Journal of Nanoparticle Research **5:** 181–189, 2003.

Perspectives

Broader societal issues of nanotechnology

M.C. Roco
National Science Foundation (NSF), 4201 Wilson Blvd., Arlington, VA 22230, USA (E-mail: mroco@nsf.gov); National Science and Technology Council's Subcommittee on Nanoscale Science, Engineering and Technology (http://nano.gov)

Received March 2003; accepted in revised form 20 March 2003

Key words: nanoscience, nanotechnology, societal implications, environment, health, international

Abstract

Nanoscale science and engineering are providing unprecedented understanding and control over the basic building blocks of matter, leading to increased coherence in knowledge, technology, and education. The main reason for developing nanotechnology is to advance broad societal goals such as improved comprehension of nature, increased productivity, better healthcare, and extending the limits of sustainable development and of human potential. This paper outlines societal implication activities in nanotechnology R&D programs. The US National Nanotechnology Initiative annual investment in research with educational and societal implications is estimated at about $30 million (of which National Science Foundation (NSF) awards about $23 million including contributions to student fellowships), and in nanoscale research with relevance to environment at about $50 million (of which NSF awards about $30 million and EPA about $6 million). An appeal is made to researchers and funding organizations worldwide to take timely and responsible advantage of the new technology for economic and sustainable development, to initiate societal implications studies from the beginning of the nanotechnology programs, and to communicate effectively the goals and potential risks with research users and the public.

Technology–society closed loop

A key motivation for nanoscale science and engineering research is to advance broad societal goals, from improved understanding of nature at the molecular level to increased productivity through efficient nanomanufacturing (Roco & Bainbridge, 2001; Roco and Tomelini, 2002). Research and development at the nanoscale, nanotechnology applications and societal implications form a coherent and interactive system, which schematically may be visualized as a closed loop (Figure 1). Nanotechnology success is determined by an architecture of factors such as creativity of individual researchers, training of students in nanoscale science and engineering, connections between organizations, patent regulations, physical infrastructure, legal aspects, state and federal policies, and the international context. The success of nanotechnology cannot be determined only by doing good R&D in academic and industry laboratories.

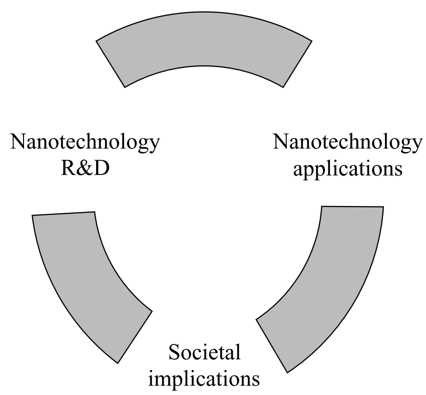

Figure 1. A closed loop.

Key questions asked by the technology users and public are about economic development and commercialization, education, infrastructure, and societal implications environmental and health effects.

Government R&D investments

The worldwide nanotechnology research and development (R&D) investment reported by government organizations has increased more than six-fold from $430 million to about $3 billion between 1997 and 2003 (see Table 1 and Figure 2). At least 35 countries have initiated national activities in this field partially stimulated by National Nanotechnology Initiative (NNI).

Scientists have opened a broad net that does not leave any major research area untouched in the physical, biological, materials, and engineering sciences. Industry has gained confidence that nanotechnology will bring competitive advantages to both traditional and emerging fields, and significant growth is noted in small businesses, large companies, and venture capital firms. The annual global impact of products where nanotechnology will play a key role has been estimated in 2000 to exceed $1 trillion by 2015, which would require about 2 million nanotechnology workers (Roco & Bainbridge, 2001). This estimate was based on the analysis of existing R&D activities in industry in the US, Japan, and Western Europe. One notes that $1 trillion represents about 10% of the US GDP in 2003. If one would extrapolate the previous experience, where for each information technology worker another 2.5 jobs are created in related areas, nanotechnology has the potential to create 7 million jobs overall by 2015 in the global market. Also, if one considers the impact of infotechnology of increasing US productivity more than 1% per year in 1990s (that is roughly half of the overall productivity growth of about 2.1% in the 1990s), a similar or possibly larger impact is expected from nanotechnology. This is because the impact is broader than a new generation of electronic hardware once nanotechnology is reaching a critical mass in knowledge and commercial markets. One may note that the initial estimates for infotechnology significantly under-evaluated its long-term positive implications (because of successive and non-scalable qualitative changes) and over-evaluated several negative effects (beginning with the risk of macroscale robots that would take over the world). By envisioning the potential synergism of many fields contributing to nanotechnology and various phases of its introduction, a similar scenario would be possible at an even more pronounced scale.

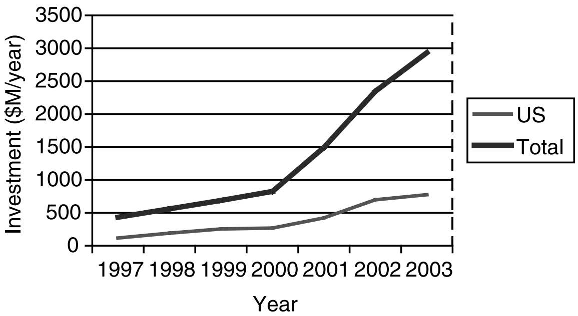

Figure 2. Government investments in nanotechnology between 1997 and 2003 (Upper curve – total worldwide including US; lower curve – US).

Table 1. Estimated government nanotechnology R&D expenditures in 1997–2003 (in $ millions/year)

Region	1997	1998	1999	2000	2001	2002	2003
Western Europe	126	151	179	200	~225	~400	~600
Japan	120	135	157	245	~465	~700	~810
USA*	116	190	255	270	422 (465)**	600 (697)**	774
Others	70	83	96	110	~380	~550	~800
Total	432	559	687	825	1492	2347	2984
(% of 1997)	100%	129%	159%	191%	346%	502%	690%

Notes: ‘Western Europe’ includes countries in EU and Switzerland; the rate of exchange $1 = 1.1 Euro until 2002; $1 = 1 Euro in 2003; Japan rate of exchange $1 = 120 yen in 2002; ‘Others’ include Australia, Canada, China, Eastern Europe, FSU, Israel, Korea, Singapore, Taiwan, and other countries with nanotechnology R&D.

Estimations use the nanotechnology definition as defined in NNI (Roco et al., 2000; this definition does not include MEMS), and include the publicly reported government spending.

*A financial year begins in USA on October 1 of the previous calendaristic year, six months before in most other countries.

**Denotes the actual budget recorded at the end of the respective fiscal year.

The US has initiated a multidisciplinary strategy for development of science and engineering fundamentals through the NNI based on a long-term vision (Roco et al., 2000). The Federal Government budget is $774 million in fiscal year 2003, and the request is $849 million for the fiscal year beginning in October 2003. Japan (Yamaguchi & Komiyama, 2001; Government of Japan, 2001), the European Community (EC, 2002) and more recently China (Bai, 2001) have initiated broad programs, and their current plans look up to five years ahead. Other countries, including Korea (Lee, 2002), Taiwan (Lee et al., 2002), Australia (Braach-Maksvytis, 2002), Canada, Eastern Europe, Israel, India, and Singapore have encouraged their own areas of strength, several of them focusing on fields of the potential markets. Their rate of increase in government spending in the last year is higher than the sum of all other three areas (US, Japan, and Western Europe). Differences among countries are observed in the research domain they are aiming for, the level of program integration into various industrial sectors, and in the time scale of their R&D targets (Figure 3).

A slightly different timescale is noted in research activities addressing societal implications (Figure 4). The US has initiated its first workshop and related activities in September 2001. Key meetings on that topic began in EC and APEC (both jointly with National

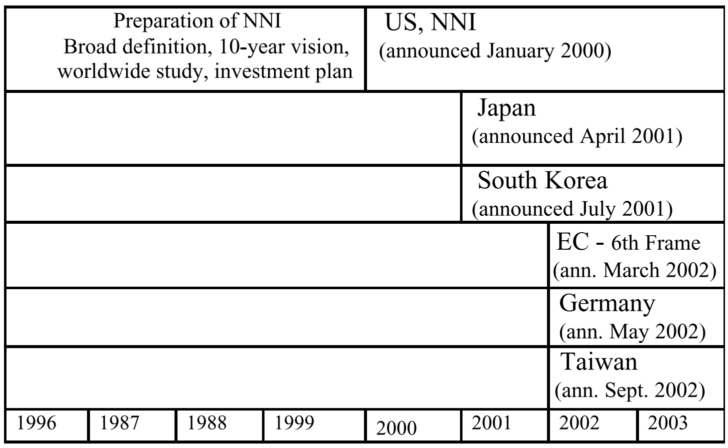

Figure 3. Comprehensive nanotechnology research programs with funding exceeding US $100million/year by national governments or EC, announced after 2000.

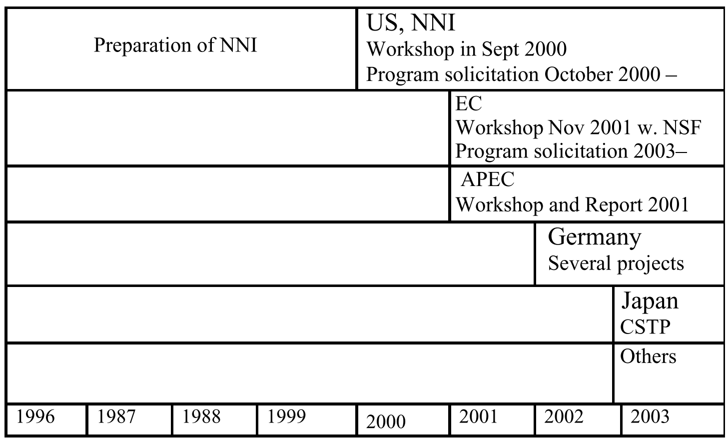

Figure 4. Timeline for beginning of major societal implications studies with funding from national governments or EC.

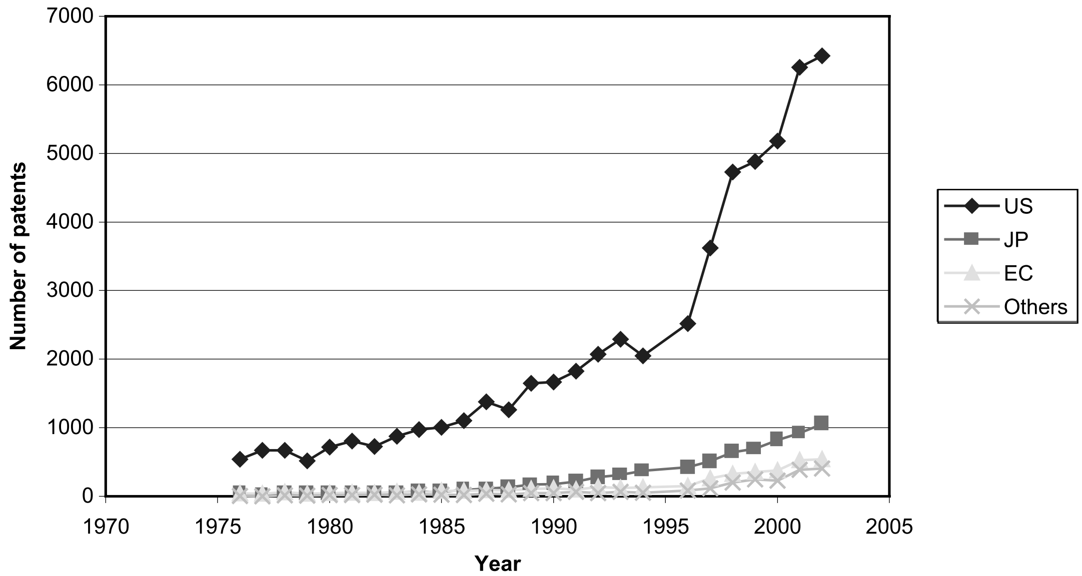

Figure 5. Number of nanotechnology patents per four regions (1976–2002, data of April 2003). The leading ten countries in 2002 are: US – 6425 patents, Japan –1050, France – 245, UK –100, Korea – 87, Taiwan – 86, NL – 66, Australia – 61, Switzerland – 55, Italy – 44. The survey was taken using the USPTO database in April 2003 (Huang et al., 2003).

Table 2. Number of patents per four regions (1976–2002)

Country group	Number of patents (1976–2002)
US	56 828
Japan	7574
Western Europe	4046
Others	2241

Science Foundation (NSF)) in 2001. Germany and Japan are showing an increased interest after 2002 and 2003, respectively.

The research outcomes are not proportional to the investments because of research productivity, various components of the infrastructure, and culture. For example, the timeline of the patents recorded with US Patent and Trade Office (USPTO) is shown in Figure 5, and a comparison of the number of patents per region is given in Table 2. That office receives domestic and foreign applications as being the main target for investors because US provides the largest single market.

Nanotechnology is growing in an environment where international interactions accelerate in science, education, and industrial R&D, while industrial competitiveness issues are surfacing at national and industry consortia levels. Government investments in nanotechnology have jump-started the development of the field, and government activities should equally prepare the societies for the future implications. This paper outlines several R&D activities sponsored by NNI and particularly NSF in order to prepare society for unexpected consequences of nanotechnology.

Evaluating societal implications

Several guiding ideas should be considered when evaluating societal implications.

(a) Societal implications should be judged *using a balanced approach* between the goals (leading to envisioned societal benefits) and unexpected consequences (which could be a combination of unexpected benefits and risks). For example, nanotechnology promises significant advances in drug synthesis and delivery, medical visualization, and tissue regeneration and replacement. At the same time, unwanted nanoparticles may enter cells or nanostructured tissues may not be biocompatible, and the risks need to be investigated. There is a social responsibility on both sides of the development. Democratic principles should be considered when evaluating the positive effects and the risks applied to various sections of the population. For example, nanoscale manufacturing will provide the means for sustainable development: less material, less water, less energy and less waste for manufacturing, and new methods to convert energy and filter water. 'Exact manufacturing' means less waste and pollution. At the same time, one must consider the potential new kind of contaminants at the nanoscale, and dislocation of the workforce of replaced technologies.

(b) Societal implications of nanotechnology *apply in a variety of areas*, including technological, economic, environmental, health, and educational, ethical, moral and philosophical. While technological and economic implications are the key drivers, issues about the unexpected positive and negative consequences of nanotechnology are competing in the other areas.

(c) Nature is already working at the nanoscale. One needs to *understand what is different* when nanostructured contaminants produced by manufacturing or combustion enter the environment. For example, there are current health and environmental risks caused by nanoparticles in mines, on construction sites and from combustion engines. Manufactured nanostructures may have special composition, reactivity, and uniformity that may increase the risks, and this must be investigated from the beginning. At the same time, novel molecular processes can be used to remove existing pollutants that cannot be separated otherwise. Nanoscale sensors might better monitor the environment. Sustainable development is a broader goal. Research activities in the US include nanoparticles in the air, soils, and water, nanoscale processes in bio-environmental systems, development of new tools, and green manufacturing. The risk of not doing nanotechnology R&D would be high.

(d) Each industrial field already has regulations for handling chemicals and biological materials. In nanotechnology studies, one needs to *follow the regulations in the respective system application*, and identify the difference caused by nanostructuring. Nanoscale is a scale with implications on most systems from chemical reactors to biotechnology and mechanical manufacturing sites.

(e) Societal implications have *an international perspective*, such as expanding fundamental knowledge of humanity and its philosophical consequences, development of markets, health concerns, international competition, and production capabilities.

(f) A significant distinction should be made between the effects that can be corrected or reversed to an *acceptable level*, and those that would lead *to unacceptable risks*. There are no conclusive research results that would show that nanotechnology consequences could not be addressed within the existing system applications. Risks are frequently balanced by benefits.

(g) There is *a complex architecture of factors*, from individual creativity, organizations, technology transfer, regional and interdisciplinary interactions to economics, and international framework. These factors are in a dynamic interaction and time scales of interaction must be considered. For instance, one needs anticipatory developments in standards and legal aspects.

(h) *Progressive advancements* will be made in societal implications as the nanotechnology field better defines itself. That is, new nanostructures are created in labs, new products are designed, and the number of qualified researchers is increasing. There is a time delay between first scientific discoveries and studies of their societal implications.

(i) *Understanding the public acceptance of risks* is important, even if concerns are not founded on scientific reasoning. For example, the effect of electromagnetic fields on cells or television radiation would be quite pervasive. However, we find it acceptable because magnetic fields already exist in the natural environment and cells have the capability to react. In a similar manner, nanoparticles already exists in natural environment and living cells routinely interact with them. Social scientists must be involved with the R&D teams in understanding and addressing public concerns.

(j) *Learning from the first industrial revolution* and other previous developments. For examples, the combustion-based engines are leading to global warming and DDT while useful to eradicate malaria has cancerogen effects. We would like to do the next industrial revolution through nanotechnology better, and optimize the entire life cycle of a product earlier. Longitudinal studies on long-time intervals are necessary.

NNI support for societal implications

NNI has considered societal implications from the first year of the initiative, as an integral part of the process. The proceedings of the workshop held in September 2000 (Roco & Bainbridge, 2001) were followed up by various program solicitations and defining a role for the National Nanotechnology Coordinating Office (NNCO) in monitoring potential risks. As a follow-up to the September 2000 report, NSF has made support for social, ethical, and economic research studies a priority by (a) including it as a new theme in the NSF annual program solicitations; (b) contributions in the research and education centers; and (c) a new initiative on the impact of technology and converging technologies form the nanoscale for improving human performance (nano-bio-info-cognition convergence; Roco & Bainbridge, 2002). The NNCO has received the role to communicate with the public and address unexpected consequences. The report has been used as reference for the interaction with the public. The international interest on societal implications lags the R&D interest, as suggested by the timeline shown in Figure 4.

Research on societal and educational implications will increase in importance as novel nanostructures are discovered, new nanotechnology products and services reach the market, and interdisciplinary research groups are established to study them. The NNI annual investment in research with societal and educational implications is estimated at about \$30 million (of which NSF awards about \$23 million), and in nanoscale research with relevance to environment at about \$50 million (of which NSF awards about \$30 million and EPA about \$6 million). Examples of NSF awards are listed in Tables 3 and 4. The total of about \$80 million is approximately 10% of the NNI budget in fiscal year 2003. NSF's Nanotechnology Undergraduate Education program has made about 35 awards in fiscal year 2003, and nanotechnology K-12 education program is planned as a new focus in fiscal year 2004. A balanced and flexible infrastructure is being developed for 2004 by participating agencies. NSF will run two user networks – the National Nanotechnology Infrastructure

Table 3. Examples of NSF awards for nanoscale processes in the environment: Understanding the implications

Topic	University (lead investigator)	Interval
Nanoparticles in the environment, agriculture and technology	UC Davis (A. Novrotski), IGERT	1999–2004
Nanoparticle formation in air pollution	WPI (B.E. Wyslouzil)	2000–2005
Nanoparticle science and engineering	U. of Minnesota (U. Kortshagen), IGERT	2001–2006
Nano-colloids (metals, actinides) in aquatic systems	TAMU (P. Santschi), NIRT; and U. Notre Dame (J.B. Fein, Environmental Molecular Science Institute)	2001–2005
Surface reactivity of nanostructures in environment	UCB (J.F. Banfield), U. Vanderbild (P.T. Cummins), TX Tech University (M.K. Ridley), NIRT	2001–2005
Application of quantum dots to environment and cell biology	Lehigh U. (A.K. Sengupta)	2001–2004
Molecular minerals–microbial interactions in the environment	U. Oklahoma (M. Nanny), (NIRT); U. Virginia (M.F. Hochella)	2001–2005
Biological and environmental nanotechnology	Rice U. (V. Colvin), NSEC	2001–2006

Table 4. Examples of NSF awards for nanoscale processes in the environment: Improving the implications

Topic	University (lead investigator)	Interval
Sequestration of volatile organic nanocompounds in environment	U. Vanderbilt (E.J. Leboeuf), CAREER	2000–2004
Nanoscale photocatalyst for destruction of environmental pollutants	MTU (J.C. Crittenden), NER	2001–2002
Environmental friendly processing of metal oxide suspensions	R.M. Davis, VPI	2001–2003
Nanoscale metal particles: Remediation in groundwater	Lehigh U. (W. Zhang), CAREER	2000–2004
Nanobiosensor using dynamic atomic force microscopy	CMU (J.W. Schneider), NER	2002–2003
Magnetic separation for environmentally benign processing	USC Columbia (J.A. Ritter)	2000–2002
Environmentally responsible solvents	UNC Chapel Hill (J.M. De Simone)	2000–2004

Network (NNIN) and the Network for Computational Nanotechnology (NCN) and eight Nanoscale Science and Engineering Centers (NSEC) and continue support for 13 Materials Research Science and Engineering Centers with research at the nanoscale. DOE has established five large scale user facilities – the Nanoscale Science Research Centers (NSRC) – NASA four nano-bio-info research centers, DOD three centers, and NIH several visualization and instrumentation centers.

Examples of recent projects related to nanoscale processes in the environment, awarded by EPA (2002) and NSF (2002a,b), can be found on the respective websites. Their goals could be separated into 'understanding' and 'improving' nanotechnology implications.

Awards on societal aspects are illustrated in Table 5. These include ethical studies, philosophical aspects, economical, longitudinal tracking, and scenarios. Awards for related educational activities in the US can be found in Roco (2002).

The NSF's Nanoscale Science and Engineering Centers were asked to address societal implications aspects related to their major research and education goals. A list of centers with interest in this area is given in Table 6.

Several public surveys have included nanotechnology only since 2002 (Table 7). The Internet survey performed by Bainbridge (2002) shows high level of enthusiasm for the potential benefits of nanotechnology and relatively little concern about possible risks. In another study, MTU participates at a comparative survey of expectations for various emerging technologies in the US, Europe, and Canada. Preliminary results show that 32% of those questioned in the US and about 54% in Europe 'don't know' about nanotechnology, and of those who know the majority thinks that nanotechnology will improve the quality of life. A recent article underlines the delay of studying societal implications as compared to basic science and engineering research at the international level (Mnyusiwalla et al., 2003).

Two bills for nanotechnology submitted in the current Congress address the need for a coherent, multi-year planning with increased interdisciplinarity and interagency coordination. The Senate bill S189 '21st Century Nanotechnology R&D Act' in the 108th Congress recommends a 5-year 'National Nanotechnology Program'. It was introduced by a group of senators led by Ron Wyden (D-OR) and George Allen (R-VA). The bill in the House, H.R.766 'Nanotechnology Research and Development Act of 2003' was introduced by a group of representatives led by Sherwood Boehlert (R-NY) and was passed in May 2003. It authorizes funding at NSF at $350 million in fiscal year 2004, $385 million in fiscal year 2005, and $424 million in fiscal year 2006. The bill also authorizes lesser amounts for DOE, NASA, NIST, and EPA. Societal goals and R&D were discussed at each of the previous Congressional nanotechnology hearings including one on March 19, and the House Committee

Table 5. Examples of NSF awards on societal implications

Topic	University (lead investigator)	Interval
Ethics and belief inside the development of nanotechnology	University of Virginia (R.W. Berne)	2001 (5-year CAREER award)
Scanning probe microscope: The genesis and practices	Cornell University (M.L. Lynch)	2001 (Dissertation Research award)
Social and ethical dimensions of nanotechnology	University of Virginia (M. Gorman)	2002–2003
Philosophical and social dimensions of nanoscale research: Developing a rational approach to an emerging S&T	University of South Carolina (D. Baird)	2002–2003 and 2003–2007
Courses on societal implications for public	University of Columbia (J. Yardley)	2002–
Shaping science and technology to serve national security (comparative study)	Potomac Institute for Policy Studies (J.J. Richardson)	2002–
From laboratory to society: Developing an informed approach to nanoscale science and technology	University of South Carolina (D.W. Baird, D. Berude, O. Bueno, R. Hughes, G. Khushf)	2003–2007
Science and Commercialization NanoBank, database and analysis	University of California at Los Angeles (L. Zucker, M.R. Darby, R. Doumani, J. Furner, E.L. Hu)	2003–2007
Preliminary study on public opinion, comparative with biotechnology survey	Michigan State University	2003–

Table 6. NNI centers established after 2000 that have nanotechnology education and societal implications research component

Center Name	Institution
NSF	
Nanoscale Systems in Information Technologies, NSEC (Nanoscale Science and Engineering Center)	Cornell University
Nanoscience in Biological and Environmental Engineering, NSEC	Rice University
Integrated Nanopatterning and Detection, NSEC	Northwestern University
Electronic Transport in Molecular Nanostructures, NSEC	Columbia University
Nanoscale Systems and their Device Applications, NSEC	Harvard University
Directed Assembly of Nanostructures, NSEC	Rensselaer Polytechnic Institute
Nanobiotechnology, Science and Technology Center	Cornell University
Network for Computational Nanotechnology	Purdue University, main node
National Nanofabrication Users Network (NNUN)	Cornell University, main node
National Nanotechnology Infrastructure Network (NNIN)	To be established in fiscal year 2004
NASA	
Institute for Cell Mimetic Space Exploration	UCLA
DOE	
Center for Integrated Nanotechnologies	SNL and LANL
Center for Nanophase Materials Sciences	Oak Ridge National Laboratory

Table 7. Workshops and reports on societal and environmental implications

Workshop, conference	Sponsor	Dates
Societal implications of nanoscience and nanotechnology (I)	NSF	September 2000
Nanoparticles in materials and environmental sciences	NSF, EC	September 2000
Converging technologies for improving human performance	NSF, DOC	December 2001
Societal implications of nanotechnology	NSF, EC	January 2002
Nanoparticles and the environment (grantees meeting)	NSF	July 2002
Nanotechnology and the environment applications and implications' (grantees meeting)	EPA	November 2002
Symposium on nanotechnology implications in the environment	ACS	March 2003
Global societal impacts of nanoscience	NSF, EC, Japan	March 2003
Vision for environmental implications and improvement by nanotechnology	NSET, EPA, NSF	May 2003
Interagency grantees meeting	NSET, EPA, NSF, DOE, FDA, NIST	September 2003
Vision for nanobiosystems in biology and medicine	NSET, NIH, NSF, FDA, USDA, others	October 2003
Societal Implications of nanoscience and nanotechnology (II)	NSET, NSF, EPA, NIH, DOD, others	Spring 2004

on Science held a special hearing on this topic on April 9, 2003. It suggested the need to increase funding in this area and to involve social scientists from the beginning in larger NNI projects. A joint Senate-House 'nanotechnology' bill is expected to be passed in 2003.

International context

Enhancing international communication and networking for exchanges of people and ideas, and developing of R&D partnerships in fundamental research, long-term technological challenges, metrology, education, and studies on societal implications will play an important role in creative growth of the field. Nanoscale science and engineering R&D is mostly in a pre-competitive phase. Priority nanoscale science and technology goals may be envisioned for international collaboration: better understanding of nature and life, development of tools for measurement and simulation, single-molecule and single-cell research, increasing productivity in manufacturing, molecular medicine, interdisciplinary education, improving human performance, and sustainable development for materials, water, energy and food. A R&D network to advance sustainable development through nanotechnology is envisioned. The network would use a systematic approach to investigate longitudinally in time the variety of technological, economical, and societal factors.

An appeal is made to researchers and funding organizations worldwide to take timely and responsible advantage of the new technology, to initiate societal implications studies from the beginning of the nanotechnology programs, and to communicate effectively the goals and potential risks with research users and public. By this message, we try to encourage various research and funding communities to raise the recognition of research on societal implications to the level of scientific and engineering topics as agents of change, and involve social scientists and economists in R&D groups. Contacts on societal implications of nanotechnology have been established with the EC, Japan, and other potential partners with whom US has nanotechnology R&D agreements.

Nanotechnology has the long-term potential to bring revolutionary changes in society and harmonize international efforts towards a higher purpose than just advancing a single field of science and technology, or a single geographical region. A global strategy guided by broad societal goals of mutual interest is envisioned.

Acknowledgements

This paper is based on the keynote presentation the Nanotech 2003 Conference in Japan on February 26, 2003. Opinions expressed here are those of the author and do not necessarily represent the position of NSET or NSF.

References

APEC, 2002. Nanotechnology – The Technology for the 21st Century, Bangkok, Thailand.

Braach-Maksvytis V., 2002. Nanotechnology in Australia – towards a national initiative. J. Nanoparticle Res. 4(1–2), 1–7.

Bainbridge W.S., 2002. Public attitudes towards nanotechnology. J. Nanoparticle Res. 4(6), 561–570.

Bai C., 2001. Progress of nanoscience and nanotechnology in China. J. Nanoparticle Res. 3(4), 251–256.

EC, 2002. Sixth R&D Framework, Draft 6, November 2002, Brussels, Thematic Area 3 'Nanotechnology and Advanced Materials', Luxembourg.

EPA, 2002. Proc. nanotechnology and the environment: Applications and implications, Published Feb. 2003, Washington, DC, 83 pp., http://www.nsf.gov/home/crssprgm/nano/GC_ENV_EPA2002_Proc_03-0204.pdf

Government of Japan, 2001. The Science and Technology Basic Plan (for 2001–2006), Tokyo, March 30.

Huang Z., H. Chen, A. Yip, G. Ng, F. Guo, Z.-K. Chen & M.C. Roco, 2003. Longitudinal patent analysis for nanoscale science and engineering: Country, institution and technology field. J. Nanoparticle Res. 5(3–4).

Lee C.K., M.K. Wu & J.C. Yang, 2002. A catalyst to change everything: MEMS/NEMS – a paradigm in Taiwan's nanotechnology. J. Nanoparticle Res. 4(5), 377–386.

Lee J.W., 2002. Overview of nanotechnology in Korea – 10 year blueprint. J. Nanoparticle Res. 4(6), 473–476.

Mnyusiwalla A., A.S. Daar & P.A. Singer, 2003. 'Mind the gap': Science and ethics in nanotechnology. Nanotechnology, 14, R9–13.

NSF, 2002a. Proc. Nanogeoscience workshop, http://www.nsf.gov/home/crssprgm/nano/geo_workshop.pdf

NSF, 2002b. Proc. Nanoscale Science and Engineering Grantees Conference, Arlington, Virginia, http://www-unix.oit.umass.edu/%7Enano/

Roco M.C., 2002. Nanoscale science and engineering educational activities in the US. J. Nanoparticle Res. 4(3), 271–274.

Roco M.C. & W. Bainbridge eds., 2001. Societal implications of nanoscience and nanotechnology. National Science Foundation Report, (also Kluwer Academic Publishers, Boston, 370 pp).

Roco M.C. & R. Tomellini eds., 2002. Nanotechnology revolutionary opportunities and societal implications. European Commission Report, Luxembourg, 205 pp.

Roco M.C., R.S. Williams & P. Alivisatos eds., 1999. 'Nanotechnology research directions'. US National Science and Technology Council, Washington, D.C., (also Kluwer Academic Publishers, Boston, 2000, 316 pp), http://nano.gov

Roco M.C., 2003. National nanotechnology investment in the fiscal year 2004 budget request by the President. AAAS Report 28: R&D in FY 2004, Washington, DC, pp. 255–264, http://nano.gov

Roco M.C. & W.S. Bainbridge eds., 2002. 'Converging technologies for improving human performance', National Science Foundation and Department of Commerce Report, (also Kluwer Academic Publishers, Boston, 2003; http://www.nsf.gov/nano).

Yamaguchi Y. & K. Komiyama, 2001. Structuring knowledge project in nanotechnology: Materials program launched in Japan. J. Nanoparticle Res. 3(2–3), 105–110.