechnology. The portion of the original, full IWGN report and strategy regarding potential environmental and health implications of nanomaterials, however, was missing from the shorter congressional summary. When asked why this EHS discussion was removed, Mike Roco stated that PCAST requested that he do so as there was no evidence of adverse effects.[19] Public opinion also influenced this omission as the fear of "nano-machines" was fueled by science fiction. While the concept of a self-replicating machine was not new,[20] it experienced a revival

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[14] Neal Lane and John Young to President Bill Clinton, December 14, 1999, reprinted in Interagency Working Group on Nanoscience, Engineering and Technology (IWGN), *National Nanotechnology Initiative: Leading to the Next Industrial Revolution*, (Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) at the request NSTC, Feb. 2000): 96–97.

[15] William J. Clinton, "Remarks at the California Institute of Technology in Pasadena, California, January 21, 2000," *Public Papers of the Presidents of the United States* (Wash., DC: Government Printing Office, 2001): 94–101, *https://archive.org/stream/4733266.2000.001.umich.edu#page/94/mode/2up* (accessed July 21, 2014).

[16] Mihail Roco (Senior Advisor for Nanotechnology, Engineering Directorate of the National Science Foundation), in discussion with Brandi Schottel, February 2014.

[17] "National Nanotechnology Initiative: Leading to the Next Industrial Revolution," The White House Office of the Press Secretary, *http://clinton4.nara.gov/WH/New/html/20000121_4.html* (accessed May 1, 2014).

[18] IWGN, *National Nanotechnology Initiative: Leading to the Next Industrial Revolution* (IWGN at the request of the NSTC, Feb. 2000).

[19] Mihail Roco in discussion with Brandi Schottel, February 2014.

[20] Arthur Burks, Herman Goldstine, and John von Neumann, "Preliminary Discussion of the Logical Design of an Electronic Computing Instrument," ch. 4 in *Perspectives on the Computer Revolution* (Norwood, NJ: Ablex Publishing Corp., 1946), 39–48.

through Eric Drexler's book *Engines of Creation*.[21] Eric Drexler twice used the term "grey goo," an example of flawed or damaged nanomachines that replicate out of control and destroy all life on earth. However, to his horror, the term took off in the media, coming back to haunt the nanotechnology community. In order to advance the initiative into law, PCAST instructed IWGN to avoid mentioning potential adverse implications to the press, as there was a concern that Congress would also balk at these speculations.

While environmental implications were not explicitly mentioned, some of the five funding themes could potentially stimulate EHS investigations of nanomaterials. For example, the first theme, fundamental research into the properties and behavior of nanomaterials, could eventually incorporate study of the environmental and health impacts of these materials. Theme two, which listed nine grand challenges, had three portions (healthcare, energy, and nanoscale processes in the environment) that loosely encompassed applications in EHS. The third theme, funding for centers and networks, did result in EHS-themed centers for nanotechnology development several years later. However, while health and environmental applications are strongly represented in the wording of these themes and grand challenges, discussion of potential hazards is missing. The closest language directly addressing any adverse effects of this technology is listed in the fifth theme, the section concerned with how the technology will be developed by a largely untrained workforce. Given the concern that the United States was falling behind in nanotechnology advancements per the IWGN International Report, the implications of poor infrastructure were paramount.[22] Thus, the only potential risks of nanotechnology included in the congressional report were those associated with economic, legal, and social issues.

Adding Agencies to the NNI

Despite the omission from the congressional report, the potential environmental and health risks of nanotechnology were not far from the IWGN's agenda. In December 1999, before Congress received the abbreviated report, Roco and colleagues contacted multiple federal agencies, including the EPA, to invite their participation in the future NNI. As few investigations into nano-EHS topics had occurred before 2000, there was a concern that

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[21] K. Eric Drexler, *Engines of Creation: The Coming Era of Nanotechnology*, ch. 11 (New York: Doubleday, 1986); Fred Hapgood, "Tinytech," *OMNI* 9, no. 6, (1986): 56ff.

[22] Siegle and Roco, eds., *Nanostructure Science and Technology: A Worldwide Study*.

nanotechnology could have some negative implications for the scientific, regulatory, and industrial communities. While Roco's invitation was too late to include EPA in the initial IWGN reports, the invitation started the process to bring the leading EHS regulatory and research agency on board with the NNI. The original request was sent to the EPA Office of Research and Development (ORD). Lawrence Friedel from ORD attended the IWGN meetings and wrote a memo to Dr. Norine Noonan, ORD's assistant administrator, supporting EPA's participation in the NNI. Eventually this memo made its way to three figures who were major influences on the future course of the NNI mission: Dr. Robert Menzer, Stephen Lingle, and Dr. Barbara Karn in the National Center for Environmental Research (NCER) at EPA.

NCER, ORD's funding arm for external research grants, had supported studies in ultrafine particles and seemed the logical place to start a nanomaterials research program.[23] Karn, Dr. Nora Savage, and Lingle in NCER represented EPA in future activities of the rapidly growing NNI. In 2000 Menzer and Karn proposed that NCER use its "Exploratory Futures" program, under the Science to Achieve Results (STAR) Program, to support external, environmentally related nanotechnology research. Menzer and Karn wrote a Request for Applications (totaling about $5 million) in Exploratory Futures research focused on "green" applications of nanomaterials. In the first round of the solicitation, 16 of 89 submitted applications received funding, and a new community of nanotechnology environmental researchers had formed.[24] In August 2002, this research was presented at EPA's "Nanotechnology and the Environment" STAR Progress Review Workshop, bringing together 48 researchers and science policy experts to discuss funded research and future directions.[25]

The second EPA STAR research solicitation (February 2002) indicated a change in the language associated with EHS. EHS strategies and regulations are usually heavily laden with the terms "risks and benefits," language that has cost/value associated with potential and current regulations. These are often calculated

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[23] Ultrafines are less than 0.1 micron (100 nanometers) and therefore include nano-sized particles.

[24] EPA Science Advisory Board, 1995, Beyond the Horizon: Using Foresight to Protect the Environmental Future (1995), *http://www.epa.gove/OSP/futures/BeyondHorizon.pdf,* (accessed, May 14, 2014).

[25] The Environmental Protection Agency, *Proceedings of the EPA, Nanotechnology and the Environment: Applications and Implications, STAR Progress Review Workshop*, August 28–29, 2002. Arlington, VA, USA.

through actual numbers and data, as well as assumptions of value (such as the access value of an open space in a park, or the estimated value of a human life). The bulk of EPA regulations involve a cost associated with implementation that cannot be exceeded, thereby putting a limit on efforts required to mitigate EHS consequences. This solicitation, however, altered the "cost" associated with EHS studies. While four topics of the solicitation still focused on green applications of nanotechnology, two portions emphasized the investigations of implications of nanotechnology. Using the terms "applications" and "implications" kept the research free from the value-laden language of risks and benefits. This altered EHS research language would eventually work its way into NNI documents. It set the stage for the promotion of constant, side-by-side EHS studies concurrent with technology development and commercialization without the restrictions of "risks versus benefits."

Convincing Congress

To help sway public opinion, the IWGN produced a brochure on the merits of nanotechnology, highlighting the potential advances it could bring to the United States.[26] Among the multiple congressional testimonies in support of the NNI, that of Nobel Laureate Richard Smalley stands out. Smalley was suffering through the effects of chemotherapy, complete with weakness and hair loss. His description of how nanotechnology would eventually result in targeted cancer therapies that would eliminate these side effects was extremely powerful. That and other testimonies helped convince Congress to consider S.189, the 21st Century Nanotechnology Research and Development Act, introduced by Senator Ron Wyden on January 16, 2003, which would ensure the long-term federal strategy of the NNI.[27]

Bill Clinton established the IWGN as a permanent part of the NSTC as the Nanoscale Science, Engineering and Technology Subcommittee (NSET) in the Committee of Technology, with Roco as its chair.[28] This new subcommittee formed its own working groups to address the goals of the original IWGN Report.[29]

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[26] Ivan Amato, *Nanotechnology: Shaping the World Atom by Atom. National Science and Technology Council Report* (U.S. Government: Interagency Working Group on Nanoscience, Engineering, and Technology, 1999).

[27] S.189: 21st Century Nanotechnology Research and Development Act, introduced by Senator Ron Wyden (2003): *https://www.congress.gov/bill/108th-congress/senate-bill/189* (accessed Feb. 3, 2014).

[28] Roco, "The US National Nanotechnology Initiative after 3 years," 3

[29] IWGN, *Nanotechnology Research Directions: IWGN Workshop Report, – Vision for Nanotechnology R&D in the Next Decade*, eds, Mihail C. Roco et al.

Nanotechnology Environmental and Health Implications (NEHI) Working Group Forms

In spring 2003, Clayton Teague, Director of the National Nanotechnology Coordination Office (NNCO), visited a university laboratory that worked with nanomaterials. During his visit, he observed a student pouring carbon nanotubes into an open-topped container without proper ventilation and essentially no protective gear.[30] It was a complete wake-up call on the indifference toward potential hazards of natural and engineered nanoparticles. In response, Teague sent a memo to the following NNI agencies sponsoring nanotechnology research: NSF, National Institute of Environmental Health Sciences (NIEHS), National Institute of Occupational Health and Safety (NIOSH), FDA, EPA, Department of Defense (DOD), National Institute of Standards and Technology (NIST), Department of Energy (DOE), and the United States Department of Agriculture (USDA). The memo addressed three topics concerning ultrafine particles: (1) current safety practices used when working with ultrafine particles; (2) existing regulatory standards, protocols, and procedures to assure safe and responsible working conditions and prevent negative impacts on the environment after particle disposal; and (3) existing examples (if any) of agency-sponsored nano-EHS research.[31] On August 26, representatives from these agencies, with members from OSTP and the NNCO, came together for a day-long meeting to discuss these topics as well as the development of improved and new practices for handling nanomaterials.

One clear theme of these discussions was the treatment of nanomaterials as unknown hazardous substances. National laboratories, agency in-house laboratories, and agency partner centers all approached the use of nanomaterials with full laboratory safety practices (gloves, lab coats, protective eyewear, handling in glove boxes or vent hoods, small sample sizes, and proper hazardous waste disposal methods). However, academic laboratories and industry conditions were unknown, and it was clear, after Teague's experience, that proper practices were not always followed. The agencies at that meeting reviewed existing laws and regulations that might be pertinent to nanomaterials, and the group decided that

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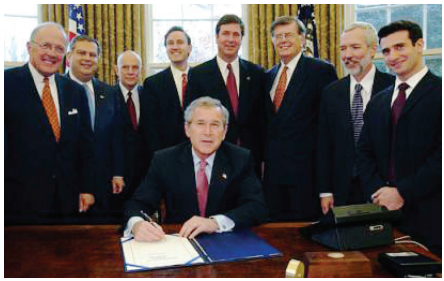
[30] Several studies at this time indicated that carbon nanotubes caused lung irritation in mice. Good examples are found in C. W. Lam, J. T. James, R. McClusky, R. L. Hunter, "Pulmonary toxicity of carbon nanotubes in mice 7 and 90 days after intratracheal instillation," *Toxicological Sciences*, 77 (2004): 124–34; D. B. Warheit, B. R. Laurence, K. L. Reed, D. H. Roach, G. A. M. Reynolds, and T. R. Webb, "Comparative pulmonary toxicity assessment of single-wall carbon nanotubes in rats," *Toxicological Sciences* 77 (2004): 117–25.

[31] Personal notes of author Barbara Karn, and Brandi Schottel's discussion with Geoff Holdridge.

there was an urgent need for more research on toxicology, environmental fate, and other unforeseen consequences. The participants tentatively agreed to form a new working group, Nanotechnology Environmental and Health Implications (NEHI, under NSET), to investigate and coordinate these possibilities.

To discuss federal EHS research, EPA/NCER held an NNCO-sponsored workshop in September 2003 to highlight current (or future) federal agency efforts in nanotechnology EHS.[32] It included 75 participants from academia, industry, and the federal agencies DOD, DOE, EPA, FDA, NIH, NIST, NSF, and USDA. This workshop was the first time that different agencies attempted to coordinate the EHS portion of nanotechnology research. As a result, several participating agencies developed their own internal research strategies that are used, in updated forms, today.[33]



The signing of Public Law 108-153, December 3, 2003. *Left* to *Right:* Sherwood Boehlert, Spencer Abraham, Richard Smalley, Steve Jurvetson, George Allen, E. Floyd Kvamme, James R. Von Ehr II, Josh Wolfe, and George W. Bush (middle).

The National Nanotechnology Initiative is Official

On January 16, 2003, Senator Ron Wyden (D-OR) introduced Senate Bill 189, the 21st Century Nanotechnology Research and Development Act, the legal culmination of President Bill Clinton's Nanotechnology Initiative.[34] The bill passed the Senate on November 18, 2003, and was sent to the House of Representatives the next day. The House passed the bill after only 40 minutes of debate with a 405–19 vote.[35] On

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[32] Environmental Protection Agency and the National Nanotechnology Coordination Office, *Nanotechnology and the Environment: Applications and Implications workshop* (2003), *http://epa.gov/ncer/publications/workshop/nano_sept15_03.html* (accessed June 12, 2014).

[33] U.S. Food and Drug Administration Task Force, *Nanotechnology: A Report of the U.S. Food and Drug Administration Task Force*. (U.S. Government: July 2007); Nanotechnology Workgroup in EPA's Science Policy Council, *U.S. Environmental Protection Agency Nanotechnology White Paper* (Wash., DC: Science Policy Council, U.S. Environmental Protection Agency, 2007); NIOSH Nanotechnology Research Center Steering Committee, *Strategic Plan for NIOSH Nanotechnology Research Filling the Knowledge Gaps* (Wash., DC: Nanotechnology Research Program, National Institute for Occupational Safety and Health, 2005).

[34] 21st Century Nanotechnology Research and Development Act of 2003, Pub. L. No. 108-153, 117 Stat. 1923 (2003).

[35] "Final Vote Results for Roll Call 167," Library of Congress, *http://clerk.house.gov/evs/2003/roll167.xml* (accessed Feb. 26, 2014).

December 3, 2003, President George W. Bush signed the act into Public Law 108-153, legitimizing the actions of the IWGN and federal agencies that were already underway.[36] Only one of the original participants in the formation of the NNI, Dr. Richard Smalley, was invited to attend. The rest of those present represented science administrators in the Bush cabinet, a senator who helped draft the original bill, the PCAST co-chair, and leaders of the Nanobusiness Alliance. Roco, Murday, Kalil, Lane, and Wyden were excluded. The administration had changed, and the original players were being replaced amid an altered political climate.

Within Public Law 108-153, several points specifically addressed EHS. Section 2B-4 promoted the IWGN goal to establish interdisciplinary centers.[37] This was already set in motion with NSF's funding of the Center for Biological and Environmental Nanotechnology (CBEN) at Rice University.[38] Section 2(b)-10 stated, "The activities of the Program shall include ensuring that ethical, legal, environmental and other appropriate societal concerns . . . are considered during the development of nanotechnology."[39] It then outlined how these activities should be present in every portion of the act through established research programs, nanotechnology centers, infrastructure, and public outreach.

Aside from the specific language addressing EHS concerns of nanotechnology, the act also officially established the NNCO, funded by the NSF and other federal research agencies. The NNCO serves as the secretariat to NSET.[40] It is designed to coordinate all aspects of the NNI, including the EHS portions, and implement triennial evaluations. The National Research Council of the National Academy of Sciences, with coordination from the NNCO, is responsible for these evaluations, which include an assessment of how the program addressed EHS and other societal concerns. In addition, the first triennial review would include two specific studies: one on molecular self-assembly[41] and its feasibility as a manufacturing tool at the molecular scale, and another on the responsible development of nanotechnology.

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[36] "S.189 - 21st Century Nanotechnology Research and Development Act," Library of Congress, *http://beta.congress.gov/bill/108th-congress/senate-bill/189/all-actions/* (accessed Feb. 26, 2014).

[37] 21st Century Nanotechnology Research and Development Act of 2003, Sect. 2B-4.

[38] Richard E. Smalley and Vicki L. Colvin, "NSEC: Center for Nanoscience in Biological and Environmental Engineering" (2001) (NSF Award 0118007), *http://nsf.gov/awardsearch/showAward?AWD_ID=0118007&HistoricalAwards=false* (accessed June 21, 2014).

[39] 21st Century Nanotechnology Research and Development Act of 2003, Sect. 2(b)-10.

[40] 21st Century Nanotechnology Research and Development Act of 2003, Sect. 3(a) 1-4.

[41] Self-assembly: The ability of designer molecules to interact in such a way as to produce one, and only one, product based on their design.

The molecular manufacturing study was to assess the need for regulatory responsibilities and strategies for the release of self-replicating nanomachines or devices in natural environments.[42] This specific add-on was included to address concerns fueled by Michael Crichton's popular science fiction book *Prey* (2002).[43] This science fiction novel, along with public speculation, led Great Britain's Prince Charles to request a threat assessment from the U.K.'s Royal Society related to Eric Drexler's "grey goo" scenario. The Royal Society report investigated all perceived risks of nanotechnology (not just the grey goo doomsday scenario) and represented the only serious nanotechnology report triggered by a science fiction novel scare.[44] As a further step in the responsible development of nanomaterials, the act also added the establishment of a National Nanotechnology Advisory Panel (NNAP) ". . . to inform and guide the president on all aspects regarding the initiative, including an assessment of "whether societal, ethical, legal, environmental, and workforce concerns are adequately addressed by the Program."[45] In July 2004 President Bush designated PCAST as the NNAP.

In addition to the triennial evaluation reports and the reports from the NNAP, the act stated that a National Nanotechnology Initiative strategic plan should be generated triennially. These reports were to describe the state of nanotechnology federal programs and advancements and include a strategic plan for the next 5–10 years.[46] The original IWGN full report from 1999 became a template for future NNI strategic plans.[47]

Preparing the EHS Section of the First NNI Strategic Plan

Before writing the NNI 2004 strategic plan, NSET held a Nanotechnology and the Environment Workshop (May 8–9, 2003), led by EPA and NSF, to help clarify the future direction of nano-EHS.[48] The workshop was attended by agency representatives

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[42] 21st Century Nanotechnology Research and Development Act of 2003, Sect. 4(b).

[43] Michael Crichton, *Prey* (New York: Harper Collins , 2002).

[44] Roger Highfield, "Prince asks scientists to look into 'grey goo,'" *The Telegraph*, June 5, 2003, *http://www.telegraph.co.uk/science/science-news/3309198/Prince-asks-scientists-to-look-into-grey-goo.html* (accessed July 2, 2014); The Royal Society & The Royal Academy of Engineering, *Nanoscience and Nanotechnologies: Opportunities and Uncertainties* (Plymouth, UK: Latimer Trend Ltd, 2004).

[45] 21st Century Nanotechnology Research and Development Act of 2003, Sec. (4) a-d.

[46] 21st Century Nanotechnology Research and Development Act of 2003, Sec. 2(c) (4).

[47] IWGN, *Nanotechnology Research Directions: IWGN Workshop Report - Vision for Nanotechnology R&D in the Next Decade*, eds. Mihail C. Roco et al.

[48] Nanoscale Science, Engineering, and Technology Committee on Technology, Nanoscale Science, Engineering, and Technology Subcommittee, *Nanotechnology and the Environment: Report of the National Nanotechnology Initiative Workshop, May 8–9th, 2003* (U.S. Government: NNCO, 2007).

from EPA, NIEHS, NIST, NSF, National Aeronautics and Space Administration (NASA), and USDA, along with NNCO representatives, and scientists and stakeholders in both academic and industry communities. It was divided into five themes for nanomaterials EHS research agendas: (1) Applications for measurement in the environment; (2) Applications for sustainable materials and resources; (3) Applications for sustainable manufacturing; (4) Implications in Natural and Global Processes; and (5) Implications in Health and the Environment. The report defined future goals and outlined a pathway for environmental research for the next 10–15 years. Improving existing sensing techniques with nanotechnology, as well as sensing of nanoparticles were both recommended research directions. These eventually appeared in FDA, EPA, and NIOSH research strategies.[49]

While the potential applications of nanotechnology promised advances in environmental and human health fields, the implications of nanomaterials use were unknown. With this in mind, the workshop participants addressed future implications of nanomaterial use and release into the environment. The foremost research challenge was proper analysis of nanomaterials in current and future use. In addition, nanomaterials toxicity testing lacked a systematic approach. To address environmental concerns, workshop participants recommended investigation of the life cycle of nanomaterials in different environments, as well as research on nanomaterial aggregation and ingestion and accumulation in biological organisms. The report recommended an increase in "targeted and sustained research funding for examining the health and environmental implications of nanotechnology" to promote this research alongside commercial applications research.[50]

Although the importance of this workshop to the future of the NNI's nanotechnology EHS research cannot be overstated, the report was not released until four years later. EPA contractors were responsible for writing up the original workshop report. However, their job was highly inadequate, and Karn and Savage took it upon themselves to improve the document. The report then languished on the desk of Dr. Celia Merzbacher at OSTP and co-chair of NSET, and was held

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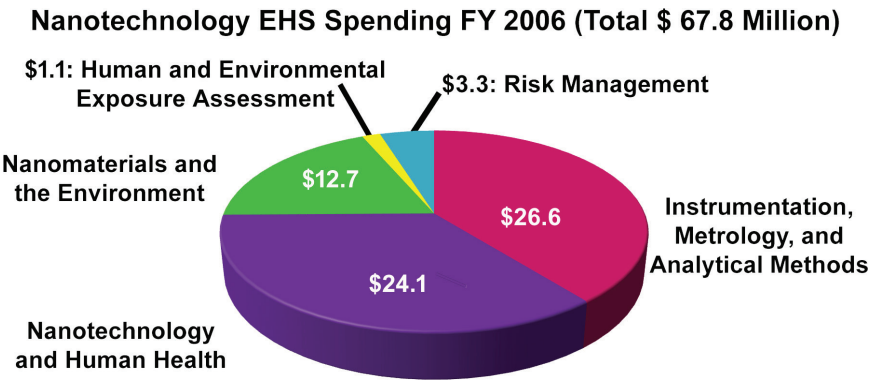
[49] Nanotechnology Workgroup of EPA's Science Policy Council, *U.S. Environmental Protection Agency Nanotechnology White Paper*, (Environmental Protection Agency, 2007); NIOSH Nanotechnology Research Center Steering Committee, *Strategic Plan for NIOSH Nanotechnology Research*; FDA Nanotechnology Task Force, *Nanotechnology: A Report of the U.S. Food and Drug Administration Nanotechnology Task Force* (U.S. Government: Department of Health and Human Services, 2007).

[50] K. Dreher, et al., "Nanotechnology Implications in Health and the Environment," ch. 6 in *Nanotechnology and the Environment:* 34.

for further revisions. When it was finally released in 2007, there were almost no changes from the original form.

2004 NNI Strategic Plan

In five years, the original 6 investing NNI agencies grew to 11 (with 22 total participating in the plan formulation), and research and development monies had doubled to an estimated $1 billion spent since 2001. Based on information gathered from 17 NNI-sponsored workshops, the 2004 NNI strategic plan addressed nanotechnology funding directions for these agencies.[51] The four major goals of the initiative were as follows: (1) maintain a world-class research and development program aimed at realizing the full potential of nanotechnology; (2) facilitate transfer of new technologies into products for economic growth, jobs, and other public benefit; (3) develop educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology; and (4) *Support responsible development of nanotechnology.* This last goal set the stage for federal promotion of sustainable nanotechnology development concurrent with scientific breakthroughs to ensure responsible and ethical development. The document named six federal agencies already studying the potential health risks of nanomaterials: NIEHS, NIOSH, EPA, DOD, DOE, and NSF. NIST was recognized for standards development, a major goal of the original IWGN report.[52] According to the language used in the "Nanotechnology and the



A representation of FY 2006 EHS spending on nanotechnology research from the 2008 NNI *Strategy for Nanotechnology-Related Environmental, Health, and Safety Research.*

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[51] Nanoscale Science, Engineering, and Technology Committee on Technology, Nanoscale Science, Engineering, and Technology Subcommittee. *The National Nanotechnology Initiative Strategic Plan* (U.S. Government: NNCO, 2004).

[52] IWGN, *National Nanotechnology Initiative: Leading to the Next Industrial Revolution* (IWGN, at the request NSTC, and February 2000).

Environment" Workshop Report, this strategy highlighted environment, health, and safety *implications* alongside ethical, legal, and social issues.[53] The traditional, value-laden "risks versus benefits" was abandoned in this strategy, a move that continues to define the course of Nanotechnology EHS research and regulatory plans to this day.

Political Change Leads to NSET Change

After the Bush administration's snub of the founders of the NNI, more sweeping changes occurred, including an administrative restructuring of NSET. In fall 2005, Karn, who had been approached by Mike Roco to lead NEHI, received a call from Merzbacher at OSTP requesting that she not attend the next NSET meeting. At that meeting, it was announced that NSET would have a "revolving chair" and an OSTP co-chair for the future of the NNI. Mike Roco was replaced by Dr. Altaf Carim and Merzbacher (the new OSTP co-chair) immediately. To this day, Mike Roco is still a part of NSET, but as an NSF representative rather than the chair. In 2006 Karn moved to the Woodrow Wilson Center for a planned detail as Senior Advisor for the Project on Emerging Nanotechnologies. She continued to work on the EHS nanotechnology research directed by EPA, including its defining white paper on the topic, with Savage and others who remained at EPA.[54]

Nanotechnology EHS Needs

In 2006, with efforts coordinated by the NEHI working group, NSET published *Environmental, Health, and Safety Research Needs for Engineered Nanoscale Materials*.[55] This document identified EHS research needs for engineered nanomaterials and was intended to inform stakeholders in their efforts to define research, risk assessment, and risk management strategies. Five different EHS areas were identified: (1) Instrumentation, Metrology, and Analytical Methods; (2) Nanomaterials and Human Health; (3) Nanomaterials and the Environment; (4) Health and Environmental Surveillance; and (5) Risk Management Methods. Federal activities occurring in these areas were highlighted, with emphasis given to existing research and regulatory structures within the EPA, FDA, NIOSH/CDC, NIH, and NSF.

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[53] NSET, *Nanotechnology and the Environment.: Report of the National Nanotechnology Initiative Workshop, May 8–9th, 2003*, (U.S. Government: NNCO, 2007).

[54] Nanotechnology Workgroup in EPA's Science Policy Council, *U.S. Environmental Protection Agency Nanotechnology White Paper (*Wash., DC: Science Policy Council, U.S. Environmental Protection Agency, 2007).

[55] Nanotechnology Environmental and Health Implications Working Group, *Environmental, Health, and Safety Research Needs for Engineered Nanoscale Materials* (U.S. Government: NNCO, Sept. 2006).

2007 NNI Strategic Plan and the 2008 Nanotechnology EHS Research Strategy

The 2007 NNI Strategic Plan, the first prepared only during the George W. Bush administration, did not update EHS plans.[56] The National Academies, in fulfillment of a requirement of the 2003 act, conducted its first review of the initiative in 2006, which included an evaluation of NNI EHS efforts.[57] This review, a result of multiple workshops, praised EHS efforts both in the United States and abroad, highlighting efforts at EPA, NIH (NIEHS), FDA, NIOSH, and NIST. The panel stated that the unknowns presented by current EHS studies, coupled with the potential societal implications of unknown risks, called for more EHS research.[58]

The 2008 NNAP/PCAST review, full of conflicting statements, praised the agencies investing in EHS research but attacked the language and aggressive approach promoted by the NNI. NNAP recommended a more "cautionary," rather than "precautionary," strategy to nanotechnology EHS research and regulation to appropriately balance risks and benefits of the nanotechnology products emerging on the marketplace. However, in the same paragraph, the evaluation states that it is difficult to achieve the goals of responsible nanotechnology and development because it is "difficult and/or costly to fully characterize (nanomaterials), and their effects on the health or the environment are not known or are poorly understood," giving rise to a notion that a precautionary approach might be warranted. Furthermore, the NNAP evaluation, contrary to the facts, suggested the United States was behind in EHS studies, potentially leading to EHS risks. However, the report claimed the EHS budget was growing appropriately, even at a greater percentage than the rest of the budget. The review neglected to point out that the EHS portion of the NNI budget ($74.6 million) comprised only five percent of the total $1.53 billion NNI budget. The evaluation states that the United States was spending just as much on EHS research as other countries, so no extra increase was required. This is puzzling as the United States was spending more on EHS studies than other countries at that time. These contradictory and weak statements did not suggest that the promised

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[56] Nanoscale Science, Engineering, and Technology Committee on Technology, Nanoscale Science, Engineering, and Technology Subcommittee. *The National Nanotechnology Initiative Strategic Plan* (U.S. Government: NNCO, 2007).

[57] Committee on Triennial Review of the National Nanotechnology Initiative, National Academies, *A Matter of Size: Triennial Review of the National Nanotechnology Initiative* (Wash., DC: National Academies Press, 2006).

[58] Outside of its general recommendations and specific EHS recommendations, the National Academies report contained the "Molecular Assembly" study required by the 2003 NNI Act. It was only three paragraphs and it basically stated that there was no threat from self-replicating machines.

addendum review to address the impending 2008 NNI Environmental, Health, and Safety Research Strategy would be particularly favorable.[59]

The political powers at that time accepted the necessity of EHS regulation, but viewed it as an impediment to businesses and jobs. This atmosphere made the 2008 NNI EHS Strategic Plan difficult to produce, and as a result, the plan was not complete and received poor reviews.[60] The document was confusing and disorganized, and its attempt to strategize EHS research across the NNI agencies was considered a failure. It presented the same five research categories, but with specific agency leads.[61] In an example of the plan's confusing explanation, the money spent on different EHS research topics since 2005 was presented in text in the executive summary of the Strategy. The largest piece of the pie, "Instrumentation, Metrology, and Analytical Methods," represents research that can also fall under other NNI categories. As a result, this $26.6 million dollar figure is "over-reported" as it is difficult to separate different classes of projects under this section from those that only involve EHS. These numbers are followed by the statement: "In short, the analysis demonstrated that the Federal Government is supporting more EHS research than has been previously identified, and the research is *well-distributed* [italics added] across key priority areas."[62] This excerpt, coupled with the clearly completely different research monies, sum up the poor quality of this document.

While the NNAP/PCAST review addendum praised NIOSH's efforts to increase funding for studies on the EHS impacts of nanotechnology in the workplace (the $1.1 million for Human and Environment Exposure Assessment in the FY 2006 spending chart), it was scathing of the separation of applications and implications research, calling for a mixture of these two topics so the value-laden "risks vs. rewards" were addressed instead.[63] NSET and the agencies involved in EHS research did not have to change this language as a new presidential administration felt that the "applications and implications" approach was more appropriate for this cutting-edge technology.

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[59] President's Council of Advisors on Science and Technology, *Addendum to the National Nanotechnology Initiative: Second Assessment and Recommendations of the National Nanotechnology Advisory Panel*, *Assessment of the NNI Strategy for Nanotechnology-Related Environmental, Health, and Safety Research* (U.S. Government: NNCO, July 2008).

[60] Nanotechnology Environmental and Health Implications Working Group, *National Nanotechnology Initiative Strategy for Nanotechnology-Related Environmental, Health, and Safety Research* (U.S. Government: NNCO, Feb. 2008).

[61] Ibid., 2.

[62] Ibid.

[63] President's Council of Advisors on Science and Technology, *Addendum to the National Nanotechnology Initiative,* 4.

The NNI Under a New Administration

In 2009, following the election of President Barack Obama, the composition of PCAST changed, resulting in significantly altered NNAP reports. The first Obama-era report, released on March 12, 2010, (the third NNAP assessment overall), had three focus areas: (1) Program management; (2) Nanotechnology outcomes; and (3) Environment, health, and safety.[64] Due to growing uncertainty about the EHS consequences of nanotechnology that offered an excuse for industry withdrawal, the NNAP evaluated the EHS expenditures and strategies in the United States. Its EHS recommendations were: (1) expansion of NNCO EHS duties and budget (including the creation of a new NNCO position to coordinate EHS research needs), (2) expansion of NEHI duties, (3) the formation of a nano-research database, and (4) a call for a new, more developed NNI EHS strategy.

The 2010 report reversed the recommendation that applications and implications research be combined: "Overly-intimate integration of these two categories of research can lead to a muddling of research priorities. At the same time, there is a danger of resource-intensive EHS research comprising exploratory and applications-based research programs."[65] In another reversal, the new NNAP did *not* conclude that EHS funding was appropriate, citing the results of a 2008 Government Accountability Office (GAO) report that found at least 20 percent of the projects that were reported to address EHS concerns were focused on remediation and detection of environmental hazards *not* caused by nanotechnology.[66] The NNAP recommended that more research funding be made available to agencies targeting EHS.

The 2011 NNI Strategic Plan represented a major shift in EHS language.[67] Under the objectives for Goal 4 (support the responsible development of nanotechnology), the previously avoided term "sustainability" made its NNI debut. While sustainability

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[64] President's Council of Advisors on Science and Technology, *Report to the President and Congress on the Third Assessment of the National Nanotechnology Initiative* (U.S. Government: NNCO, 2010).

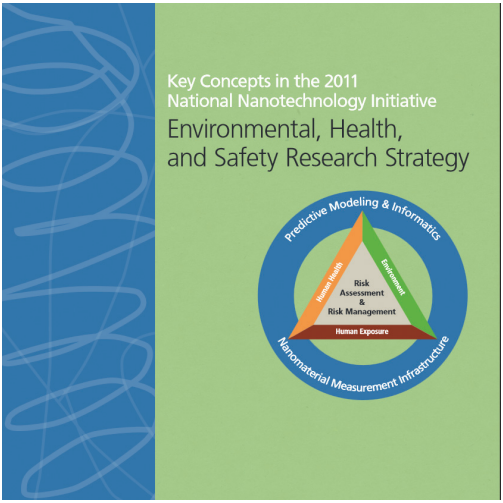
[65] Ibid., 40.

[66] United States Government Accountability Office (GAO-08-709T), *Nanotechnology: Accuracy of Data on Federally Funded Environmental, Health, and Safety Research Could Be Improved,* Testimony before the Subcommittee on Science, Technology, and Innovation, Committee on Commerce, Science, and Transportation, U.S. Senate (Statement of Robert A. Robinson, Managing Director, Natural Resources and Environment), *www.gao.gov/products/GAO-08-709T* (accessed June 9, 2014).

[67] Nanoscale Science, Engineering, and Technology Committee on Technology, Nanoscale Science, Engineering, and Technology Subcommittee. *The National Nanotechnology Initiative Strategic Plan* (U.S. Government: NNCO, 2011).

was not clearly defined, the term was used liberally. Of the four objectives of Goal 4, two involved sustainable development: (4.1) "foster responsible development, and where appropriate, sustainability across the nanotechnology innovation pipeline,"[68] and (4.4) "Employ nanotechnology and sustainable best practices to protect and improve human health and the environment."[69] All of the goals were presented differently, with specific lists of ideal research directions, a contrast to the two previous NNI research strategies.

The 2011 NNI EHS Strategy was drastically altered from the much-criticized 2008 version, and was composed from the information from previous stakeholder meetings and four NNI workshops coordinated by Sally Tinkle, the NNCO Deputy Director and Coordinator for Environment, Health, and Safety Research.[70] It presented a clearer view of EHS research and modified the list of research needs and goals to promote a more organized approach to EHS for any federal agency. The 2011 EHS Strategy listed the following development principles: (1) prioritization of engineered nanomaterials and nano-enabled products for EHS research (with research-focused criteria); (2) establishment of standardized measurements, terminology, and nomenclature of nanomaterials (a crosscutting goal of every NNI strategy); (3) pursuit of reliable, reproducible data; (4) stratification of risk assessment knowledge (i.e.,



A brochure summarizes the 2011 NNI EHS strategy: The six core research areas in the NNI EHS Research Strategy.

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[68] Ibid., 30.

[69] Ibid., 32.

[70] (a) Nanotechnology Environmental and Health Implications Working Group, *NNI 2011 Environment, Health, and Safety Research Strategy* (U.S. Government: NNCO, Oct. 2011). (b) Sally Tinkle, *Key Concepts in the 2011 NNI Environment, Health, and Safety Research Strategy* (U.S. Government: National Nanotechnology Coordination Office, Editorial services were provided by WTEC, Arlington, VA; OmniStudio of Washington, DC, designed the booklet; and PCA of Timonium, MD, printed the document, 2011), *http://www.nano.gov/sites/default/files/pub_resource/2011_brochure_ehsresearchstrategy.pdf* (accessed Jan. 1, 2016).

Is qualitative vs. quantitative assessment appropriate?); (5) development of partnerships with nonfederal entities to achieve NNI research goals, and (6) engagement with the international community on nano-EHS. The suggested ways to promote these goals were presented in the context of the original 2008 prioritization, with re-classifications of different gaps in EHS priorities in an adaptive strategy method. This approach set the stage for future modifications as the priorities for EHS research changed. Also new in the 2011 EHS Strategy was the inclusion of ethical, legal, and social implications throughout the document, a topic that was excluded from the 2008 strategy.

Nanotechnology EHS Today

Today, the NNI includes 11 funding federal departments and independent agencies, and 9 other participating federal agencies, with a proposed FY 2015 budget of $1.5 billion. Since 2001, the total spent on the NNI is estimated at $21 billion.[71] While the number of agencies appears reduced, this is not an accurate observation as only the parent agency is listed. The most current NNI Strategy, published in February 2014, represents the culmination of efforts associated to highlight and fund EHS research.[72] The fourth goal, "Support the responsible development of nanotechnology," has four objectives that fit the ever-changing needs of nanotechnology research and development:

> (1) Support the creation of a comprehensive knowledge base for evaluation of the potential risks and benefits of nanotechnology to the environment and to human health and safety; (2) Create and employ means for timely dissemination, evaluation, and incorporation of relevant EHS knowledge and best practices; (3) Develop the national capacity to identify, define, and responsibly address concepts and challenges specific to the ethical, legal, and societal implications of nanotechnology; and (4) *Incorporate sustainability in the responsible development of nanotechnology* [italics added].[73]

This last objective clearly emphasizes sustainability in the context of the NNI. It effectively established a set of parameters for member agencies that involves the

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[71] Nanoscale Science, Engineering, and Technology Committee on Technology, Nanoscale Science, Engineering, and Technology Subcommittee. *The National Nanotechnology Initiative Strategic Plan*, (U.S. Government: NNCO, 2014).

[72] Ibid.

[73] Ibid. 35–36.

intersection of the environment, the economy, and society, leading to overlapping categories of socio-environmental, socio-economic, and enviro-economic issues that all add up to sustainable development.[74]

The most recent NNAP (PCAST) review continues to stress that researchers investigate EHS implications of all nanomaterials as they are being developed, and the 2014 NNI Strategy also reflects this strong suggestion.[75] Researchers are encouraged to approach their investigations with an eye on potential implications, a philosophy that is a shift from the pursuit solely of application discoveries and advancements. After almost 15 years of hard work, collaboration, and federal and private investment, the NNI has evolved into an important example of how EHS can be incorporated into every step of scientific research and development. Nanotechnology improvements permeate almost all markets—ranging from smart phones to airplane wings, from better catalysts to nanomedicines. With the "grey goo" fears essentially dead, nanotechnology has largely escaped public fear campaigns that can destroy new technologies. No accidents directly traced to unknown nanomaterials hazards have occurred in the United States, an accomplishment attributed to careful coordination and management of nanotechnology research at the federal level. Due mainly to the efforts of dedicated federal workers, such as Roco, Murday, Teague, Karn, Savage, Tinkle, this paradigm shift of tackling EHS issues in conjunction with basic and applied research represents an admirable model for all future scientific research.

Photo credits: President Bush signing the bill, timeline, pie chart, report covers, courtesy of the authors

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[74] Ibid. 37.

[75] President's Council of Advisors on Science and Technology, *Report to the President and Congress on the 4th Assessment of the National Nanotechnology Initiative* (U.S. Government: National Nanotechnology Coordination Office, April 2012), *http://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST_2012_Nanotechnology_FINAL.pdf* (accessed July 14, 2014).