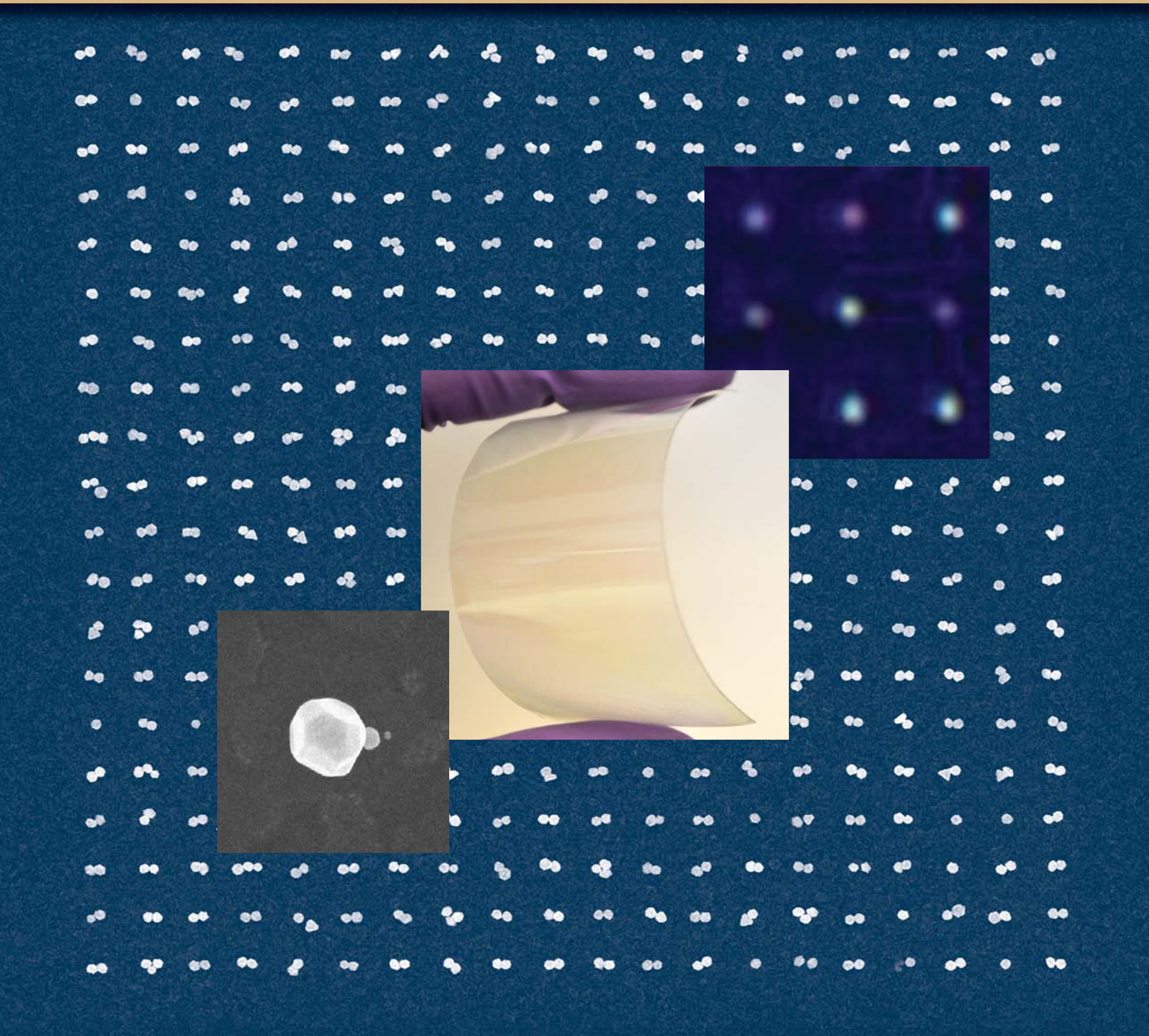
THE NATIONAL NANOTECHNOLOGY INITIATIVE

Supplement to the President's 2016 Budget



About the National Science and Technology Council

The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the Federal research and development enterprise. A primary objective of the NSTC is establishing clear national goals for Federal science and technology investments. The NSTC prepares research and development strategies that are coordinated across Federal agencies to form investment packages aimed at accomplishing multiple national goals. The work of the NSTC is organized under committees that oversee subcommittees and working groups focused on different aspects of science and technology. The National Nanotechnology Initiative (NNI) is managed by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC Committee on Technology. More information is available at www.WhiteHouse.gov/administration/eop/ostp/nstc.

About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976. OSTP's responsibilities include advising the President in policy formulation and budget development on questions in which science and technology are important elements; articulating the President's science and technology policy and programs; and fostering strong partnerships among Federal, state, and local governments, and the scientific communities in industry and academia. The Director of OSTP also serves as Assistant to the President for Science and Technology and manages the NSTC. More information is available at www.ostp.gov.

About this document

This document is a supplement to the President's 2016 Budget request submitted to Congress on February 2, 2015, and serves as the Annual Report for the National Nanotechnology Initiative called for under the provisions of the 21st Century Nanotechnology Research and Development Act of 2003 (Public Law 108-153, 15 U.S.C. §7501). The report also addresses the requirement for Department of Defense reporting on its nanotechnology investments, per 10 U.S.C. §2358. Chapter 1 provides an overview of the NNI, including a discussion of external reviews. Chapter 2 reports actual investments for 2014, estimated investments for 2015, and requested investments for 2016 by NNI Program Component Area (PCA), including investments under the Small Business Innovation Research (SBIR) and Small Business Technology Transfer Research (STTR) programs. Chapter 3 outlines changes in the balance of investments by PCA made by Federal agencies participating in the NNI. Chapter 4 describes activities that have been undertaken and progress that has been made toward achieving the four goals set out in the NNI Strategic Plan of 2014, including activities in support of the NNI Nanotechnology Signature Initiatives. Appendices include a list of abbreviations and acronyms and a contact list of staff members at NNI participating agencies and at the National Nanotechnology Coordination Office (NNCO). Additional information regarding the NNI is available on the NNI website at www.nano.gov.

About the cover

The cover images depict arrays of gold nanoparticle assemblies that were manufactured by a process termed "selective spatial absorption." This technique can be used to fabricate arrays of custom-made nanoparticle heterostructures on a variety of substrates, including flexible polymers (*center picture*). The *background image* features pairs of identical 150 nm-sized gold particles that are about 5 nm apart. The *lower left image* is a close-up of a "heterotrimer" assembly comprised of 250, 80, and 30 nm gold nanoparticles with surface-to-surface separations of 12 and 5 nm, respectively. The *upper right image* is a dark-field micrograph displaying scattering from an array of individual "heterodimers."

The ability to spatially address the localized and enhanced electromagnetic fields within these nanostructures provides the basis for a wide scope of applications for emerging photonic technologies, including quantum computing, solar energy conversion, and optical sensing and communications. Such nanomanufacturing concepts are among the innovations funded under the NNI that will be investigated and scaled up in the Integrated Photonics and Flexible Hybrid Electronics Manufacturing Innovation Institutes. This is also a good example of how technology developed under the NNI is impacting other Presidential priorities such as Advanced Manufacturing. (Images courtesy of Xiaoying Liu and Paul Nealey, University of Chicago, and Sushmita Biswas and Richard Vaia, U.S. Air Force Research Laboratory; see dx.doi.org/10.1021/nl504613q.)

Cover and book design

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Supplement to the President's Budget for Fiscal Year 2016

The National Nanotechnology Initiative

Subcommittee on Nanoscale Science, Engineering, and Technology
Committee on Technology
National Science and Technology Council

March 2015

Report prepared by

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EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
WASHINGTON, D.C. 20502

March 10, 2015

Dear Members of Congress:

I am pleased to forward this annual report on the multiagency National Nanotechnology Initiative (NNI), in the form of the NNI Supplement to the President's Budget for Fiscal Year 2016. This document summarizes the programs and coordinated activities taking place across the many departments, independent agencies, and commissions participating today in the NNI — an initiative that continues to serve as a model for effective coordination of Federal science and technology R&D.

The proposed NNI budget for Fiscal Year 2016 of $1.5 billion will continue to advance our understanding of nanoscale phenomena and our ability to engineer nanoscale devices and systems that address national priorities and global challenges. Nearly half of this budget request is focused on applied R&D and support for the Nanotechnology Signature Initiatives (NSIs), reflecting an increased emphasis on commercialization and technology transfer. The NSIs are multiagency initiatives focusing on priority technology areas selected for rapid advancement through enhanced interagency coordination and collaboration, and this report for the first time highlights their progress made to date. NNI activities also intersect with and support national priorities in other domains, including advanced manufacturing, advanced materials, neurotechnologies, and the recently announced precision medicine initiative and efforts to combat antibiotic resistance.

The proposed budget sustains vital support for fundamental, ground-breaking R&D, infrastructure, and education and training programs that collectively constitute a major U.S. innovation enterprise. Nanotechnology-related environmental, health, and safety activities — hallmarks of the NNI — now account for over 10% of the NNI budget request. Proposed NNI investments in research facilities and infrastructure in 2016 are $240 million, a 4% increase over actual 2014 levels. These investments continue to provide funding for world-class facilities in nanomanufacturing and fabrication, characterization, and testing that support fundamental and applied R&D and commercialization.

Continuing U.S. leadership in innovation will be enabled by nanotechnology and other emerging technologies. Sustained support for the NNI is vital to providing the transformational knowledge and technologies that can benefit society and create the businesses, jobs, and opportunities of the future. Thank you for sharing and supporting that vision.

Sincerely,

John P. Holdren

John P. Holdren
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

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EXECUTIVE SUMMARY

The National Nanotechnology Initiative (NNI), first announced by President Clinton in January 2000, is a partnership of 20 Federal agencies and departments with activities in nanotechnology research and development (R&D), policy, and regulation. Since the inception of the NNI, participating agencies have invested more than $22 billion in funding (including the President's 2016 Budget request[1]) in fundamental and applied nanotechnology R&D; world-class characterization, testing, and fabrication facilities; education and workforce development; and efforts directed at understanding and controlling the environmental, health, and safety (EHS) aspects of nanotechnology.

In 2014, Federal agencies invested a total of $1.57 billion in nanotechnology-related activities. The 2016 request calls for a total investment of $1.50 billion, affirming the Administration's continuing commitment to a robust U.S. nanotechnology effort. Nearly half (43%) of this Budget request is focused on applied R&D and support for the Nanotechnology Signature Initiatives (NSIs), reflecting an increased emphasis within the NNI on commercialization and technology transfer.

The NSIs are multiagency initiatives designed to focus a spotlight on technology areas of national importance that may be more rapidly advanced through enhanced interagency coordination and collaboration. The following are some highlights from each of the five current NSIs:

- *Nanotechnology for Solar Energy Collection and Conversion: Contributing to Energy Solutions for the Future* spans efforts in fundamental and applied research to improve photovoltaic and thermophotovoltaic devices and advance the development of solar fuels. These efforts include research on understanding and characterizing essential processes in photovoltaic materials and devices; low-cost conversion of solar energy to electricity through the development of organic photovoltaic solar cells; and the development of high-efficiency, flexible photovoltaics for use in solar aircraft and portable power applications. Agencies participating in this NSI also support interdisciplinary centers and provide early-stage assistance to startup companies to overcome technological barriers to commercialization.
- *Sustainable Nanomanufacturing: Creating the Industries of the Future* includes efforts focused on the development of robust nanomanufacturing methods for the cost-effective production of nanoscale materials and devices. These efforts include the development and scaled-up production of carbon nanotube bulk materials and their demonstration in lightweight, high-strength composites and lightweight data and power cables. Nanomanufacturing advances also include the development of nanocrystalline alloys for lightweighting vehicles and lightweight, durable ceramics for structural applications. Agencies participating in this NSI, with support from the National Nanotechnology Coordination Office (NNCO), conducted two workshops in 2014 that identified key barriers to broader adoption of carbon nanotubes and cellulose nanomaterials and their commercialization.
- *Nanoelectronics for 2020 and Beyond* is aimed at discovering and using novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures to advance the field of nanoelectronics. Federal agencies participating in this NSI have provided strong support for multidisciplinary university research through two public–private research initiatives in collaboration with the semiconductor industry: the Nanoelectronics Research

[1] All references to years in this document are by fiscal year unless otherwise noted.

Initiative, co-funded by the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST), and the Semiconductor Technology Advanced Research Network (STARnet), supported by the Defense Advanced Research Projects Agency (DARPA). One area of rapidly growing emphasis is the development and application of novel materials for nanoelectronics. Recently initiated efforts in nanophotonics provide the potential for collaboration with other national efforts, such as the recently announced Integrated Photonics Institute for Manufacturing Innovation.

- *Nanotechnology Knowledge Infrastructure (NKI): Enabling Leadership in Sustainable Design* is focused on providing a community-based, solutions-oriented knowledge infrastructure to accelerate nanotechnology discovery and innovation. Agencies participating in this NSI are building upon existing activities, such as the National Institutes of Health (NIH) caNanoLab and the NSF-funded nanoHUB, to facilitate sharing of data and models, respectively, and to promote collaboration. For example, the National Institute for Occupational Safety and Health (NIOSH) is working in 2015 to migrate the GoodNanoGuide to nanoHUB. The GoodNanoGuide is a compilation of data on workplace exposures, experimental evidence, and modeling results on the toxic effects of various nanomaterials and other nanotechnology-related EHS information. Other efforts currently being pursued under this NSI include the development of high-throughput combinatorial methods to probe nanomaterial growth and processing methods, and the development of standard procedures to validate computational techniques developed to predict the properties of engineered nanomaterials.
- *Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety and the Environment* is focused on the utilization of nanotechnology to develop physical, chemical, and biological sensors that have higher sensitivity and selectivity, are more portable, and have lower power demands than conventional sensors. Another focus of this NSI is the development of sensors for the detection of nanomaterials in biological and environmental media. In 2014, agencies participating in this NSI, with support from NNCO, sponsored a workshop to identify key challenges faced by sensor developers and critical needs in standards development, testing and evaluation facilities, and manufacturing. The workshop highlighted the need for broader access to test beds for the evaluation of sensor performance and for fabrication facilities that address the gaps in transitioning from prototypes to large-scale commercial production.

Federal agencies are committed to promoting the transition of nanotechnology-based discoveries from the laboratory to market. In 2013, the Small Business Innovation Research (SBIR) and Small Business Technology Transfer Research (STTR) programs provided more than $85 million to small businesses in nanotechnology R&D and commercialization. NNI agencies promote commercialization and entrepreneurship through such programs as NSF's Innovation Corps (I-Corps), NIH's Translation of Nanotechnology in Cancer (TONIC) consortium, and the Nano-Bio Manufacturing Consortium (NBMC), supported by the Air Force Office of Scientific Research. In 2015, NNCO initiated a series of webinars focused on identifying and addressing problems confronting small- and medium-sized nanotechnology businesses.

Although there is a renewed emphasis for 2014–2016 on activities aimed at promoting accelerated translation of nanotechnologies into commercial products, NNI agencies remain committed to strong and sustained support for fundamental research in nanoscience. Accordingly, the President's Budget requests $512 million for Foundational Research in 2016, or 34% of the total NNI funding. Continued investment in this area is critical to maintaining the pipeline of basic discoveries in nanoscience that will enable future innovations in support of national priorities. Research in this category includes the development of novel nanostructured materials with mechanical, electrical, and other properties not previously possible, which could lead to revolutionary applications such as more fuel-efficient lightweight vehicles, quantum computing, and novel energy conversion and storage devices; modeling and simulation coupled with experimental efforts to develop a better understanding of structure–property relationships of nanostructured materials, making possible true "materials by design" at the molecular and atomic scale; basic studies of biomimetic and chemistry-based self-assembly techniques that could enable future advances in large-scale nanomanufacturing; and studies to improve fundamental understanding of the interactions between nanomaterials and biological systems, which could facilitate future medical applications of nanotechnology as well as enhanced understanding and control of its possible EHS implications.

Proposed NNI investments in research facilities and infrastructure in 2016 are $240 million, a 4% increase over actual 2014 levels. These investments continue to provide funding for world-class facilities in nanomanufacturing and fabrication, characterization, and testing that support fundamental and applied R&D and commercialization. These facilities include five Department of Energy (DOE) Nanoscale Science Research Centers (NSRCs), NIST's Center for Nanoscale Science and Technology (CNST), NSF's National Nanotechnology Infrastructure Network (NNIN), and two state-of-the-art nanomaterial characterization laboratories established by the Food and Drug Administration (FDA). There are also a wide variety of education and training activities ongoing and planned to develop and maintain a skilled workforce for nanotechnology R&D and commercialization. For example, in 2014, NSF, in collaboration with other NNI participating agencies and NNCO, sponsored the Nanoscale Science and Engineering Education (NSEE) Workshop, which identified the need for the establishment of regional NSEE hubs to share educational resources and promote the incorporation of nanotechnology in science, technology, engineering, and mathematics (STEM) education. NNCO is working with the Commonwealth of Virginia, the first state to formally incorporate nanotechnology-based concepts in its K–12 science standards and curricula, to help develop educational content and transition these activities nationwide.

Nanotechnology EHS (nanoEHS) activities have become a hallmark of the NNI, with R&D, policy, and regulation in this area extensively coordinated among Federal agencies. NanoEHS activities, including relevant topics incorporated into the NSIs, account for over 10% of the NNI budget request in 2016. In 2014, the NNI released the *Progress Review on the Coordinated Implementation of the National Nanotechnology Initiative 2011 Environmental, Health, and Safety Research Strategy,*[2] which summarizes the extensive, ongoing collaborations, and recent accomplishments in this area. A key component of the strategy is extensive communication and coordination with academic, industrial, and international nanoEHS communities. Examples of these efforts include the U.S. participation in the European Union (EU) 2014 European Research Area Network (ERA-NET) Safe Implementation of Innovative Nanoscience and Nanotechnology[3] program; the U.S.–EU Communities of Research;[4] collaboration with dedicated multidisciplinary academic centers such as the NSF's Centers for Environmental Implications of Nanotechnology at the University of California, Los Angeles, and Duke University; and strong U.S. participation in the development of nanoEHS-related standards.

[2] www.nano.gov/2014EHSProgressReview

[3] www.siinn.eu/en

[4] www.us-eu.org

1. Introduction and Overview

Overview of the National Nanotechnology Initiative

The National Nanotechnology Initiative (NNI), established in 2001,[5] is a U.S. Government research and development (R&D) initiative involving 20 Federal departments, independent agencies, and commissions[6] working together toward the shared and challenging vision of "*a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society*."[7] The combined, coordinated efforts of these agencies have accelerated discovery, development, and deployment of nanotechnology to benefit agency missions in service of the broader national interest. The Federal agencies participating in the NNI are shown in Table 1; as indicated there, 11 of these report specific budget data for nanotechnology R&D.

The NNI is managed within the framework of the National Science and Technology Council (NSTC), the Cabinet-level council by which the President coordinates science and technology policy across the Federal Government. The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC Committee on Technology (CoT) coordinates planning, budgeting, program implementation, and review of progress for the Initiative. The NSET Subcommittee is composed of representatives from participating agencies and the Executive Office of the President. A listing of official NSET Subcommittee members is provided at the front of this report, and contact information for NSET Subcommittee participants is provided in Appendix B. The National Nanotechnology Coordination Office (NNCO) acts as the primary point of contact for information on the NNI; provides technical and administrative support to the NSET Subcommittee, including the preparation of multiagency planning, budget, and assessment documents; develops, updates, and maintains the NNI website www.nano.gov; provides public outreach on behalf of the NNI; and promotes access to and early application of the technologies, innovations, and expertise derived from NNI activities.

What is Nanotechnology?

Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale.

A nanometer is one-billionth of a meter. A sheet of paper is about 100,000 nanometers thick; a single gold atom is about a third of a nanometer in diameter. Dimensions between approximately 1 and 100 nanometers are known as the nanoscale. Unusual physical, chemical, and biological properties can emerge in materials at the nanoscale. These properties may differ in important ways from the properties of bulk materials and single atoms or molecules.

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[5] General note: In conformance with Office of Management and Budget style, references to years in this report are to fiscal years unless otherwise noted.

[6] Hereafter within this document the Federal departments, independent agencies, and commissions participating in the NNI are referred to collectively as "agencies."

[7] *National Nanotechnology Initiative Strategic Plan* (NSTC, Washington, DC, 2014; www.nano.gov/2014StrategicPlan), p. 5.

Table 1: Federal Departments and Agencies Participating in the NNI
Federal departments and independent agencies and commissions with budgets dedicated to nanotechnology research and development (11)
Consumer Product Safety Commission (CPSC)†
Department of Commerce (DOC)
National Institute of Standards and Technology (NIST)
Department of Defense (DOD)
Department of Energy (DOE)
Department of Health and Human Services (DHHS)
Food and Drug Administration (FDA)
National Institute for Occupational Safety and Health (NIOSH)
National Institutes of Health (NIH)
Department of Homeland Security (DHS)
Department of Transportation (DOT)
Federal Highway Administration (FHWA)
Environmental Protection Agency (EPA)
National Aeronautics and Space Administration (NASA)
National Science Foundation (NSF)
U.S. Department of Agriculture (USDA)
Agricultural Research Service (ARS)
Forest Service (FS)
National Institute of Food and Agriculture (NIFA)
Other participating departments and independent agencies and commissions (9)
Department of Education (DOEd)
Department of the Interior (DOI)
U.S. Geological Survey (USGS)
Department of Justice (DOJ)
National Institute of Justice (NIJ)
Department of Labor (DOL)
Occupational Safety and Health Administration (OSHA)
Department of State (DOS)
Department of the Treasury (DOTreas)
Intelligence Community (IC)
Office of the Director of National Intelligence (ODNI)
National Reconnaissance Office (NRO)
Nuclear Regulatory Commission (NRC)†
U.S. International Trade Commission (USITC)†
Also participating from the Department of Commerce, listed above:
Bureau of Industry and Security (BIS)
Economic Development Administration (EDA)
U.S. Patent and Trademark Office (USPTO)

† Denotes an independent commission that is represented on NSET but is non-voting

The NSET Subcommittee has identified critical issues that will benefit from focused interagency attention and activity, facilitated through the structure afforded by subsidiary working groups and/or direction by coordinators. NSET has therefore established two working groups—the Nanotechnology Environmental and Health Implications (NEHI) Working Group, and the Nanomanufacturing, Industry Liaison, and Innovation (NILI) Working Group—and four coordinators—for global issues; standards development; environmental, health, and safety research; and education, engagement, and societal dimensions. For additional details on these working groups and coordinators, see the Coordination and Assessment section of the 2014 NNI Strategic Plan.[8]

The 2014 NNI Strategic Plan sets out the vision for the NNI stated above and specifies four goals aimed at achieving that overall vision:

1. Advance a world-class nanotechnology research and development program.
2. Foster the transfer of new technologies into products for commercial and public benefit.
3. Develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology.
4. Support responsible development of nanotechnology.

For each of the goals, the strategic plan identifies specific objectives aimed at collectively achieving the NNI vision. Chapter 4 provides details about these objectives and related NNI activities.

As directed by the 21st Century Nanotechnology Research and Development Act,[9] the strategic plan also identifies R&D investment categories. The five Program Component Areas (PCAs), listed below, include research and development activities that contribute to one or more of the NNI goals:

1. Nanotechnology Signature Initiatives.
2. Foundational Research.
3. Nanoscale-Enabled Applications, Devices, and Systems.
4. Research Infrastructure and Instrumentation.
5. Environment, Health, and Safety.

Nanotechnology Signature Initiatives (NSIs) are designed to accelerate innovation in areas of national priority through enhanced interagency coordination and collaboration. The NSI topics for 2014 through 2016 are as follows:

- Nanotechnology for Solar Energy Collection and Conversion: Contributing to Energy Solutions for the Future (Solar NSI).
- Sustainable Nanomanufacturing: Creating the Industries of the Future (Nanomanufacturing NSI).
- Nanoelectronics for 2020 and Beyond (Nanoelectronics NSI).
- Nanotechnology Knowledge Infrastructure (NKI): Enabling National Leadership in Sustainable Design (NKI NSI).
- Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment (Sensors NSI).

The NNI R&D investment is also guided by the 2011 NNI Environmental, Health, and Safety Research Strategy.[10] The strategy supports all four NNI goals but is most closely aligned with NNI Goal 4 and PCA 5.

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[8] *National Nanotechnology Initiative Strategic Plan* (NSTC, Washington, DC, 2014, www.nano.gov/2014StrategicPlan), p. 51.

[9] 21st Century Nanotechnology Research and Development Act (15 U.S.C. §7501(c)(4), P.L. 108-153); www.gpo.gov/fdsys/pkg/PLAW-108publ153/html/PLAW-108publ153.htm.

The NNI funding represents the sum of the nanotechnology-related funds allocated by each of the participating agencies (the "NNI budget crosscut"). Each agency separately determines its budget for nanotechnology R&D in coordination with the Office of Management and Budget (OMB), the Office of Science and Technology Policy (OSTP), and Congress. The NNI agencies participating in the budget crosscut collaborate closely with each other to create an integrated scientific program. This close communication, facilitated through the NSET Subcommittee and its working groups and coordinators, has led to interagency coordination and collaboration in a variety of forms, including sharing of knowledge and expertise; joint sponsorship of solicitations and workshops; and leveraging of funding, staff, and equipment/facility resources at NNI participating agencies. While highlights of these activities are detailed in Chapter 4 by the four goals and their respective objectives, a summary of the activities for each goal (with a focus on the signature initiatives for Goal 1) is provided below.

Goal 1. Advance a World-Class Nanotechnology Research and Development Program

Although there is a renewed emphasis for 2014–2016 on activities aimed at promoting accelerated translation of nanotechnologies into commercial products, NNI agencies remain committed to strong and sustained support for fundamental research in nanoscience. The aim of Goal 1 is to advance nanoscience and nanotechnology by expanding the boundaries of knowledge and by developing technologies through comprehensive and focused R&D. NNI agencies invest at the frontiers and intersections of many disciplines, including biology, chemistry, engineering, materials science, and physics. Progress in R&D depends upon the availability of a skilled workforce, infrastructure, and tools (Goal 3), and lays the foundation for responsible incorporation of nanotechnology into commercial products (Goals 2 and 4).[11] Examples of coordinated activities under Goal 1 include establishing new interagency collaborations in developing 2-D nanoscale materials beyond graphene and their hybrids; scalable manufacturing strategies, characterization tools and methods, and novel devices; validating nanoparticle measurement methods and developing documentary standards; and continuing partnerships with academic and industry players to accelerate progress towards translational success. Overall, the NNI agencies support a wide range of foundational research and other activities advancing Goal 1. The NSIs provide a spotlight on critical areas and define the shared vision of the participating agencies for accelerating the advancement of nanoscale science and technology from research through commercialization. The NSIs (Objective 1.4) are summarized in more detail following the overview of each of the four NNI goals.

Goal 2. Foster the Transfer of New Technologies into Products for Commercial and Public Benefit

The purpose of Goal 2 is to establish processes and resources to facilitate the transfer of nanotechnology research into practical applications and capture its benefits for national security, quality of life, economic development, and job creation. Several enabling factors are necessary to successfully commercialize any new technology. Scalable, repeatable, cost-effective, and high-precision manufacturing methods are required to move a technology from the laboratory into commercial products. Investments by both the public and private sectors are needed to shepherd technologies to maturity. As for any technology, maximizing the benefits of nanotechnology developments to the U.S. economy requires efforts to remove barriers to global commercialization, an understanding of the potential markets for a given product, and

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[10] *National Nanotechnology Initiative Environmental, Health, and Safety Research Strategy* (NSTC, Washington, DC, 2011; www.nano.gov/2011EHSStrategy).

[11] See Table 4 in the *National Nanotechnology Initiative Strategic Plan* (NSTC, Washington, DC, 2014, www.nano.gov/2014StrategicPlan), p. 49.

appropriate protection of intellectual property. Similarly, nanotechnology research, development, and commercialization also require access to and retention of a skilled workforce. Goal 2 encompasses four objectives that detail how the NNI will focus its resources and broaden its engagement with academia, industry, and the international community to reach this goal. [12]

The NNI member agencies also have a number of activities uniquely targeting technology transfer and commercialization, for example, workshops to obtain input from industry and academia, Small Business Innovation Research (SBIR) and Small Business Technology Transfer Research (STTR) programs to fund innovations in small businesses, and cutting-edge research infrastructure for use by all nanotechnology researchers, including those in industry.

In addition to the agency activities, the NNCO Director and Deputy Director and NNCO's dedicated industrial liaison staff member conduct outreach activities to engage with and learn from the commercial sector. This outreach includes participation in meetings and symposia to establish and maintain connections to the business and technical communities and site visits to gather information concerning nanotechnology commercialization and share public information about the NNI with the private sector. Additionally, the NNCO industrial liaison staff member conducts 15–20 outreach calls per month with companies to keep abreast of developments and concerns. During these calls, key private-sector concerns such as funding, partnerships, intellectual property, and the regulatory environment are discussed and tracked and then conveyed to the NNI agencies.

In calendar year 2015, NNCO will conduct a series of webcasts focused on identifying challenges faced by companies in the commercialization of nanotechnology and providing information to help address some of these challenges.[13] NNCO is also co-sponsoring, together with NNI agencies and the U.S. Patent and Trademark Office (USPTO), a series of nanotechnology technical seminars to broaden the knowledge base of patent examiners and to enhance the technical community's understanding of the patent examination process.

Goal 3. Develop and Sustain Educational Resources, a Skilled Workforce, and a Dynamic Infrastructure and Toolset to Advance Nanotechnology

A strong infrastructure is fundamental to the successful development of nanotechnology. A substantial investment, strengthened by interagency cooperation and collaboration through the NNI, is required to develop the talent and facilities necessary to achieve the complementary NNI goals of advancing a world-class R&D program (Goal 1), fostering the transfer of new technologies into products for commercial and public benefit (Goal 2), and supporting responsible development of nanotechnology (Goal 4). This goal encompasses three objectives that detail how the NNI will responsibly engage and educate the public and the workforce regarding the opportunities that nanotechnology offers and the skills it requires, along with providing the needed access to advanced facilities and tools.

Education is among the chief objectives of NNI-funded university research, especially at the graduate level. Specific programs target K–16 education, improve nanotechnology curricula in U.S. schools and universities, and educate the public about nanotechnology. In addition to agency programs, the NNI website www.nano.gov provides extensive introductory information and links to educational resources for students and teachers, training and degree programs, and job opportunities. In December 2014, a

[12] For the full descriptions of the objectives of this NNI goal, see the 2014 National Nanotechnology Initiative Strategic Plan, www.nano.gov/2014StrategicPlan or www.nano.gov/about-nni/what/vision-goals.

[13] www.nano.gov/SMEwebinars2015

Nanoscale Science and Engineering Education (NSEE) Workshop (sponsored by NSF with participation from NNCO and NNI agencies)[14] brought together international experts to discuss the state of the art in NSE education and available resources for six educational sectors: (1) informal, (2) K–12, (3) community/technical, (4) undergraduate, (5) graduate, and (6) continuing. One of the key aspects of this meeting was an open exhibition of NSEE materials (including instrumentation, teaching tools, lesson plans, demonstration kits, etc.). These educational resources will be cataloged in the appendix of the workshop report, and access will be promoted through www.nano.gov.

As nanotechnology continues to mature and the commercialization of nanomaterials, devices, and systems expands, the need for a trained, highly skilled workforce grows. Community colleges across the country are developing programs to support this increasing need, often in collaboration with local industry. More information about these programs, including the Nanotechnology Applications and Career Knowledge (NACK) Network, can be found at www.nano.gov/education-training-workforce. NNCO is also engaged in efforts funded by the U.S. Department of Labor to develop descriptions of emerging occupations in nanotechnology, such as engineers, technicians, and technologists. This information will be included in the O*NET (Occupational Information Network) online database and will be available, along with information from the Bureau of Labor Statistics and other occupational sources, at onetonline.org, which can also be found at www.nano.gov/education-training-workforce.

The Commonwealth of Virginia has incorporated nanotechnology into its K–12 science standards, which will help promote nanoscience literacy for its citizens. As Virginia implements these standards, NNCO is working closely with the Virginia Department of Education to facilitate access to existing resources and provide technical guidance as required. Educational resources and lessons learned will be made available nationwide to assist other states as they develop or expand their nanotechnology-related education offerings.

The continued transition of nanotechnology research into products emphasizes the need to engage and inform all segments of the public to help them understand the basic principles of nanoscale science and engineering and the benefits and risks of nanotechnology. This knowledge will enable the public to better understand and assess the opportunities and potential impacts presented by nanotechnology. The NNI partners with public and private organizations to create informal educational materials that institutions across the country can use to engage with their local communities. For example, NanoDays,[15] a nationwide, week-long festival of educational programs about nanoscale science and engineering coordinated by the Nanoscale Informal Science Education Network (NISE Net), now takes place annually at over 250 sites. Outreach also takes the form of public lectures, science cafes, and development of print and video content.

The required toolkit for nanotechnology research and development includes access to specialized physical infrastructure such as instrumentation for fabrication and characterization, as well as access to models, simulations, and data. The NNI continues to support the cyber and physical infrastructure for nanotechnology through its extensive network of research centers and user facilities. The NNI also leverages activities of other Federal programs such as the Materials Genome Initiative (MGI), the National Robotics Initiative (NRI), and the National Network for Manufacturing Innovation (NNMI).

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[14] nseeducation.org/2014

[15] www.nisenet.org/nanodays

Goal 4. Support Responsible Development of Nanotechnology

Well-coordinated nanotechnology-based environmental, health, and safety (nanoEHS) research is essential to ensure a future in which responsible development of nanotechnology provides maximum benefit to the environment and to human social and economic well-being. These efforts are pivotal in contributing to American innovation, advanced manufacturing, and economic competitiveness. Progress in nanoEHS research, as well as in developing a robust understanding of the ethical, legal, and societal implications (ELSI) of nanotechnology, is vital to establishing the regulatory certainty and public confidence needed for companies to bring their nanotechnology products to market, and to ensuring that these products are safe and sustainable throughout their life cycles.

The NSET Subcommittee's NEHI Working Group is a forum for focused interagency collaboration on nanoEHS and ELSI. It provides leadership in establishing the national nanotechnology EHS research agenda, in addition to communicating EHS information among NNI agencies and to the broader stakeholder community. The combined efforts of the nanotechnology R&D community, public health advocacy groups, and the public are required to fully address EHS research priorities and strengthen the scientific foundation of risk assessment and risk management of nanotechnology. The NEHI Working Group, the NNI EHS Coordinator, and NNCO, as appropriate, support interactions between agencies and these diverse communities. The sum of these interactions and activities enhances the value of NNI efforts and provides a collaborative approach to examining public health and environmental concerns about nanomaterials. These efforts are guided by the 2011 NNI EHS Research Strategy.[16]

In 2014, the NEHI Working Group developed a nanoEHS progress review as part of the NNI's continuous process of monitoring the Federal Government's progress in nanoEHS science. This report, *Progress Review on the Coordinated Implementation of the National Nanotechnology Initiative 2011 Environmental, Health, and Safety Research Strategy*,[17] documents the extensive, ongoing coordination and cooperation among the NNI agencies, as well as the breadth and depth of recent nanoEHS and ELSI research activities in support of the responsible development of nanotechnology.

Goal 4 is also advanced by activities within the Sensors, NKI, and Nanomanufacturing NSIs, as well as activities supported by the NNI coordinators for global implications and standards development. Ongoing communication and coordination among these many efforts are critical and are facilitated by the structure of the NNI and NNCO. Examples of these efforts include the U.S.–EU Communities of Research (CoRs),[18] U.S. participation in the European Union's 2014 ERA-NET Safe Implementation of Innovative Nanoscience and Nanotechnology (SIINN)[19] activity, collaboration with dedicated multidisciplinary academic centers such as the Centers for Environmental Implications of Nanotechnology at the University of California, Los Angeles (UCLA) and Duke University, and the coordination of nanoEHS-related standards among various organizations (e.g., the Organisation for Economic Co-operation and Development, the American Society for Testing and Materials, and the International Organization for Standardization). Additionally, the nano.gov website provides an FAQ page for businesses[20] to help them understand EHS and other regulatory issues important in developing and marketing their nanotechnology-enabled products and services. The NNI participating agencies and the NNCO will continue to engage with the stakeholder

[16] *National Nanotechnology Initiative Environmental, Health, and Safety Research Strategy* (NSTC, Washington, DC, 2011; www.nano.gov/2011EHSStrategy).

[17] www.nano.gov/2014EHSProgressReview

[18] www.us-eu.org

[19] www.siinn.eu/en

[20] www.nano.gov/bizfaqs

community to establish a broad EHS knowledge base in support of regulatory decision making and responsible development of nanotechnology.

Overview of the Nanotechnology Signature Initiatives

In support of the President's priorities and innovation strategy, the Federal agencies participating in the NNI have identified focused areas of national importance that may be more rapidly advanced through enhanced interagency coordination and collaboration. The NSIs provide a spotlight on critical areas and define the shared vision of the participating agencies for accelerating the advancement of nanoscale science and technology from research through commercialization. By combining the expertise, capabilities, and resources of appropriate Federal agencies, the NSIs accelerate research, development, or insertion, and overcome challenges to application of nanotechnology-enabled products. Each contributing agency is committed to coordinating research to achieve the expected outcomes defined in the NSI white papers in order to avoid duplication of effort and maximize the return on the Nation's research investments. While called out as Objective 1.4 of Goal 1, the focused goals and outcomes of each signature initiative were developed in the context of all four foundational NNI goals and across several PCAs. An overview of each NSI is provided below; additional details can be found in Chapter 4.

Nanotechnology for Solar Energy Collection and Conversion Signature Initiative

Solar energy is a promising alternative energy source that can mitigate global climate change, reduce dependence on foreign oil, improve the economy, and protect the environment. The Solar NSI[21] was launched in 2010 based upon the realization that the levelized cost of energy (LCOE) of solar technology was not yet economically competitive with conventional fossil fuel technologies. The white paper for this initiative[22] identified new innovations and fundamental breakthroughs that are expected to overcome the limits of existing technologies and help accelerate the development of economically viable solar energy technologies. The goals of the Solar NSI are to enhance understanding of conversion and storage phenomena at the nanoscale; improve nanoscale materials, characterization, and properties for solar technology; and help enable economical nanomanufacturing of robust devices.

The spotlight provided by the formation of the Solar NSI has brought together representatives from the participating agencies to address strategically important technical areas identified in the 2010 white paper. The enhanced cross-agency communication has led to heightened knowledge of ongoing and planned activities within the agencies, allowing for greater leveraging of resources through mechanisms such as collaborative programs. Individual agency-funded or mission-specific programs have also benefited from improved awareness of complementary activities at other agencies and have been developed in the context of broader Federal activities.

Industry engagement is critical to ultimately realizing the potential of solar energy. By working together to involve industry in workshops, as well as research and development efforts, participating agencies better understand what is necessary to translate laboratory advances into market applications. These collaborative agency–industry endeavors are accelerating the widespread implementation of scientific breakthroughs and have helped ensure that the results of research and development projects supported by participating agencies can be efficiently transitioned into commercial applications.

[21] www.nano.gov/NSISolar

[22] www.nano.gov/sites/default/files/pub_resource/nnisiginitsolarenergyfinaljuly2010.pdf

Although DOE is the natural hub for many of this NSI's activities, significant efforts have been leveraged across the participating agencies through extensive collaboration, including cooperative research within the national laboratories, interagency review panels, and jointly funded research programs.

One example of a Solar NSI participant supporting the evolution of an R&D breakthrough to large-scale manufacturing is the Intelligence Community (IC). In this example, the IC supported the transition of quantum dot solar cell technology to a major manufacturer of commercial solar cells. This technology is essential to achieving up to 35% efficiency in space-based solar cells and greater than 40% efficiency in terrestrial solar cells. It is expected to provide up to a 23% increase in available power for U.S. satellites. Another example is the development of a nanoparticle-based material for solar thermal energy applications that is designed to absorb and convert to heat more than 90% of the sunlight that it captures; this project is funded under the DOE SunShot Initiative.

The formation of the Solar NSI has provided a valuable spotlight on critical scientific challenges facing solar technologies and on the programs within the participating agencies that address these issues. The NSI has also brought together representatives from the participating agencies, thereby seeding a community of interest composed of researchers and program managers across the Federal Government and the federally funded research community. The research activities and interagency collaborations in these important areas will continue even as the NSI spotlight transitions to new high-priority areas for the NNI.

Sustainable Nanomanufacturing Signature Initiative

Nanomanufacturing involves the scaled-up, reliable, cost-effective, and responsible production of nanoscale materials, structures, devices, and systems. An important long-term vision for nanomanufacturing has been the ability to create flexible, "bottom-up" or "top-down/bottom-up" continuous assembly methods. To address this vision, the Nanomanufacturing NSI[23] was launched in 2010 to establish manufacturing technologies for economical and sustainable integration of nanoscale building blocks into complex, large-scale systems.

NNI agencies have worked together to advance scientific understanding and strengthen the community in support of the Nanomanufacturing NSI, including the outcomes envisioned in the areas of carbon-based and cellulose nanomaterials. Public–private consortia have formed around each of these materials to accelerate the development of commercial products. Efforts supporting the advancement of carbon-based materials include a project under the Defense Production Act Title III[24] Program, Advanced Carbon Nanotube (CNT) Volume Production, which is providing infrastructure for the world's first industrial-scale manufacturing facility producing CNT yarn, sheet, tape, and slurry materials. Further, the agencies, with support from the NNCO, recently organized a technical interchange meeting on Realizing the Promise of Carbon Nanotubes: Challenges, Opportunities, and the Pathway to Commercialization.[25] The objectives of the meeting were to identify, discuss, and report on technical barriers to the production of CNT-based materials with electrical and mechanical properties approaching values of individual CNTs, and to explore ways to overcome these barriers. The meeting gathered some of the Nation's leading experts in CNT R&D, as well as executives and experts from the Federal Government, academia, and private sector. The meeting report will highlight the key challenges in large-scale production of CNT materials to help focus a coordinated effort to commercialize CNT-based technologies.

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[23] www.nano.gov/NSINanomanufacturing

[24] www.dpatitle3.com/Title_III%202012%20Brochure.pdf

[25] www.nano.gov/2014CNTTechInterchange

Cellulosic nanomaterials are biorenewable, naturally occurring structural building blocks that hold great promise for many new and improved commercial products. Collaboration efforts within the Nanomanufacturing NSI have identified intramural and extramural Federal research activities that span diverse application areas including substrates for flexible electronics or sensors, transparent high-strength composites and films, wound dressings, and packaging. These efforts are enabled by the availability of material from two pilot production plants at the USDA Forest Products Laboratory and at the University of Maine. Public–private partnerships have been formed to focus on the research and development of these materials and products that will exploit their novel properties. In support of the signature initiative, a wide range of experts representing industry, academia, and government were brought together at a workshop entitled Cellulose Nanomaterials: A Path Towards Commercialization[26] in an effort to strengthen cross-sector partnerships and ensure that future research, development, and deployment efforts are informed by market needs. The workshop generated market-driven input in three areas: opportunities for commercialization; barriers to commercialization; and research and development roles and priorities.[27] Issues identified by participants included the need for more data on materials properties, performance, and environmental, health, and safety implications, and the need for a more aggressive U.S. response to opportunities for advancing and developing cellulose nanomaterials. These outcomes will inform future directions of the cellulose nanomaterial activities of the signature initiative.

Many other nanomanufacturing efforts supported by NNI agencies, including active engagement with industry to ensure responsible development, are highlighted in Chapter 4.

Nanoelectronics for 2020 and Beyond Signature Initiative

Continuing to shrink the dimensions of electronic devices is necessary to further increase processor speed, reduce device switching energy, increase system functionality, and reduce manufacturing cost per bit. However, as the dimensions of critical elements of devices approach atomic size, quantum tunneling and other quantum effects degrade and ultimately prohibit the operations of conventional devices. Recognizing this challenge, the Nanoelectronics NSI[28] was launched in 2010 to discover and use novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures.

There are broad efforts across the Federal Government, including strong collaboration with academia and industry, to address the five thrust areas identified in the Nanoelectronics NSI: (1) exploring new or alternative "state variables" for computing; (2) merging nanophotonics with nanoelectronics; (3) exploring carbon-based nanoelectronics; (4) exploiting nanoscale processes and phenomena for quantum information science; and (5) developing a national nanoelectronics research and manufacturing infrastructure network.

For example, the Nanoelectronics Research Initiative (NRI) is a public–private partnership to collaboratively prioritize and fund university research for the semiconductor industry.[29] NRI, a subsidiary of the Semiconductor Research Corporation, leverages expertise and resources from industry (the Semiconductor Industry Association and 2014 NRI member companies GLOBALFOUNDRIES, IBM, Intel Corporation, Micron Technology, and Texas Instruments), Federal agencies (NIST and NSF), and State governments (Nebraska, New York, and Texas). NRI supports long-range research toward the discovery of the fundamental building

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[26] www.nano.gov/ncworkshop

[27] www.fpl.fs.fed.us/documnts/pdf2014/usforestservice_nih_2014_cellulose_nano_workshop_report.pdf.

[28] www.nano.gov/NSINanoelectronics

[29] www.src.org/program/nri

blocks for tomorrow's nanoscale electronics—new devices and circuit architectures for computing—that are viewed as essential to continuing advances in performance of information technology. A key aspect of this program is the close connection between NRI member companies and the student researchers who will become the innovators and leaders of tomorrow's technology industry.

Although current Federal contributions to the NRI are from NIST and NSF, other agencies participating in the Nanoelectronics NSI are engaged with this activity and benefit from the technical advancements made through this targeted research program. Beyond the interagency communication under the signature initiative, NRI has granted representatives from several agencies Government Observer status to better enable information sharing and access to research progress. Representatives from many agencies also participate in the annual NRI review meeting, further strengthening the community and information sharing across the many programs that support the goals of the NSI.

Further, the Semiconductor Technology Advanced Research Network (STARnet) Program,[30] which leverages resources from industry (Semiconductor Industry Association and 2014 member companies Applied Materials, GLOBALFOUNDRIES, IBM, Intel Corporation, Micron Technology, Raytheon, Texas Instruments, and United Technologies) and the Defense Advanced Research Projects Agency (DARPA), continues to explore devices and approaches that may transcend the end of the scaled transistor, including other applications for new devices to realize new types of circuits with advantages and functionalities that are not possible with conventional technologies. The NRI and STARnet communities are closely tied and engage together in benchmarking activities.

Many other efforts and programs across the Government support the goals of the Nanoelectronics NSI. For example, the Integrated Photonics Institute for Manufacturing Innovation,[31] which is focused on developing an end-to-end photonics "ecosystem" in the United States—including domestic foundry access, integrated design tools, automated packaging, assembly and test, and workforce development—will likely advance the merging of nanophotonics with nanoelectronics. Federal and academic characterization and fabrication facilities remain a key enabling resource for the advancement of nanoelectronics. Strong and continuous communication among the agency representatives and within the broader community is critical to optimize the use of resources and accelerate technology development and deployment.

Nanotechnology Knowledge Infrastructure Signature Initiative

Nanotechnology has the ability to solve global challenges by generating and applying new multidisciplinary knowledge of nanoscale phenomena and engineered nanoscale materials, structures, and products. Data underlying this new knowledge are vast, disconnected, and challenging to integrate into the broad scientific body of knowledge. The NKI NSI[32] was initiated in 2012 to leverage and extend existing and emerging resources, programs, and technologies to support the broader goals of the NNI by creating an infrastructure to accelerate the vetting of new knowledge and to enable effective data utilization. The goal of this initiative is to coordinate the nanoscale science, engineering, and technology communities around the fundamental, interconnected elements of collaborative modeling, a cyber-toolbox, and data infrastructure that will capitalize on American strengths in innovation, shorten the time from research to new product development, and maintain U.S. leadership in sustainable design of engineered nanomaterials.

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[30] www.src.org/program/starnet

[31] manufacturing.gov/ip-imi.html

[32] www.nano.gov/NSINKI

Agencies participating in the NKI NSI recognize that the development of a robust and functional informatics infrastructure will require broad communication and collaboration among the various nanotechnology communities. As such, the participating agencies engage, leverage resources, and collaborate with vibrant groups from the nanoinformatics community—including the National Cancer Institute (NCI) National Cancer Informatics Program (NCIP) Nanotechnology Working Group, the European NanoSafety Cluster's Databases Working Group, and the U.S.–EU nanoEHS Communities of Research—to build and manage the nanotechnology knowledge infrastructure. Agencies participating in the NKI NSI have engaged with the nanoinformatics community by organizing and participating in a wide range of relevant events, such as an NSI-hosted symposium at the TechConnect World Innovation Conference, a Town Hall Meeting on the National and International Materials Data Infrastructure at the Materials Science and Technology 2014 conference in collaboration with the Materials Genome Initiative, and the 2013 U.S.–EU: Bridging NanoEHS Research Efforts joint workshop. NSI participants are also on the steering committee of the Nanoinformatics 2015 workshop, held in January 2015.

The NKI NSI is working with NNI-funded collaborators to examine data sharing needs and mechanisms within the research enterprise. A critical component of sharing data among researchers and technology developers is a common nomenclature for describing and understanding the maturity and quality of the data. Toward this goal, representatives from the collaborating agencies developed a Data Readiness Levels (DRLs) discussion document in 2013.[33] Analogous to Technology Readiness Levels, the DRLs provide a shorthand method for conveying coarse assessments of data from experiments or model predictions for use in improving analytical methods and validating or calibrating models, and for comparisons with legacy datasets. That draft document was intended to engage the broader community regarding key issues critical to achieve the NKI NSI's goals. An online forum, launched in 2014, provides a public venue to discuss these concepts.[34]

Nanotechnology for Sensors and Sensors for Nanotechnology Signature Initiative

Nanotechnology-enabled sensors (nanosensors) are providing new solutions in physical, chemical, and biological sensing that enable increased detection sensitivity, specificity, multiplexing capability, and portability for a wide variety of health, safety, and environmental assessments. The Sensors NSI[35] addresses both the opportunity of using nanotechnology to advance sensor development and the challenges of developing sensors to keep pace with the increasingly widespread use of engineered nanomaterials.

NNI agencies participating in the Sensors NSI coordinate efforts and stimulate existing and emerging projects to explore the use of nanotechnology for the development and commercialization of nanosensors. Agency representatives hold periodic teleconferences to address pressing technical questions and keep each other informed of ongoing and planned activities of mutual interest. These regular exchanges have led to tangible results such as revised solicitations based on the knowledge of other agencies' priorities, needs, and plans; cross-agency participation in review of proposals and grantee meetings; and the identification of collaborators for specific project needs. In addition, the ongoing research dialogues inform agency members of opportunities for collaboration in the formulation of both agency-specific and joint funding announcements that support the overall goals of the initiative.

An important priority remains engaging with stakeholders to identify the barriers they face in the development and commercialization of nanosensors. The Sensors NSI serves as a focal point for relevant

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[33] www.nano.gov/node/1015

[34] nciphub.org/groups/drldiscussionforum

[35] www.nano.gov/NSISensors

stakeholder communities and the public to address opportunities and barriers through the Request for Information (RFI) mechanism, town hall discussions, and community meetings. Common themes continue to be identified through these inputs and interactions. For example, the needs for improved stakeholder awareness, communication, and collaboration at the convergence of testing and operational standards, and for access to test and fabrication facilities, have been particularly highlighted in the stakeholder interaction activities of the Sensors NSI.[36]

With support from NNCO, the feedback from the aforementioned community-building efforts was used in the planning for the Sensor Fabrication, Integration, and Commercialization Workshop held September 10–11, 2014.[37] This event focused on identifying key challenges faced by sensor developers and on determining the critical needs of the community, especially with respect to necessary standards, testing facilities, and advances in manufacturing. Several key outcomes from this workshop will inform the path forward for the signature initiative. One area discussed was the critical need to access test conditions beyond standard laboratory environments. Realistic test beds are essential for the relevant and reliable transition of prototype sensors from research to commercial use. Sensor developers also expressed the need for access to fabrication facilities beyond the prototype stage, but prior to large-scale production, to demonstrate performance characteristics, reproducibility, and other measures required for adoption. Support for enhanced communication and a desire to share best practices were also strongly expressed by the community. In response to this and other feedback, the Sensors NSI page[38] has been revised to more effectively serve as a portal for information and guidance to the nanosensor development community regarding sensor fabrication and test facilities, funding opportunities, regulatory information, standards, and other relevant resources. The Sensors NSI will continue to work and engage with community leaders to improve this portal and explore opportunities and forums to facilitate communication and collaboration in the quest to accelerate sensor development.

External Reviews of the NNI

The 21st Century Nanotechnology Research and Development Act (Public Law 108-153) calls for periodic external reviews of the NNI by the National Research Council (NRC) of the National Academies[39] and by the National Nanotechnology Advisory Panel (NNAP).[40] The most recent reviews of the NNI by the NRC were issued in 2013 and are addressed in the *NNI Supplement to the President's 2015 Budget*.[41]

Executive Order 13539 designates the President's Council of Advisors on Science and Technology (PCAST) to serve as the NNAP. In that capacity, PCAST published a report reviewing the NNI in October 2014 entitled *Report to the President and Congress on the Fifth Assessment of the National Nanotechnology Initiative*.[42] The findings of the report include the following:

- The NNI has been a truly successful venture for the past 13 years, and the nanotechnology community has built strong foundations for the future. The sustained funding for the NNI to date

[36] federalregister.gov/a/2013-23916

[37] www.nano.gov/2014SensorsWorkshop

[38] www.nano.gov/NSISensors

[39] 15 U.S.C. §7504.

[40] 15 U.S.C. §7503.

[41] www.nano.gov/2015BudgetSupplement

[42] www.WhiteHouse.gov/sites/default/files/microsites/ostp/PCAST/pcast_fifth_nni_review_oct2014_final.pdf

has delivered significant scientific and technological progress, and continued innovation calls for a healthy research effort to continue.

- International competition for leadership in nanotechnology has increased on many fronts; while the United States remains preeminent in nanotechnology research, it has fallen behind other countries in developing the necessary infrastructure and workforce required to manufacture many nanotechnology-based products.
- The nanotechnology field is at a critical transition point and has entered a second era, which PCAST calls "NNI 2.0." This era will see the evolution from nanoscale components to interdisciplinary nanosystems and the movement from a foundational research-based initiative to one that also provides the necessary focus to ensure rapid commercialization of nanotechnology.
- A "primary conclusion" is that the United States will only be able to claim the rewards that come from investing in nanotechnology research and sustaining an overarching Federal initiative if the Federal interagency process, the Office of Science and Technology Policy (OSTP), and the NNI participating agencies transition their nanotechnology programmatic efforts beyond supporting and reporting on basic and applied research and toward building program, coordination, and leadership frameworks for translating the technologies into commercial products.

In order to address these findings, the report includes 12 recommendations to the NNI participating agencies, the NSET Subcommittee, and OSTP under five major headings: (1) Grand Challenges for NNI 2.0, (2) Program Management, (3) Commercialization, (4) Research Enterprise, and (5) Environmental, Health, and Safety. These recommendations are succinctly summarized on pages 5–7 of the PCAST/NNAP report. The NSET Subcommittee is in the process of carefully considering each of these recommendations and developing an action plan to address them.

2. NNI Investments

Budget Summary

The President's 2016 Budget provides $1.5 billion for the National Nanotechnology Initiative (NNI), a continued investment in support of the President's priorities and innovation strategy. Cumulatively totaling more than $22 billion since the inception of the NNI in 2001 (including the 2016 request), this support reflects nanotechnology's potential to significantly improve our fundamental understanding and control of matter at the nanoscale and to translate that knowledge into solutions for critical national needs. NNI research efforts are guided by two strategic documents developed by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council (NSTC), the 2014 NNI Strategic Plan[43] and the 2011 NNI Environmental, Health, and Safety Research Strategy.[44] These strategic documents guide how NNI agencies address the full range of nanotechnology research and development, technology transfer and product commercialization, infrastructure, and education, as well as the societal issues that accompany an emerging technology. The NNI investments in 2014 and 2015 and those proposed for 2016 reflect a renewed emphasis on accelerating the transition from basic R&D to innovations that support national priorities, while also maintaining a strong foundation of broad, fundamental research in nanoscience that provides a continuing pipeline of new discoveries that will enable future revolutionary applications.

The 2016 Budget is the second in which the funding for nanotechnology at the NNI participating agencies is being reported under the revised Program Component Areas (PCAs), or budget categories, outlined in the 2014 NNI Strategic Plan. Although the updated PCAs do not reflect a change in the overall scope of the Initiative, direct comparisons should not be made between spending figures by PCA for 2013–2016 and previous years, with the exception of PCA 5 (Environment, Health, and Safety), which remains unchanged between the old and new PCA categories.

As outlined in the 2016 OMB/OSTP R&D Priorities Memo,[45] nanotechnology is among the key enablers for advanced manufacturing and for industries of the future. It is also critical to progress in most of the other multiagency priority areas called out in that memo, including clean energy, information technology, national and homeland security, and innovation in life sciences, biology, and neuroscience. The Nanotechnology Signature Initiatives (NSIs, PCA 1; see the list of NSIs on page 9), which are targeted at a number of national priorities, therefore are a key investment category for the NNI in 2016, as are the investments in PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems).

The President's 2016 Budget supports nanoscale science, engineering, and technology R&D at 11 agencies. Federal organizations with the largest investments are:

- DHHS/NIH (nanotechnology-based biomedical research at the intersection of life and physical sciences).
- NSF (fundamental research and education across all disciplines of science and engineering).

[43] www.nano.gov/2014StrategicPlan

[44] www.nano.gov/2011EHSStrategy

[45] www.WhiteHouse.gov/sites/default/files/omb/memoranda/2014/m-14-11.pdf

- DOE (fundamental and applied research providing a basis for new and improved energy technologies).
- DOD (science and engineering research advancing defense and dual-use capabilities).
- DOC/NIST (fundamental research and development of measurement and fabrication tools, analytical methodologies, metrology, and standards for nanotechnology).

Other agencies and agency components investing in mission-related nanotechnology research are DHS, DHHS/FDA, EPA, NASA, USDA/NIFA, DHHS/NIOSH, USDA/FS, CPSC, USDA/ARS, and DOT/FHWA.[46]

Table 2 presents NNI investments for 2014 through 2016 for Federal agencies with budgets and investments for nanotechnology R&D, including funding for the NSIs. Tables 3–5 list the investments by agency and by PCA for 2014 through 2016, respectively. Table 6 shows the NNI investments within Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs for 2009 through 2013. Figure 1 shows NNI funding by agency over time since the inception of the NNI in 2001. Figure 2 shows the breakdown of funding by PCA in the 2016 Budget.

Table 2: NNI Budget, by Agency, 2014–2016
(dollars in millions)

Agency	2014 Actual	2015 Estimated*	2016 Proposed
CPSC	2.0	2.0	7.0
DHS**	25.0	28.4	17.0
DOC/NIST	97.8	83.6	86.3
DOD	189.6	141.7	130.4
DOE***	309.4	329.7	342.2
DOT/FHWA	2.1	1.5	1.5
EPA	15.5	15.1	15.3
DHHS (total)	430.3	437.8	448.6
FDA	9.3	15.8	14.6
NIH	410.0	411.0	423.0
NIOSH	11.0	11.0	11.0
NASA	22.4	19.1	15.8
NSF	464.5	413.4	416.4
USDA (total)	15.6	15.6	14.8
ARS	2.0	3.0	3.0
FS	5.6	4.6	4.5
NIFA	8.0	8.0	7.3
TOTAL****	**1574.3**	**1487.8**	**1495.3**

* 2015 numbers are based on 2015 enacted levels and may shift as operating plans are finalized.

** As of the date the 2016 Budget was released, final 2015 appropriations for DHS were not yet enacted. Therefore, the 2015 column of this table reflects amounts requested for the Department of Homeland Security in the 2015 Budget.

*** Funding levels for DOE include the combined budgets of the Office of Science, the Office of Energy Efficiency and Renewable Energy (EERE), the Office of Fossil Energy, and the Advanced Research Projects Agency for Energy (ARPA-E).

**** In Tables 2–6, totals may not add, due to rounding.

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[46] See Table 1 or Appendix A for explanations of the agency abbreviations used on this page and throughout the remainder of this report.

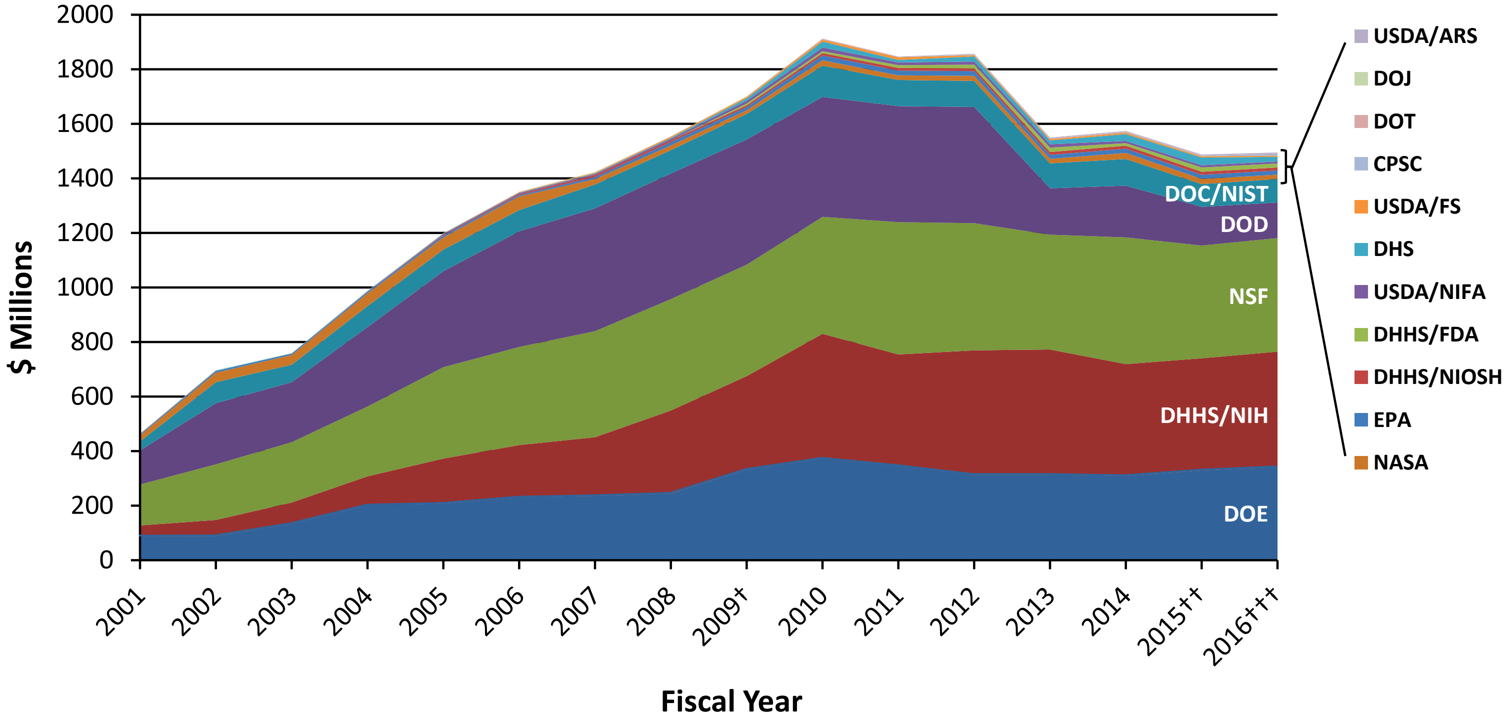

Figure 1. NNI Funding by Agency, 2001–2016.

† 2009 figures do not include American Recovery and Reinvestment Act funds for DOE ($293 million), NSF ($101 million), NIST ($43 million), and NIH ($73 million).

†† 2015 estimated based on 2015 enacted levels and may shift as operating plans are finalized.

††† 2016 Budget.

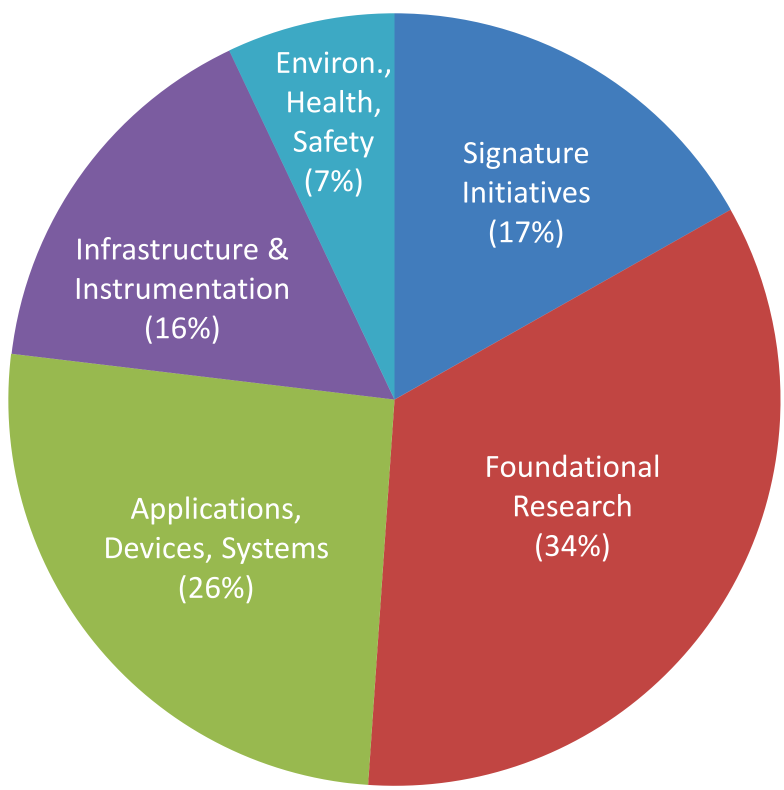

Figure 2. Breakout of NNI Funding by Program Component Area in the 2016 Budget.

Table 3: Actual 2014 Agency Investments by Program Component Area (dollars in millions)											
Agency	**1. Nanotechnology Signature Initiatives (NSIs)***	1a. Solar Energy	1b. Nanomanufacturing	1c. Nanoelectronics	1d. NKI	1e. Sensors	**2. Foundational Research**	**3. Nanotechnology-Enabled Applications, Devices, and Systems**	**4. Research Infrastructure and Instrumentation**	**5. Environment, Health, and Safety**	**NNI Total**
CPSC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.0
DHS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	25.0
DOC/NIST	29.2	3.3	5.6	17.3	1.0	2.1	15.3	8.7	39.5	5.1	97.8
DOD	52.0	2.6	2.3	25.7	2.5	18.9	86.6	33.6	2.3	15.1	189.6
DOE	40.3	36.8	0.0	0.0	0.0	3.5	130.3	28.9	109.8	0.0	309.4
DOT/FHWA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	2.1
EPA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.5	15.5
DHHS (total)	15.0	0.0	1.0	0.0	1.0	13.0	92.0	257.0	24.0	42.3	430.3
FDA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.3	9.3
NIH	15.0	0.0	1.0	0.0	1.0	13.0	92.0	257.0	24.0	22.0	410.0
NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.0	11.0
NASA	8.6	0.5	5.9	0.2	0.1	1.9	8.8	4.6	0.4	0.0	22.4
NSF	122.5	29.5	30.7	34.4	11.3	16.6	212.2	54.9	53.5	21.5	464.5
USDA (total)	5.2	0.4	1.8	1.0	0.0	2.0	3.7	4.0	2.1	0.6	15.6
ARS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	2.0
FS	2.2	0.0	1.2	1.0	0.0	0.0	2.2	0.0	1.2	0.0	5.6
NIFA	3.0	0.4	0.6	0.0	0.0	2.0	1.5	2.0	0.9	0.6	8.0
TOTAL	**272.8**	73.2	47.2	78.6	15.9	58.0	**548.9**	**418.8**	**231.6**	**102.1**	**1574.3**

* Abbreviated titles for the Nanotechnology Signature Initiatives are used in Tables 3–5. See Chapter 1, p. 9, for full NSI titles.

Key Points about the 2014–2016 NNI Investments

- Total 2014 actual NNI investments ($1.57 billion) reported in this document increased slightly (1.6%) from 2013 actual investments (and increased 2.4% over 2014 estimated investments) previously published in the NNI Supplement to the President's 2015 Budget.[47] This indicates an overall pattern of sustained investment in the NNI. NSF, DOD, and NIST report significant increases from 2013 actual levels (10.4%, 11.5%, and 7.1%, respectively). These increases reflect the importance of nanotechnology to these agencies' missions and the success of nanotechnology research proposals in competing for funding within the agencies' core programs.
- Total NNI requested investments in the President's 2016 Budget are slightly less than the 2014 actual investments (a 5% reduction). However, such comparisons should be viewed with caution because many agencies (e.g., NSF, DOD, and NIST) do not necessarily categorize requested funding in their core research programs as "nanotechnology," but subsequently find that research actually funded under those programs does fall into that category—hence their requests tend to be less than their later reporting of actual funding. As indicated in the bullet above, for those agencies more valid comparisons can be made from year-to-year actual funding.

[47] www.nano.gov/2015BudgetSupplement

Table 4: Estimated 2015 Agency Investments by Program Component Area
(dollars in millions)

Agency	1. Nanotechnology Signature Initiatives (NSIs)*	1a. Solar Energy	1b. Nanomanufacturing	1c. Nanoelectronics	1d. NKI	1e. Sensors	2. Foundational Research	3. Nanotechnology-Enabled Applications, Devices, and Systems	4. Research Infrastructure and Instrumentation	5. Environment, Health, and Safety	NNI Total
CPSC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.0
DHS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.4	0.0	0.0	28.4
DOC/NIST	24.4	3.1	6.1	11.5	1.3	2.4	11.3	5.0	36.2	6.7	83.6
DOD	38.6	2.3	0.8	22.6	1.5	11.4	74.9	23.5	1.6	3.1	141.7
DOE	43.7	38.2	0.0	0.0	0.0	5.5	135.6	22.8	127.5	0.0	329.7
DOT/FHWA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	1.5
EPA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.1	15.1
DHHS (total)	15.0	0.0	1.0	0.0	1.0	13.0	92.0	258.0	24.0	48.8	437.8
FDA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.8	15.8
NIH	15.0	0.0	1.0	0.0	1.0	13.0	92.0	258.0	24.0	22.0	411.0
NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.0	11.0
NASA	6.1	0.0	4.0	0.3	0.0	1.8	6.3	6.7	0.0	0.0	19.1
NSF	114.6	27.7	23.4	37.0	19.0	7.5	186.8	45.0	44.5	22.5	413.4
USDA (total)	4.2	0.4	1.8	0.0	0.0	2.0	3.7	5.0	1.9	0.8	15.6
ARS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	3.0
FS	1.2	0.0	1.2	0.0	0.0	0.0	2.2	0.0	1.2	0.0	4.6
NIFA	3.0	0.4	0.6	0.0	0.0	2.0	1.5	2.0	0.7	0.8	8.0
TOTAL	**246.5**	71.7	37.1	71.4	22.8	43.6	**510.6**	**395.9**	**235.8**	**98.9**	**1487.8**

- Several NNI participating agencies (e.g., DOE, NIH, FDA, and CPSC) are requesting significant increases in their 2016 nanotechnology investments compared to 2014, reflecting plans to initiate, increase, or continue dedicated nanotechnology R&D activities or other programs that are known to include significant nanotechnology components.
- The combined investments for PCA 1 (Nanotechnology Signature Initiatives) and PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems) is over 42% of the total NNI investments in 2014–2016. This shows the renewed emphasis within the NNI on activities aimed at promoting accelerated translation of nanotechnologies into commercial products and is consistent with the 2014 PCAST recommendation to strengthen NNI efforts in those areas.
- Total investments in Nanotechnology Signature Initiatives (PCA 1) have grown since their inception, from approximately $246 million in 2011[48] to $273 million in 2014 actual expenditures. Although the requested PCA 1 investments for 2016 are slightly lower than the 2014 actual levels, these figures may change when agencies later evaluate their actual 2016 investments. Overall, NSI investments are sustained at over $240 million in 2014–2016, or over 16% of the NNI total.

[48] www.nano.gov/2013BudgetSupplement

Table 5: Proposed 2016 Agency Investments by Program Component Area (dollars in millions)											
Agency	**1. Nanotechnology Signature Initiatives (NSIs)***	1a. Solar Energy	1b. Nanomanufacturing	1c. Nanoelectronics	1d. NKI	1e. Sensors	**2. Foundational Research**	**3. Nanotechnology-Enabled Applications, Devices, and Systems**	**4. Research Infrastructure and Instrumentation**	**5. Environment, Health, and Safety**	**NNI Total**
CPSC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	7.0
DHS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0	0.0	0.0	17.0
DOC/NIST	26.4	3.4	6.8	12.0	1.8	2.4	11.8	5.0	36.5	6.7	86.3
DOD	31.1	2.0	0.7	23.8	1.8	2.8	68.7	25.9	0.0	4.7	130.4
DOE	51.2	43.7	3.0	0.0	0.0	4.5	140.7	17.1	133.2	0.0	342.2
DOT/FHWA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	1.5
EPA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.3	15.3
DHHS (total)	16.0	0.0	1.0	0.0	1.0	14.0	95.0	264.0	25.0	48.6	448.6
FDA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.6	14.6
NIH	16.0	0.0	1.0	0.0	1.0	14.0	95.0	264.0	25.0	23.0	423.0
NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.0	11.0
NASA	4.0	0.0	2.7	0.0	0.0	1.3	5.7	6.1	0.0	0.0	15.8
NSF	118.1	27.7	26.4	37.5	19.0	7.5	187.0	44.2	44.6	22.5	416.4
USDA (total)	4.8	0.3	2.0	0.5	0.0	2.0	3.5	5.0	0.9	0.6	14.8
ARS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	3.0
FS	2.0	0.0	1.5	0.5	0.0	0.0	2.0	0.0	0.5	0.0	4.5
NIFA	2.8	0.3	0.5	0.0	0.0	2.0	1.5	2.0	0.4	0.6	7.3
TOTAL	**251.5**	77.0	42.6	73.8	23.6	34.5	**512.4**	**385.8**	**240.2**	**105.4**	**1495.3**

- PCA 5 (Environment, Health, and Safety) investments for 2014–2016 stand at about $100 million per year, and have risen from under 3% of the total NNI investment in 2005 to 7% in the 2016 request. Cumulative EHS investments from 2006 through 2015 have now reached nearly $1 billion.[49]
- PCA 2 (Foundational Research) constitutes over a third of the total NNI investment portfolio for 2014 through 2016. The NNI agencies continue to view this PCA as a critical investment category: nanoscale science and technology enables and intersects with most of the scientific and engineering disciplines that these agencies are supporting through their research programs, and foundational research will enable future innovations in support of national priorities.
- Investments in PCA 4 (Research Infrastructure and Instrumentation) are growing steadily, increasing from $212 million to $232 million (or over 9%) between 2013 and 2014 actual spending levels, and continuing to grow to over $240 million in the 2016 Budget (or another 4% increase over 2014). Between 2013 and 2016, the PCA 4 investments have grown from 13.7% of total NNI spending to 16.1%. These figures demonstrate the NNI participating agencies' commitment to sustaining and building on the NNI infrastructure investments of the past decade.

[49] nanodashboard.nano.gov

- The Department of Health and Human Services accounts for the largest portion of the total NNI investment in 2015–2016, reflecting progress in the development of potentially revolutionary nanomedicine applications at NIH and a strong and sustained EHS research program at FDA, NIOSH, and NIH's National Institute of Environmental Health Sciences. The DHHS percentage of the NNI total investment has grown from 9% at the inception of the Initiative in 2001 to 30% in 2016.
- The Consumer Product Safety Commission is proposing to more than triple its nanotechnology investments for 2016 compared to previous years. CPSC's plans for this increased investment are outlined in Chapters 3 and 4 of this report and reflect its leadership role in the overall NNI EHS investment portfolio, as well as its extensive engagement with other agencies participating in the NNI.
- Nanotechnology investments at mission agencies (e.g., DOD, DHS, USDA, and NASA) fluctuate from year to year as specific programs are initiated, reach fruition, and then sunset.
- As in several recent years, NNI agencies are also actively participating in and contributing to other complementary and synergistic Administration R&D priorities, including the Networking and Information Technology Research and Development (NITRD) Program, the Materials Genome Initiative (MGI), Advanced Manufacturing, and the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative. Nanoscale science and technology is related to, enables, or is enabled by each of these other priority topics in various ways, and NNI investments may overlap with investments reported for each of them. NNI agency representatives and NNCO staff continue to explore opportunities to take full advantage of these synergies.
- Investments in SBIR and STTR funding by the participating agencies, reported outside of the formal NNI funding crosscut as tabulated in the budget tables shown above, play a critical role in transitioning nanotechnology innovations into products for commercial and public benefit (NNI Goal 2), as discussed below.

Utilization of SBIR and STTR Programs to Advance Nanotechnology

As called for by the 21st Century Nanotechnology Research and Development Act, this report includes information on the use of the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs in support of nanotechnology development. Five NNI agencies—DOD, NSF, NIH, DOE, and NASA—have both SBIR and STTR programs. In addition, NIOSH, EPA, USDA, and NIST have SBIR programs. Table 6 shows agency funding for SBIR and STTR awards for nanotechnology R&D from 2009 through 2013 (the latest year for which data are available).

Some NNI agencies (e.g., NSF and NIH) have included nanotechnology-specific topics in their SBIR and STTR solicitations. The NSF SBIR program has an ongoing nanotechnology topic included within its advanced materials, manufacturing, electronics, and biotechnology solicitations. Some agencies have had topical or applications-oriented solicitations for which many awardees have proposed nanotechnology-based innovations. SBIR/STTR data for 2004 through 2013 indicate that the NNI agencies have funded over $900 million of nanotechnology-related SBIR and STTR awards. A complete listing by year (including data from 2004 through 2008) can be found at a download link in the Overview section of nanodashboard.nano.gov.

Table 6: 2009–2013 Agency SBIR and STTR Awards (dollars in millions)															
	2009			**2010**			**2011**			**2012**			**2013**		
Agency	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**	**SBIR**	**STTR**	**Total**
DOD	19.3	3.9	23.2	32.2	10.4	42.6	16.2	5.6	21.8	25.4	7.6	33.0	22.6	5.5	28.1
NSF	13.2	7.0	20.2	25.2	3.9	29.2	13.2	1.3	14.5	18.0	2.5	20.5	17.9	0.9	18.9
DHHS/NIH	23.0	3.7	26.7	21.7	1.6	23.2	22.6	1.5	24.1	21.7	3.9	25.6	22.9	1.9	24.8
DHHS/NIOSH	0.7	0.0	0.7	0.0	0.0	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
DOE*	31.9	5.7	37.6	19.4	4.4	23.8	4.7	1.1	5.8	7.8	1.7	9.5	3.9	2.3	6.2
NASA	15.0	1.7	16.7	11.6	2.1	13.7	12.1	3.7	15.8	17.0	3.9	20.8	5.7	1.3	7.1
EPA	0.7	0.0	0.7	0.4	0.0	0.4	0.9	0.0	0.9	0.7	0.0	0.7	0.5	0.0	0.5
USDA**	0.5	0.0	0.5	0.0	0.0	0.0	1.0	0.0	1.0	0.5	0.0	0.5	0.1	0.0	0.1
DOC/NIST	0.4	0.0	0.4	0.2	0.0	0.2	0.3	0.0	0.3	0.4	0.0	0.4	0.6	0.0	0.6
TOTAL	**104.6**	**22.0**	**126.6**	**110.6**	**22.4**	**133.0**	**71.2**	**13.2**	**84.4**	**91.4**	**19.6**	**111.0**	**74.2**	**11.9**	**86.1**

* A significant portion of SBIR/STTR funding reported by DOE for 2009 and 2010 came from the American Recovery and Reinvestment Act (ARRA) of 2009.

** SBIR/STTR award levels for USDA include FS.

3. Changes in Balance of Investments by Program Component Area

The 21st Century Nanotechnology Research and Development Act calls for this report to address changes in the balance of investments by NNI member agencies among the Program Component Areas (PCAs). These investment changes are summarized in this chapter for those member agencies with specific budgets for nanotechnology.

CPSC: CPSC is reporting nanotechnology investments for 2014 through 2016 in PCA 5 (Environment, Health, and Safety). The 2016 request is higher than previous years to support anticipated activities in this area (see Chapter 4 for examples of research activities). The CPSC staff has continued to develop interagency agreements with a number of Federal agencies to understand the use of nanomaterials in consumer products, the mechanisms that impact the release of nanomaterials, and robust methods to quantify and characterize exposures to consumers. Research from agreements developed in previous fiscal years has resulted in publications in peer-reviewed scientific journals that outline methods and approaches for product testing. Some of these projects involved graduate students and postdoctoral fellows, thus contributing to the development of scientists with expertise in EHS research. In 2014, CPSC established 6 interagency agreements with several agencies, including DOD, NIST, NIOSH, and NSF. In 2015, the CPSC staff will continue to develop collaborative efforts with Federal agencies to address EHS implications for nanomaterials in products, and to develop methods that will assist stakeholders in addressing nanomaterial implications.

DHS: The Department of Homeland Security is reporting investments for 2014 through 2016 in PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems). See DHS text in Chapter 4 (Individual Agency Contributions to Objective 1.1) for details.

DOD: Overall DOD 2016 investment levels and distribution by PCA are expected to remain fairly constant compared to 2015, although with changes in some individual programs. The basic thrusts of the constituent DOD agencies are described below.[50]

- DOD/Army: There are no significant changes in level of investment or PCA balance.
- DOD/Navy: The President's 2016 Budget request for the Office of Naval Research (ONR) and Naval Research Laboratory (NRL) will continue to support research in nanotechnology. Classification of 2015 and 2016 investments highlights a focus on PCA 2 (Foundational Research) and PCA 3 (Nanotechnology-Enabled Applications, Devices and Systems), with overall levels of 3% in PCA 1 (NSIs), 66% in PCA 2, 29% in PCA 3, and 2% in PCA 4 (Research Infrastructure and Instrumentation). Minor redistribution of investments across the PCAs has occurred due to the refinement of PCAs from 2013 to 2015, but the relative balance across PCAs from 2015–2016 is relatively unchanged. 2016 Budget requests will maintain focus on Foundational Research and Nanotechnology-Enabled Applications, Devices and Systems in support of defense applications. There was a rise in the reported numbers for 2014 actuals due to a $4 million Congressional increase in budget that had not yet been allocated at the time of last year's report.

[50] Department of Defense is providing additional details in this document per the statutory requirement for DOD reporting on its nanotechnology investments (10 U.S.C. §2358).

- DOD/Air Force: There are no significant changes in the Air Force Office of Scientific Research (AFOSR) nanotechnology investments by PCA that are focused in basic research or in "performers," which include universities, the Air Force Research Laboratory (AFRL), and industrial laboratories utilizing individual investigator programs, international initiatives, the Multidisciplinary University Research Initiative (MURI), Defense University Research Instrumentation Program (DURIP), and Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. AFRL Materials and Manufacturing Directorate (AFRL/RX) nanotechnology investments also remain steady, although with adjustments in the NSIs (PCA 1) to add contributions to the Nanotechnology Knowledge Infrastructure (NKI) NSI and to move the reporting of work in the Nanoelectronics NSI to Nanotechnology-Enabled Applications, Devices, and Systems (PCA 3).
- DOD/DARPA: The 2016 Budget request will continue to support research in nanotechnology across three key PCAs: PCA 1 (Nanotechnology Signature Initiatives); PCA 2 (Foundational Research); and PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems). Compared with 2014 levels, the funding in 2015 increased the total budget for PCA 1 by 9%, which reflects an increase of $1.6 million in the Sensors NSI associated with planned program funding adjustments in the Basic Photon Science and Enabling Quantum Technologies Programs. At the same time, the 2016 request includes a decrease of 96% for the Sensors NSI that reflects a decrease of $18.1 million in funding for Basic Photon Science and Enabling Quantum Technologies, primarily due to the completion of the Quantum-Assisted Sensing and Readout (QuASAR) program in 2015. Compared with 2014 levels, the 2015 reduction in funding request of $0.15 million for PCA 2 (Foundational Research) reflects the planned completion of the Physics in Biology program, and the funding for the DOD–industry–university Semiconductor Technology Advanced Research Network (STARnet) remains balanced at $2.0 million from 2014 to 2016. Compared with 2014 levels, the 2015 reduction in the funding request of $6.5 million for PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems) reflects the planned completion of the Mesodynamic Architectures (Meso) Program.
- DOD/DTRA: The Defense Threat Reduction Agency's (DTRA) Basic and Applied Sciences program continues to support the NNI through targeted research that seeks exploration of novel materials and material production processes relevant to the counter-WMD (weapons of mass destruction) mission. Classification of 2014 and 2015 investments highlight a focus on PCA 2 (Foundational Research). Minimal changes are anticipated in the overall investment for nanotechnology projects in 2016.

DOE: No significant changes are expected in the balance of DOE investments by PCA in 2016.

DOT/FHWA: The agency's current and planned investment is in PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems). FHWA's investment seeks to leverage developments in nanotechnology by focusing them on transportation applications such as corrosion protection, lightweight structural and multifunctional materials, and *in situ* and onboard sensing and communications devices.

EPA: The EPA 2016 Budget request continues EPA's strong support for research in nanotechnology. The investment balance of EPA is unchanged from last year and remains aligned with PCA 5 (Environment, Health, and Safety). This research evaluates the chemical and physical properties of engineered nanomaterials that influence their potential for release into the environment; fate, transport, and transformation; and potential for exposure and adverse effects to humans or sensitive ecological species. Although EPA research aligns primarily within PCA 5, the agency maintains collaborative relationships with other Federal partners in other program areas.

FDA: FDA primarily invests in PCA 5 (Environment, Health, and Safety) to develop methods, validate models, and generate data, which enables the agency to evaluate the safety and efficacy of products containing nanomaterials or involving the use of nanotechnology. Investments in PCA 5 for 2014 decreased from the 2013 level due to project delays; however, investments in PCA 5 are projected to remain roughly at the 2013 level for 2015 and 2016.

NASA: NASA support for nanotechnology R&D has focused mainly on PCA 1 (NSIs), PCA 2 (Foundational Research), and PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems). Nanotechnology R&D has been supported primarily by the Aeronautics Research Mission Directorate (PCA 3) and the Space Technology Mission Directorate (PCAs 1, 2, and 3). Research investments in PCA 3 are higher in 2016 compared to 2014 levels.

NIH: Currently NIH invests over $400 million annually in nanotechnology initiatives that consist of a number of projects/programs funded through several intramural and extramural laboratory activities across the Nation. In 2015 and 2016, the majority of investments in nanotechnology are expected to support both new and existing investigator-initiated projects aimed at novel R&D in PCA 2 (Foundational Research), PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems), PCA 5 (Environment, Health and Safety), and PCA 1 (under the Sensors and NKI NSIs). In addition, a significant change in the four major NIH nanotechnology programs will occur in 2016 due to the changes that occurred in 2014 to the funding of the NIH Common Fund Nanomedicine Initiative and the proposed changes to current initiatives within the NIH/NCI Alliance for Nanotechnology in Cancer. However, these adjustments of research support within the development pipeline are not expected to significantly change the balance of investments by PCA for 2016. For example, the overall level of funding for the Alliance is expected to decrease in 2016, as the network of Centers of Cancer Nanotechnology Excellence reduces its number of centers from 9 to an expected 5–6 as the next phase of the Alliance begins in 2015. Some of the Nanomedicine Initiative projects are also being supported by individual NIH institutes whose missions align with the network's goals.

NIOSH: All NIOSH support for nanotechnology R&D continues to be reported under PCA 5 (Environment, Health, and Safety). NIOSH will increase its support for researchers at academic institutions in 2016 as a mechanism for accelerating key areas of investigation. In 2016, NIOSH will extend its efforts in nanotechnology along the natural technology development pathway into Advanced Manufacturing and will provide direct support to the EHS needs of the emerging National Network for Manufacturing Innovation. A critical focus area beginning in 2015 and increasing in 2016 will be the development and implementation of engineering control strategies and solutions that mitigate worker exposures to nanomaterials, resulting in reduced potential risk and more efficient nanomanufacturing processes. Given anticipated market growth, NIOSH will increase its investment in providing relevant guidance for high-volume materials such as titania and carbon nanotubes; developing prospective guidance for emerging materials such as cellulose nanocrystals and graphene; closing knowledge gaps for high-profile materials such as nanosilver; and evaluating the EHS needs created by next-generation active nanomaterials. A key area of research that will increase in 2016 will be to conduct hazard assessment employing *in vitro* and *in vivo* models of exposure–response relationships.

For 2016, the NIOSH investment will focus in the five strategic areas described in the NIOSH Nanotechnology Research and Guidance Strategic Plan:[51]

[51] www.cdc.gov/niosh/docs/2014-106/pdfs/2014-106.pdf

- Increase understanding of new hazards and related health risks to nanomaterial workers.
- Expand understanding of the initial hazard findings of engineered nanomaterials.
- Support the creation of guidance materials to inform nanomaterial workers, employers, health professionals, regulatory agencies, and decision makers about hazards, risks, and risk management approaches.
- Support epidemiologic studies for nanomaterial workers, including medical, cross-sectional, prospective cohort, and exposure studies.
- Assess and promote national and international adherence with risk management guidance.

NIST: NIST's intramural research laboratories, user facilities, and services work at the cutting edge of science and technology to ensure that U.S. companies, as well as the broader science and engineering communities, have the nanoscale measurements, data, and technologies to further innovation and industrial competitiveness in nanotechnology areas. The 2016 Budget request continues NIST's strong support for research in nanotechnology and sustains investments in all of the PCAs. NIST continues to participate in each of the NSIs (PCA 1), with significant efforts in the Nanoelectronics and Nanomanufacturing NSIs. The largest investment in nanotechnology continues to be in PCA 4, for major research facilities and instrumentation investments in the Center for Nanoscale Science and Technology user facility as well as across the NIST laboratories in areas that underpin nanotechnology-related measurement capabilities central to the NIST metrology mission.

NSF: NSF supports nanoscale science and engineering (NSE) throughout all of its research and education directorates as a means to advance discovery and innovation and integrate various fields of research. The NNI enables increased interdisciplinarity through research at atomic and molecular levels for about 5,000 active awards with full or partial content related to NSE. An increased focus is on support of convergence research and education activities in confluence with other priority areas in programs such as Science, Engineering, and Education for Sustainability/Sustainable Chemistry, Engineering and Materials (SusChEM); Research at the Interface of Biological, Mathematical and Physical Sciences, and Engineering (BioMaPS); and Cyber-Enabled Materials, Manufacturing, and Smart Systems (CEMMSS), which includes Designing Materials to Revolutionize and Engineer our Future (DMREF), and Understanding the Brain. NSF's Directorates for Mathematical and Physical Sciences (MPS), Engineering (ENG), and Computer and Information Science and Engineering (CISE) will support additional nanotechnology emphasis in the areas of optics and photonics in 2016. NSF activity that supports the Materials Genome Initiative and BioMaPS has significant NSE components.

The NSF 2015 enacted investments reflect an 11% decrease as compared to the 2014 actuals. The decrease is caused in part by the results of the peer review of unsolicited proposals—moving a fraction of projects into programs more related to their areas of relevance—and by co-funding made available by other NNI agencies. Part of the NSF investments under PCA 3 (Nanoscale-Enabled Applications, Devices, and Systems) will be dedicated to research on breakthrough materials and advanced manufacturing as part of the NSF-wide CEMMSS investment framework.

Additional Nanosystems Engineering Research Centers (NERCs) are under competition in 2015 and will be in operation in 2016. In 2016, the agency will continue its contributions to translational innovation programs, including Grant Opportunities for Academic Liaison with Industry (GOALI), Industry/University Cooperative Research Centers (I/UCRC), the Innovation Corps (I-Corps) program, Accelerating Innovation Research (AIR), Partnerships for Innovation (PFI), and PFI's Building Innovation Capacity (BIC) component. The NSF SBIR program has an ongoing nanotechnology topic with subtopics for nanomaterials, nanomanufacturing, nanoelectronics and active nanostructures, nanotechnology for biological and medical applications, and instrumentation for nanotechnology. Currently, almost 60% of the Materials Research Science and Engineering Centers (MRSECs) pursue NSE-related research.

NSF has under competition in 2015 the National Nanotechnology Coordinated Infrastructure (NNCI) with an annual budget estimated at $16 million, which will be operational in 2016 and replace the National Nanotechnology Infrastructure Network (NNIN).

NSF has mainstreamed nanotechnology-related research in core programs in several directorates. There is continuing strong interest from the communities in nanotechnology research, education, and infrastructure through those core programs.

USDA/ARS: The Agricultural Research Service (ARS) is relatively new to the nanotechnology field. ARS research projects address issues relevant to nanostructured materials; technologies to rapidly and accurately identify pathogens and toxins; food alloys with improved functional properties; food packaging; and applications in non-food bioproducts. The Budget request in nanotechnology for 2016 will increase by $1 million from the 2014 investment level, an increase of 50%.

USDA/FS: The Forest Service nanotechnology research supports the agency priorities of sustaining forest health, stimulating rural development, and creating value for our Nation’s landowners. The majority of Forest Service nanotechnology research will continue in the area of cellulose nanomaterials, with the remaining balance of the budget focused on understanding wood properties using nanoscale methods. In support of the Administration’s emphasis on advanced manufacturing, the NNI’s emphasis on commercialization, and the Forest Service priority of creating value for landowners, the Forest Service has formed a public–private partnership to invest in application-related R&D and facilitate technology transfer related to cellulose nanomaterials.

USDA/NIFA: The National Institute of Food and Agriculture (NIFA) supports research, education, and extension activities in nanotechnology for agriculture and food systems. About 400 research and education projects are recorded in the agency’s current research information system for advancing nanoscale science, engineering, and technology. These projects collectively address grand societal challenges facing agriculture, food, health and nutrition, the environment, and rural communities. NIFA has maintained a balanced investment distribution in all five PCAs. The Budget request in nanotechnology for 2016 will essentially remain the same as compared to the 2014 investment level.

4. Progress Towards Achieving NNI Goals, Objectives, and Priorities

Activities Relating to the Four NNI Goals and Fifteen NNI Objectives

As called for in the 21st Century Nanotechnology Research and Development Act, this NNI Supplement to the President's Budget provides an analysis of the progress made toward achieving the goals established for the NNI. The NNI's activities for 2014 and 2015 and plans for 2016 are reported here in terms of how they promote progress toward the four NNI goals and fifteen objectives set out in the 2014 NNI Strategic Plan (Figure 3). It is important to note that many agency programs and activities, although listed below under their primary NNI goals and objectives, address components of multiple goals simultaneously. Therefore an integrated perspective across the four goals is needed to understand progress towards achieving the NNI vision.

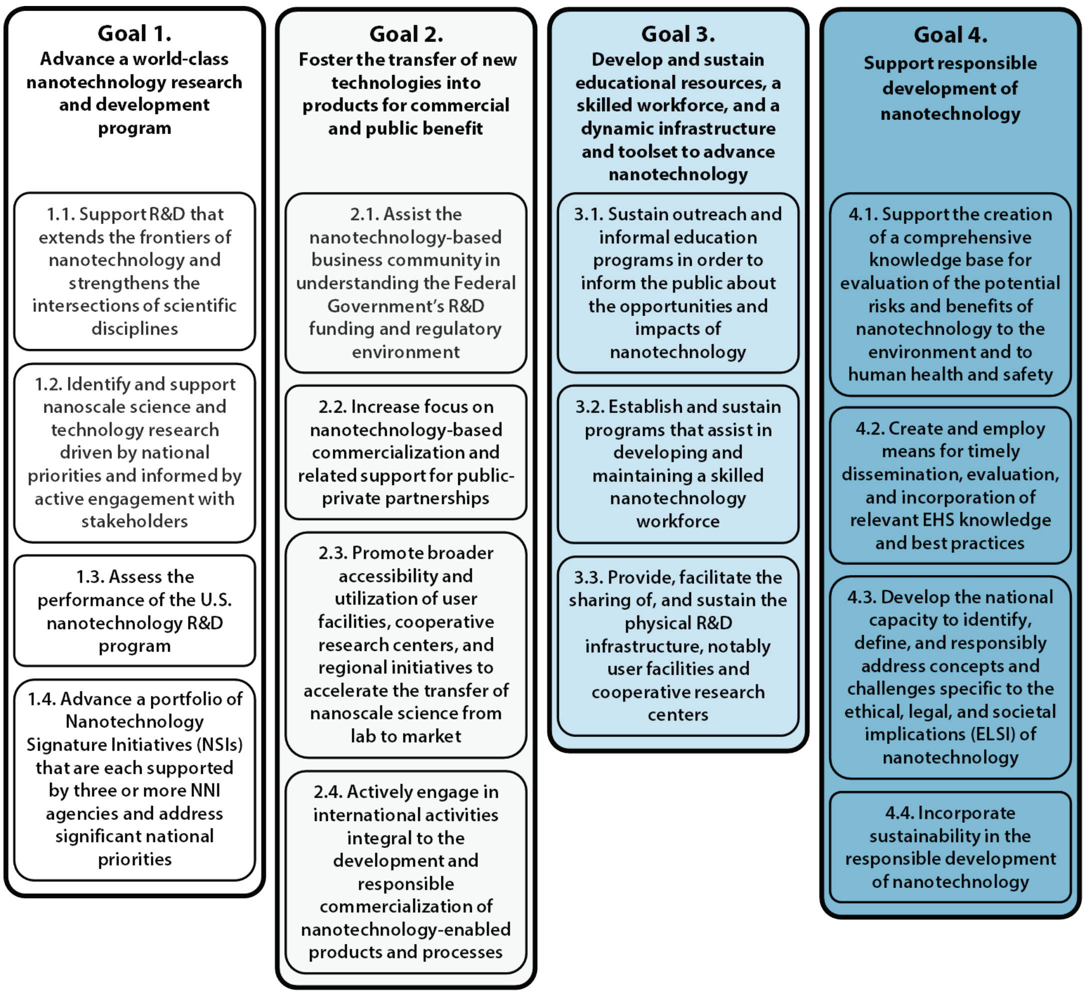

Figure 3. A summary of NNI goals and objectives from the 2014 NNI Strategic Plan.[52]

[52] Details on NNI strategic goals and objectives can be found in the 2014 *National Nanotechnology Initiative Strategic Plan*, www.nano.gov/2014StrategicPlan or www.nano.gov/about-nni/what/vision-goals.

Goal- and objective-related activities are reported below in two categories: (1) individual agency activities and (2) coordinated activities of NNI agencies with other agencies and with groups external to the NNI, including international activities. *The activities described below in these two categories are only selected highlights of current and planned work of the NNI member agencies and are not an all-inclusive description of ongoing NNI activities.*

Goal 1: Advance a world-class nanotechnology research and development program.

U.S. leadership in nanotechnology R&D depends on the continued investment of participating agencies in the stimulation of discovery and innovation. These activities expand the boundaries of knowledge through a comprehensive R&D program that builds on the foundation established over the past fourteen years. The Nanotechnology Signature Initiatives (NSIs), while developed in the context of all four NNI goals, are explicitly called out in Objective 1.4 under Goal 1, as detailed in the 2014 NNI Strategic Plan. The NSIs provide a spotlight on critical areas and define the shared vision of the participating agencies to accelerate the advancement of nanoscale science and technology from research through commercialization. The enhanced coordination of national nanotechnology R&D activities afforded by the NSIs enables the leveraging of individual agency programs, resources, and capabilities in addition to the development of collaborative programs; both categories are reported below.

Objective 1.1 – Support R&D that extends the frontiers of nanotechnology and strengthens the intersections of scientific disciplines.

Individual Agency Contributions to Objective 1.1

DHS: The DHS Science and Technology Directorate is conducting nanotechnology research in several areas related to explosives and explosives detection. These technology areas include the following:

- Understanding heterogeneity of energetic materials: this research explores novel synthesis routes using three-dimensional hierarchical porous materials that can potentially lead to controlled and tunable particle sizes and shapes of energetic materials on the nanoscale and microscale.
- Explosive/polymer interactions: the interactions of explosives with other media, specifically polymers as nanoparticles and microstructures, are explored to identify surfaces with switchable properties for swabbing or use in preconcentrating explosive samples.
- Multifunctional nano-electro-optical-mechanical sensing platforms: multifunctional explosives detection technology is being investigated by combining nanoscale aluminum nitride piezoelectric transduction, graphene, and metamaterials.

DOD/Air Force: The Air Force Office of Scientific Research (AFOSR) Space Power and Propulsion Program is exploring smart, functional nanoenergetics for propulsion purposes. The program sponsors the "Smart Functional Nanoenergetic Materials" MURI to design energetic materials from the atomistic/molecular scale through the mesoscale. Using the latest techniques in molecular self-assembly, supramolecular chemistry, and integrated fabrication that links nanoscale to micro- and macrostructures, the MURI team led by the Pennsylvania State University (Penn State) is investigating the synthesis and assembly of nanostructured energetic materials based on novel functionalized graphene sheets and metallic clusters with control over length scales from 1 nanometer to 1 millimeter. The goals are (1) to develop new macroscale (micrometer-sized or larger) energetic materials with nanoscale features that will provide concurrent improvement in performance and managed energy release while providing reduced sensitivity and ease of processing and handling; and (2) to obtain fundamental understanding of the relationship between the integrated multi-length-scale design of these newly developed energetic materials and their reactive and mechanical behaviors, particularly with regard to sensitivity, ignition, burning characteristics, mechanical properties, and controllability.

The AFOSR Low Density Materials Program focuses on the development of lightweight, multifunctional structures. In particular, the program seeks to advance the understanding of how to translate the exceptional mechanical properties of carbon nanotubes (CNTs) on the nanoscale into ultrahigh-strength macroscale structures. The work includes computational as well as experimental studies. More specifically, the program supports research on CNT nanostructured materials in the form of CNT fibers, CNT buckypaper-reinforced composites, and electrically conductive CNT fibers and films. The portfolio also has investments supporting advances in the synthesis, modeling, and structure–property relationships of boron nitride nanotubes, and in the fabrication of three-dimensional nanostructures.

DOD/Army: The Army Research Laboratory (ARL) is investing in energy-coupled matter research to utilize physics-based external fields (electric, magnetic, microwave, acoustic, etc.) to expand materials-by-design and manufacturing science innovation capabilities for producing outcomes that are unattainable by conventional means. The resulting field–material interactions are being used to develop novel materials and enhance processing and manufacturing technologies. Ongoing research is focused on furthering understanding of the underlying behaviors to enable materials and materials processing to realize their full potentials.

The Army Engineer Research and Development Center (ERDC) has a multidisciplinary nanotechnology research program with expertise in chemistry, physics, engineering, high-performance computing (HPC), multiscale materials modeling and simulation, and nanoscale fabrication and testing. This program couples experimental technologies with HPC to shorten the time to delivery for ultrahigh-strength materials; guide development of high-performance polycrystalline structural ceramics; develop new software technology using HPC resources; extend the size and complexity of problems that can be solved with the aid of modeling and simulation; identify new manufacturing processes needed to produce the next generation of ultrahigh-strength materials; and develop the modeling and simulation technology necessary to understand the processes that govern the behavior of materials at the nanoscale. Materials simulations complement experimental efforts to develop a better understanding of structure–property relationships and the synergy that exists between mechanisms operating at the nano-, micro-, and mesoscales. This information provides new insights into general design concepts to optimize the performance and guide the experimental efforts to produce the next generation of advanced materials for civil-military applications including composites for facility protection.

DOD/CBDP: The Chemical and Biological Defense Program (CBDP), through a collaboration between the University of California, San Diego, and Sandia National Laboratory in nanocatalytic machines, has established a proof-of-concept new method for accelerated detoxification of nerve agent simulants. A plan to apply this method to actual nerve agents is being developed in consultation with Edgewood Chemical Biological Center. Foci of this program in the coming fiscal year also include nanocatalytic machines that target the multistep degradation of nerve agents *in vivo* for medical countermeasures.

There is a planned increase in funding for understanding and controlling the interaction of engineered nanoparticles with the olfactory system and the blood–brain barrier in order to enable more rapid development of therapeutics to counter neurotoxins and neuropathogens.

DOD/DARPA: DARPA is funding leading U.S. universities to advance nanotechnologies for creating useful material systems, devices, and architectures for future microsystems. DARPA, in collaboration with companies from the semiconductor and defense industries—Applied Materials, GLOBALFOUNDRIES, IBM, Intel, Micron, Raytheon, Texas Instruments, and United Technologies—established the Semiconductor Technology Advanced Research Network (STARnet). This effort has built a large multiuniversity research community to explore beyond current evolutionary directions to make discoveries that drive technology innovation beyond what can be imagined for electronics today. The universities are organized into six multiuniversity centers, each focused in a specific challenge area. Researchers in these centers are advancing R&D in physics theory, materials, processes, circuits, and related areas (design, off-chip communications, etc.) for new devices that operate using unique information tokens due to physical phenomena that occur at the nanoscale.

Technologies satisfying future demands of military and civilian systems require harnessing the quantum nature and nonlinearities of nanoscale devices to transition from classical to quantum engineering. Advances in several scientific disciplines are accelerating this transition. Topological insulators were discovered under DARPA sponsorship (along with insulating bulk and topologically ordered metallic surfaces) resulting in remarkable properties promising for electronics beyond the current state of the art. Other developments include new approaches to sensing and information transduction, techniques to control quantum states, and progress in nanoscale manufacturing. DARPA's Meso Program has worked at the intersection of these disciplines, exploiting mesoscale and nonlinear dynamics to create technologies with exotic functionality and unprecedented performance in sensing, computation, communication, and navigation, while being amenable to harsh environments. Accomplishments include very high-performance microelectromechanical systems (MEMS) oscillators, the first piezoelectronic transistor, an electronic biomolecular sensor detecting minimum injury concentrations of neurotoxins, and the first-ever topological insulator thermoelectric device.

DOD/DTRA: The DTRA Basic and Applied Sciences Program supports investigations of nanoscience, which may lead to development of nanotechnologies applicable to a number of counter-weapons-of-mass-destruction (WMD) mission needs. Areas of interest include tamper-evident nanostructures to help with securing and monitoring WMDs, nanoelectronics for radiation-hardening and life extension of counter-WMD systems, conventional weapons effect testing with novel diagnostics, radiation sensing systems with novel interfacial materials, and alternative methods for photon or electron multiplication. Programmatic interests are supported through current investment in exploratory research efforts in areas such as (1) engineered nanomaterials for unattended sensing applications; (2) nanomaterials as fast-responding diagnostics to measure temperature, pressure, and mechanical strain within reacting energetic materials during the early phases of detonation; (3) two-dimensional nanomaterials for development of microelectronic components with low radiation cross section; (4) radiation effects in nanophotonic resonators and waveguides; and (5) nanoparticle scintillators for radiation detection. One example of noteworthy research is that at Washington State University, which has demonstrated that novel europium-doped yttrium (III) oxide (Y_2O_3) and erbium/ytterbium-doped zirconium dioxide (ZrO_2) can evaluate thermal history of a detonation to within 50 °C and 10-second accuracy. Other examples are efforts that incorporate nanotechnology into the study of laser-driven x-ray sources. These grants have resulted in materials science advancement for laser targets. Researchers at Lawrence Livermore National Laboratory, in collaboration with the University of California, Davis, have synthesized low-density metal–carbon composites with nanoscale pore walls. Targets based upon the cited materials were tested at the Omega laser facility located at the University of Rochester's Laboratory for Laser Energetics, and experimental results were in agreement with nonlocal thermodynamic equilibrium models developed by the research team. Another team of researchers at Colorado State University irradiated vertically aligned nanostructures with femtosecond optical pulses to investigate efficient generation of picosecond x-ray pulses. The plasma conditions achieved extraordinarily high degrees of ionization, e.g., 52-times ionized gold atoms, using energies on the order of a single joule.

DOD/Navy: Significant advances are being made in the understanding and manipulation of nanomaterials in a wide variety of program areas, including quantum computing, nanoelectronics, power generation, and "lightening the load" technologies for the warfighter and combat vehicles. The nanoscience program at NRL is a coordinated effort directed at innovative, interdisciplinary basic research conducted at the intersections of the fields of materials, physics, electronics, chemistry, and biology. The program is divided into four areas: materials, interactions between materials and their environment, nanosystems (with an emphasis on bioinorganic systems), and quantum systems. The goal of the research program is to establish the scientific principles that will enable revolutionary technologies for the Navy, DOD, and the Nation. Examples of Foundational Research include the creation of high-strength, high-stiffness armor and structural materials using biomimetic nanocomposites; creating living, self-reproducing catalysts using biologically supported heterogeneous metallic nanocrystals; and creating bioinorganic hybrid nanostructures for the real-time imaging of neuronal signals. Supported research has combined synthetic biology and nanotechnology to develop a broad platform for engineering hybrid "living materials" made from bacterial cells and inorganic matter that can adapt to changing environmental conditions to change their structure and composition, and be patterned across multiple length scales. The platform is based on engineering the extracellular "curli" amyloid fibers that are secreted by the bacterium *Escherichia coli*. The research addresses a major challenge in materials science, and the platform is expected to yield new capabilities for biomaterials engineering and applications that are relevant to naval operations.

DOE: In support of the DOE mission, the Office of Science (DOE-SC) provides a diverse investment in nanoscience research and development, primarily through grants to researchers at universities, funding for research groups at DOE laboratories, and support of interdisciplinary efforts such as the Energy Frontier Research Centers (EFRCs) and two Energy Innovation Hubs—the Joint Center for Artificial Photosynthesis (JCAP) and the Joint Center for Energy Storage Research (JCESR). The Office of Basic Energy Sciences supports fundamental research in materials science, chemical science, geoscience, and bioscience with the goal of understanding, predicting, and ultimately controlling matter and energy at the level of electrons, atoms, and molecules. This research provides the foundation for future new energy technologies and supports the DOE mission in energy, environment, and national security. Selected examples of such research include the following:

- Nanostructured materials for optimum electron and ion transport in next-generation batteries and fuel cells.
- Controlled synthesis and assembly of functional nanoscale and mesoscale materials with desired properties.
- Use of controlled interfaces and nanostructures to drive heat flow and energy generation in novel thermoelectric materials.
- Structural and dynamical studies of atoms, molecules, and nanostructures to provide complete knowledge and rigorous understanding of reactive chemistry in gas and condensed phases.
- Predictive understanding, at molecular and nanoscale dimensions, of the basic chemical and physical principles involved in separations systems including the removal of combustion byproducts.

NASA: NASA continues to support both foundational and applied research in nanotechnology through its field centers and in university and industry laboratories. One particular example is the NASA Space Technology Research Fellowship Program. Since its inception in 2011, it has funded 41 graduate fellowships, 11 of which were awarded in 2014, to perform nanotechnology-related research in collaboration with NASA scientists and engineers. Current NASA research efforts have been supported through the Space Technology Mission Directorate and the Aeronautics Research Mission Directorate. Center Innovation Funds and Seedling Funds from these directorates have funded topics such as the development of nanoscale coatings to improve the aerodynamic efficiency of aircraft, nanotechnology-based sensors for high temperatures and harsh environments, carbon nanotube and boron nitride nanotube-based materials and devices, and nanoscale vacuum electronics.

NIH: NIH advances creative, fundamental discoveries and translational nanotechnology research and development to ultimately enhance health, lengthen life, and reduce illness and disability through a variety of mechanisms and approaches. The NIH investment portfolio encompasses both basic and clinical research in areas such as drug delivery, tissue engineering, regenerative medicine, biomedical imaging, and biomaterials, just to name a few. Research funded through grants is the primary method utilized by the majority of NIH institutes and centers. Scientists funded through that mechanism are developing nanoscale multifunctional materials that capitalize on progress in genomics and proteomics and allow targeted delivery of molecular therapies to enhance efficacy. Others are employing nanotechnology techniques and concepts focused on biological processes that will give completely new insights into the physical relationships between cellular components and functional irregularities that trigger pathological abnormalities. Other opportunities include the design of programmable diagnostic and delivery systems that not only define early-stage changes or progression to a disease state, but also allow the identification of unique biological molecules, chemicals, and structures not addressable by current assays.

Due to the comprehensive nature and diversity of research supported by NIH, the following highlights are limited to certain investment programs to illustrate the frontiers of science and new opportunities representing a world-class basic and translational nanotechnology research program.

Scientific advances in 2014 and 2015:

- Research supported by the NIH National Heart, Lung, and Blood Institute (NHLBI) Programs of Excellence in Nanotechnology (PENs) continues to demonstrate the promise of nanotechnology focused on interdisciplinary research in cardiovascular disease. Researchers at Massachusetts General Hospital (MGH), for example, have adapted their research to study the interactions between inflammation and cardiovascular disease by using nanoparticle-based siRNA delivery to manipulate macrophage phenotype. By pushing macrophages from a proinflammatory to a prohealing phenotype, they were able to improve cardiac recovery following a myocardial infarction in a mouse model.[53] Investigators at Mount Sinai School of Medicine, in collaboration with MGH researchers, demonstrated that loading statins into nanoparticles that mimic high-density lipoprotein (HDL) could reduce atherosclerotic plaque in a mouse model, giving the potential to reduce future myocardial infarctions and stroke.[54]
- The NIH Nanomedicine Centers funded through the Common Fund Nanomedicine Phase II Initiative also strengthen the intersections of science as fundamental scientists work with clinical consultant boards to meet their translational goals, as illustrated in several publications.[55]
- The NIH National Institute on Drug Abuse investments are leading to novel delivery platforms and pharmacotherapies for substance use disorders. This includes new nanoparticle conjugates for the treatment of methamphetamine abuse and synthetic nanofiber vaccines for cocaine addiction.

[53] content.onlinejacc.org/article.aspx?articleID=1789394

[54] www.ncbi.nlm.nih.gov/pubmed/24445279

[55] www.ncbi.nlm.nih.gov/pmc/articles/PMC4121856, www.ncbi.nlm.nih.gov/pubmed/?term=23761039, and www.ncbi.nlm.nih.gov/pubmed/24315106

New opportunities in 2015, with continuation into 2016:

- In 2014, the NIH National Cancer Institute (NCI) awarded $90 million in support for extramural nanotechnology research and maintained its $3 million investment in the Nanotechnology Characterization Laboratory at Frederick National Laboratory for Cancer Research. NIH/NCI also supported projects in PCA 4 (Research Infrastructure and Instrumentation). A significant portion of NIH/NCI's extramural investment in nanotechnology is awarded through the Alliance for Nanotechnology in Cancer, which consists of 9 Centers of Cancer Nanotechnology Excellence (CCNE; U54 awards), 12 Cancer Nanotechnology Platform Partnerships (U01 awards), 6 Cancer Nanotechnology Training Centers (R25 institutional training awards), and 7 Pathway to Independence in Cancer Nanotechnology Research awards (K99/R00 personal career development awards). Due to the overall success of the Alliance program to date, NIH/NCI has set aside funds in 2015 to support a third round of CCNE awards ($12–13 million total cost for U54 awards made through RFA CA-14-013) and institutional training awards ($2 million for T32 awards made through PA-14-015) as part of the NCI Alliance for Nanotechnology in Cancer. The Alliance centers will serve as a network to develop research and translational capabilities in cancer nanotechnology, and individual programs should enable multidisciplinary team research in cancer prevention, detection, diagnosis, and treatment.
- NIH/NCI reissued a program announcement with special review for Innovative Research in Cancer Nanotechnology (IRCN) awards to be made using the U01 mechanism (PAR-14-285). These awards are designed to enable multidisciplinary research and transformative discoveries in cancer biology and/or oncology through the use of nanotechnology. Proposed projects are expected to address major barriers in cancer biology and/or oncology using nanotechnology and should emphasize fundamental understanding of the interactions of nanomaterials with biological systems and/or mechanisms of their *in vivo* delivery.
- The NIH National Institute of Dental and Craniofacial Research (NIDCR) will launch a new multidisciplinary Dental Oral and Craniofacial Tissue Regeneration Consortium (DOCTRC) in 2015, which is expected to utilize nanomaterials. DOCTRC will conduct preclinical studies in support of submissions of Investigational New Drug/Investigational Device Exemption applications to FDA to develop safe, predictive, and effective clinical strategies for regeneration of functional tissues of the human dental, oral, and craniofacial complex. DOCTRC will bring together professionals working in different disciplines, including clinicians, biologists, material scientists with expertise in nanotechnology, bioengineers, and regulatory experts to work on a common goal of advancing the most promising tools and approaches of tissue engineering and regenerative medicine toward clinical trials. It is expected that nanomaterials will be widely utilized in developing such tools and approaches.

For 2016, NIH will continue to invest in nanotechnology and nanomedicine supporting the creative research ideas of scientists and engineers in universities and small businesses across the country, with technologies expected to emerge from the physical and life sciences to further develop novel advanced medical diagnostics, therapeutics, and approaches to disease management. Examples include clinical lab tests that search for multiple biomarkers to detect trace molecules that signal the presence of disease or infection before a patient has become extremely ill; and clinical evaluation of medical imaging technologies that target defining not only anatomy but also the molecular events that precede advanced symptoms.

NIST: NIST is developing a wide range of measurement methods and instrumentation for nanomaterials and nanoscale devices. For example, in an effort to widen the range of nanomaterials and nanostructures that can be probed using a focused ion beam (FIB) microscope, NIST researchers built the first low-energy FIB that uses a lithium ion source. The team's new approach opens up the possibility of creating a whole category of FIBs using any one of up to 20 different elements, greatly increasing the options for imaging, sculpting, or characterizing materials. NIST is advancing the scale and breadth of carbon nanotube purification and processing methods and continues to advance nanoscale imaging capabilities, for example, in the development of a new magnetic resonance imaging technique with breakthrough sensitivity. To accelerate the understanding and deployment of nanotechnology-reinforced polymeric composites, NIST is generating performance data and models for the damage tolerance of these materials when subjected to environmental degradation, and optical microscopy methods to image critical interfacial regions. NIST is developing semiconductor nanosystems to push the next generation of quantum optical photonics needed for precision sensing, metrology, and quantum technologies. Practical, chip-scale, deployable nanoelectronic devices and standards for high-precision electrical metrology (such as current and resistance) are in development. In 2014, NIST issued Reference Material 8027, well-characterized silicon nanoparticles certified to be close to 2 nanometers in diameter. As the smallest known reference material ever created, this product will help researchers ensure the accuracy of their nanoscale measurements. In 2015, NIST will make available a unique thin-film standard for measuring stress and strain at the nanoscale by x-ray, electron, and optical methods.

The NIST Innovations in Measurement Science (IMS) Program is a competitive internal funding program to support high-risk, leading-edge research that anticipates future measurement and standards needs of industry and science. Several IMS teams are working on measurement methods to advance nanoscale science, for example, device technologies based on graphene and related 2-D materials. In 2015, three new projects were awarded to multidisciplinary IMS research teams in the area of nanoscience. The research teams will develop new microscope instrumentation to spatially resolve reactivity at the solid–liquid interface of nanomaterials; aim to fabricate prototype atom-based devices to provide the metrology and understanding needed by the silicon electronics industry to thrive in this new frontier; and advance cold-atom focused ion beams to create breakthrough battery measurements.

NSF: NSF supports fundamental nanoscale science and engineering in and across all disciplines. NSF's nanotechnology research is supported primarily through grants to individuals, teams, and centers at U.S. academic institutions. The efforts in team and center projects have been particularly fruitful because nanoscale research and education are inherently interdisciplinary pursuits, often combining elements of materials science, engineering, chemistry, physics, and biology.

The NSF nanotechnology investment in 2014 supported about 5,000 active projects, over 30 research centers, and several infrastructure networks for device development, computation, and education. It impacted over 10,000 students and teachers. Approximately 150 small businesses were funded to perform research and product development in nanotechnology through the SBIR and STTR programs. NSF sponsors an annual Nanoscale Science and Engineering Grantee Conference to assess the progress in nanotechnology and facilitate identification of new research directions.

Several new directions planned for 2016 are nanotechnology for water-energy-food processes; nanomodular materials and systems by design, including two-dimensional nanoscale materials; and aspects of nanoelectronics and photonics. *[See also the section below on coordinated activities in support of Objective 1.1.]*

USDA/NIFA: NIFA continues to advance the frontiers of interdisciplinary nanoscale science, engineering, and technology for solutions to a range of grand societal challenges facing agriculture and food systems through various extramural research funding mechanisms. NIFA supports nanoscience research and development primarily through competitive and formula grants to individual researchers at land grant universities and other public and private research institutes.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 1.1

DOD/Army, universities, and industry: The Army-sponsored Institute for Soldier Nanotechnologies (ISN) brings together researchers from the Massachusetts Institute of Technology (MIT), the Army, and industry to discover and field technologies that dramatically advance soldier protection and survivability capabilities. Nanotechnology milestones emerging from the ISN are unique and revolutionary in scope. Novel materials and devices under development include the following:

- Nanostructured metal alloys, representing a new material form, with the strength of steel and the weight of aluminum for protective armor for soldiers and vehicles.
- Nanostructured optoelectronic fiber devices that could be incorporated in the weaves of soldiers' uniforms for multifunctional capabilities such as active/passive combat identification, infrared laser-to-uniform communications, sniper detection, power storage, and blast/blunt-impact monitoring.
- Frequency-downconverting nanoparticles for low-cost, room-temperature infrared night imaging together with ultraviolet communications, all in a single night-vision device.
- Interbilayer-cross-linked nanoparticle encapsulants for extremely potent vaccine and drug delivery with orders-of-magnitude increases in performance over existing technologies.
- Nanolayered conformal coatings for sutures, surgical sponges, and bandages enabling unprecedented wound healing and hemostasis capabilities on the battlefield.

DOD/DARPA, DOD/AFOSR, NSF, NIST, and industry: The STARnet Program is jointly funded by U.S. member companies, DARPA, and AFOSR. Management is provided by DARPA, AFOSR, and the U.S. member companies, with the Microelectronics Advanced Research Corporation (MARCO) administering day-to-day operations. DARPA routinely shares the results with NSF, NIST, and the other DOD component organizations. *[This program also applies to Objective 1.2, where it is described in greater detail on page 44.]*

DOD/Navy and NNI agencies: Research supported by the Office of Naval Research (ONR) is coordinated through the DOD Advanced Materials and Processes Community of Interest, the Defense Basic Research Advisory Group, and the NSET Subcommittee of the NSTC Committee on Technology. Professional collaborations among agencies are well established at the program officer level.

NASA and NIST: NIST is collaborating with NASA to demonstrate improved photocathode performance from nanostructured semiconductors for ultraviolet spectroscopy in space.

NIH/NIDCR and NIST: In 2016, NIH/NIDCR will continue to collaborate with NIST through an interagency agreement to support the development of standard reference materials and new analytical instrumentation for characterization. Over the years, NIST efforts in producing tooth-mimetic substrates have focused on early mineralization events involving development of nanometer-size building-block-based restorative materials.

NIST, DOE, and industry: NIST and DOE are working with SBIR-supported companies to develop advanced synchrotron imaging capabilities. Recently commissioned instruments include a large-area imaging near-edge x-ray absorption fine structure (NEXAFS) microscope that provides high-efficiency measurements of thousands of compositional samples in parallel, and an x-ray photoelectron spectroscopy (XPS) microscope that provides full 3-D mappings of nanomaterials and nanodevices, combining nanometer-scale spatial resolution with chemical and electronic state specificity. These instruments are being transferred to the new DOE synchrotron facility, NSLS-II, in 2015, which is designed specifically for nanoscale measurements, and the instruments are expected to be fully operational in 2016.

NIST and universities: NIST collaborated with Rensselaer Polytechnic Institute (RPI) to develop and patent a method and system utilizing multiple nanopositioners for use in the fabrication and microassembly of MEMS devices. The multiplicity of nanopositioners enables the capability of six degrees of spatial motion in configuring MEMS components during the assembly process.

NIST, universities, and industry: NIST continues to support the Center for Hierarchical Materials Design (CHiMaD), a NIST center of excellence led by Northwestern University in partnership with Argonne National Laboratory, the University of Chicago, and other contributing organizations. CHiMaD is advancing the Materials Genome Initiative vision of integrating computation, data, and experiment for the design of new materials through projects with a focus on nanotechnology, including directed self-assembly for nanomanufacturing, 2-D nanoscale materials, and organic electronics.

NSF and DOD/AFOSR: Both agencies collaborate in the Two-Dimensional Atomic-layer Research and Engineering (2-DARE) program that has two competitions in 2014 and 2015 for four-year group awards. This program addresses fundamental challenges in the creation of 2-D nanoscale materials beyond graphene and their hybrids, scalable manufacturing strategies, characterization tools and methods, and novel devices. These may lead, among other things, to solar cells that exploit the unique properties of stacked, heterogeneous layers.

Objective 1.2 – Identify and support nanoscale science and technology research driven by national priorities and informed by active engagement with stakeholders.

Individual Agency Contributions to Objective 1.2

DOD/Air Force: Two key areas of immediate military relevance include propulsion and munitions systems, where nanomaterials could be employed in reducing sensitivity to accidental initiation during storage and delivery, as well as in generating more energetic propulsion or explosions and ensuring long-term storage stability.

The Information Directorate of the Air Force Research Laboratory (AFRL/RI) is developing novel approaches to meet the challenge of developing next-generation nanotechnology for energy-efficient processing and neuromorphic computing. AFRL/RI's research in this area covers a wide spectrum from nanodevice development and characterization to architecture and nanosystem design and fabrication. AFRL/RI's development of technology to advance the state of the art of memristive devices, or "memristors," is a key contributor to advancing nanocomputing. Memristor technology shows promise to foster a giant leap toward the development of nanoelectronic systems that can mimic the computational decision-making capabilities of a mammalian brain. AFRL/RI also has initiated new work in the area of nanoscale information assurance and next-generation neurosynaptic processor development. A 40,000-neuron neural network model was created using CogniMem™ technology. This hardware-based network was used to execute a radial basis function three times faster and 60 times more power-efficient than a state-of-the-art 8-core Intel Xeon® processor performing the same function in software. AFRL/RI's 3-D project achieved a test fabrication of a metallization stack. The test affirmed and lowered the risk for use of 10 nm "through-silicon vias" for three-dimensional nanologic. The result was passed on to the IBM operators of the fabrication process at the College of Nanoscale Science and Engineering (CNSE) of the State University of New York in Albany, New York. The Information Directorate's Nanotechnology Project completed fabrication of a 1T1M (1 transistor/1 memristor) memory cell on the full CNSE/SEMATECH 300 mm fabrication line. A subcircuit design was completed for the XOR gate used in the memristor-based Advanced Encryption Standard.

Numerous Information Directorate patents have been awarded or are in the pending stages in the areas of physical unclonable functions for information assurance, neural circuit memristive device design, hardware-based analog computing with memristors, and hardware design for analog computing.

The AFRL Information Directorate will continue to invest in nanotechnologies for greatly improved onboard processing and neuromorphic computing. Basic research is planned in the area of secure circuit design at the nanoscale level. Memristor modeling will be conducted to determine optimal materials and switching properties for devices that will one day form advanced nano- and neuromorphic computing circuitry. Leveraging advances in the areas of CMOS/nanologic, memristance, CMOS-memristor hybrid mixed-signal circuits, and nanoscale memristor crossbar arrays, the Information Directorate will develop a novel neuromorphic computing processor. It will also continue to utilize and leverage commercial nanotechnology and neuromorphic computing breakthroughs for conducting military-utility developments and experiments.

The AFRL Directed Energy Directorate is developing nanoengineered magnetics and dielectrics to enable game-changing directed energy (DE) applications. These enable military options by increasing reliability, efficiency, operating temperature, and energy and power density; and by reducing the size of key DE power components.

DOD/DARPA: A competitive electronics industry is a national priority to maintain commercial technology leadership and ensure new defense capabilities. DARPA is identifying promising new approaches for using nanotechnologies to drive advances in new devices to replace transistors or to augment the performance of conventional transistor integrated circuits. The STARnet Program is advancing fundamental research for creating highly functional circuits using these devices and understanding their inherent limitations. In this case, the program is partnering directly with several of the industrial stakeholders, including equipment supplier Applied Materials, semiconductor integrated device manufacturers Intel and Micron, foundries IBM and GLOBALFOUNDRIES, and defense contractors Raytheon and United Technologies. The STARnet Program funds research directly at U.S. universities.

DARPA's Meso Program has exploited nonlinearities intrinsic to the meso and nanoscale to produce frequency sources with performance and stability well beyond the state of the art for their size. These resources offer increased performance and new capabilities for military systems, including longer ranges for radios and the ability to maintain radar performance on vibrating platforms. The Meso program has engaged with NIST to conduct independent performance evaluation. Demonstrations using prototype devices can enable Global Positioning System (GPS) tracking and longer-range radio transmissions at lower operating power. Typically, the performance of measurement devices is limited by deleterious effects such as thermal noise and vibration. Notable exceptions are atomic clocks, which operate very near their fundamental limits. Driving devices to their physical limits will open new application spaces critical to future DOD systems. In fact, many defense-critical applications already require exceptionally precise time and frequency standards enabled only by atomic clocks; GPS and the Internet are two key examples. DARPA’s Enabling Quantum Technologies Program is building upon established control and readout techniques from atomic physics to develop a suite of measurement tools that will find broad application across DOD, particularly in the areas of biological imaging, inertial navigation, and robust global positioning systems. Recent progress under this program includes the demonstration of a first-of-its-kind compact atomic optical clock with stability ten times better than current GPS clocks and nanoscale magnetic sensing of spins using a diamond nitrogen vacancy (NV) magnetometer.

Defense applications such as geolocation, navigation, communication, coherent imaging, and radar depend on the generation and transmission of stable, agile electromagnetic radiation. Improved radiation sources—for example, lower-noise microwaves or higher-flux x-rays—could enhance existing capabilities and enable entirely new technologies. The Basic Photon Sciences Program is investigating ways to exploit the exquisite stability and control achieved in ultrafast lasers to enable novel radiation sources that span the electromagnetic spectrum with improved performance while reducing size, weight, and power. It is envisioned that such devices, once demonstrated by DARPA, will find broad application across DOD, particularly in the areas of secure communications, electronic warfare and countermeasures, coherent radar, nondestructive evaluation, biological imaging, and materials characterization. Recent key achievements in this program include the first biological, three-dimensional, cryogenic imaging of a whole, hydrated cell by coherent x-ray diffractive imaging and the identification and demonstration of a new regime of high harmonic generation that can improve by 1000-fold the efficiency of extreme ultraviolet radiation generation.

DOD/Navy: Individual projects include the development of new experimental methods to study Coulomb transport in electrochemical systems with nanometer spacing between electrodes such that charge transport is influenced by the overlap of the electrochemical double layers, and how the fundamental electrochemical properties of three-dimensional electrodes are influenced by architecture.

DOE: DOE-SC continues to support two Energy Innovation Hubs: the Joint Center for Artificial Photosynthesis and the Joint Center for Energy Storage Research. A significant fraction of the effort in both hubs involves nanotechnology. By fostering unique, cross-disciplinary collaborations, these hubs will help advance highly promising areas of energy science and engineering from the early stages of research to the point where the technology can be handed off to the private sector. For example, atomistic calculations performed by researchers in JCESR allowed for the tailored design of a new binder for lithium-sulfur batteries that resulted in record-breaking performance in capacity and lifetime. A major thrust of JCAP is "science-based scaleup," which develops the scientific understanding and capabilities for linking together nanoscale objects to form fully functional artificial photosynthetic units and then assemble these units into systems that function on increasingly larger scales.

The Advanced Research Projects Agency-Energy (ARPA-E) supports a broad range of early-stage, potentially disruptive energy technology projects that involve both applications of current nanotechnology and applied R&D in new areas of nanotechnology. A major focus is on the challenging translation of nanotechnology from the laboratory to commercial viability.

The Solar Energy Technologies Office (SETO) in the Office of Energy Efficiency and Renewable Energy (DOE-EERE) supports a variety of projects that use nanotechnology to drive down the cost of solar power installations. Approaches to reach the SunShot Initiative $1 per watt target using nanotechnology include quantum dot solar cells, nanostructures for bandgap engineering, monolayers to adjust a material's work function or passivate surfaces, and nanostructured materials for plasmonics and antireflective coatings.

The Solid-State Lighting (SSL) Program in DOE-EERE supports research and development of promising SSL technologies in areas such as emitter materials research at the nanoscale level to reduce current droop and thermal sensitivity in light-emitting diodes (LEDs) and light extraction approaches for organic LEDs (OLEDs).

The Hydrogen and Fuel Cell Technologies (HFCT) program in DOE-EERE conducts nanomaterials research and development for fuel cell, hydrogen production, and hydrogen storage applications. These efforts will lead to lower costs and improved performance in hydrogen and fuel cell technologies and will help to enable widespread commercialization of these technologies.

DOT/FHWA: The Federal Highway Administration is pursuing nanotechnology-enabled improvements in the durability, performance, and resiliency of transportation infrastructure. Current nanomaterials efforts focus on conventional and alternative cementitious materials. Durability and performance enhancements have been demonstrated through modification and enhancement of interface behavior. Nanoscale interrogation and characterization techniques are expanding the fundamental understanding of cement hydration kinetics and the ability to model them. Structural health monitoring, self-repair capability, and the ability to detect and mitigate corrosion will all benefit from advancements in multifunctional infrastructure materials.

NIH: Concurrent with the expected start of the third round of the Alliance for Nanotechnology in Cancer funding in 2015, NIH/NCI expects to release an updated version of the caNanoPlan, a vision for the future of cancer nanotechnology R&D that is coordinated by the NIH/NCI Office of Nanotechnology Research and prepared with input from the cancer nanotechnology research community. Researchers from academia, small business, government labs, and pharmaceutical companies have participated in drafting previous editions of the caNanoPlan, which included milestones and strategic insight for cancer nanotechnology development.

NSF: NSF is supporting a study on Nanomodular Materials and Systems by Design[56] to identify international activities and research directions to help inform NSF's setting of its R&D priorities.

USDA/ARS: Nanotechnology investments include research in the following areas:

- Environmentally friendly processes and new applications for animal hides and leather, including collagen-based nanofibers for high-efficiency, biodegradable air filters.
- Development of new bioactive and bio-based products from plant cell wall polysaccharides in sugar beet pulp, citrus peel, and other processing residues, including polysaccharide-based nanoparticles for controlled release of bioactive food ingredients and for active packaging applications.
- Imaging technology for food safety and security, including use of Raman scattering with silver nanorods or use of nanoscale peptides and DNA aptamers to detect food-borne pathogens and toxins.
- Processing technologies to produce healthy, value-added foods from specialty crops, including applications of methylcellulose and chitosan nanoparticles in edible films.
- Development of nanoscale coatings to make cotton flame resistant, and deposition of enzymes/peptides on cotton nanocrystals for applications in biosensors, antimicrobials, and bioremediation.
- Novel methods for manufacturing of bioproducts from agricultural feedstocks, including blow spinning and electrospinning of biopolymers to produce nanocomposites, nanofoams, nanofibers, microemulsions, and hydrogels.

USDA/NIFA: The NIFA nanotechnology program supports foundational sciences and innovative ideas to develop nanotechnology-enabled solutions for a range of national priorities, including global food security through improving productivity, quality, and biodiversity; adaptation and mitigation of agricultural production systems to climate changes; improvement of the nutritional quality of food and feeds; early detection and effective intervention technologies for ensuring food safety and biosecurity; more effective therapies that significantly improve animal health and wellness; development of the biology-based economy; and increased protection for natural resources, the environment, and agricultural ecosystems.

[56] www.wtec.org/nmsd

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 1.2

DOD/Air Force, industries, and universities: The Munitions Directorate of AFRL is collaborating with the State University of New York (SUNY) at Stony Brook and Brookhaven National Laboratory (BNL). Early results indicate unprecedented quality, density, and sizes of nanoparticles; tests are underway to find evidence of enhanced catalytic activity for CO_2 reduction and CO oxidation. The AFRL Information Directorate is currently collaborating with SUNY Polytechnic Institute (a merger of the former Albany College of Nanoscale Science and Engineering and SUNY Institute of Technology in Marcy, NY) under an educational partnership agreement to study emerging nanotechnologies. In addition, AFRL/RI is collaborating with IBM, Hewlett-Packard, Boise State University, University of Massachusetts, SUNY Binghamton, San Francisco State University, University of Pittsburgh, Rochester Institute of Technology, ARL, Sandia National Laboratory, and the National Security Agency on grants and other agreements.

DOE and NSF: NSF and DOE co-sponsor the Quantum Energy and Sustainable Solar Technologies (QESST) Engineering Research Center (ERC), which conducts photovoltaic (PV) research. The DOE Hydrogen and Fuel Cell Technologies Program activities are coordinated primarily with DOE-SC and NSF working to understand the fundamental science behind relevant nanomaterials. The findings from the fundamental work are then applied to the HFCT R&D efforts to further develop and then to commercialize nanoscale technologies in hydrogen fuel cells.

NIH and other NNI agencies: NIH/NCI, the NIH National Institute of Biomedical Imaging and Bioengineering (NIBIB), and the NIH National Institute of Environmental Health Sciences (NIEHS) participate in the Sensors and NKI National Nanotechnology Signature Initiatives *[also applicable to Objective 1.4]*. Numerous stakeholder engagement efforts have been undertaken through these initiatives.

NIH/NIDCR will utilize an interagency agreement with NIST to evaluate novel dental composite restorative polymers and the complete dental restorative systems generated as a result of the U01 effort.

NIOSH, industry, and universities: NIOSH continues to provide broad support to advancing nanotechnology research through active partnership with the private sector and with public research institutes. Research collaboration agreements with organizations such as the Center for High-rate Nanomanufacturing, the Colleges of Nanoscale Science and Engineering, and Purdue University give NIOSH unique insight into the materials and processes that are being explored for commercialization. Direct partnership with private-sector nanomanufacturers gives NIOSH an opportunity to make a significant contribution to safe and responsible development early in the material and/or product life cycle. In addition to protecting the nanotechnology workforce from R&D to production, this activity has the potential to enhance speed to market and to create a competitive advantage by developing effective risk management practices.

NIST, NIOSH, FDA, industry, and universities: NIST, working closely with other Government agencies, industry, and academics, has coordinated interlaboratory studies to validate a measurement protocol for transmission electron microscopy, a technique commonly employed to determine nanoparticle size and size distribution. Now that the comparison on the national level is complete, work is underway with international partners, including many national metrology institutes, to corroborate findings for different particle types and then develop documentary standards describing the processes.

NSF, NIH, EPA, DOD, NASA, and USDA/NIFA: Convergence of nanotechnology with other technologies and areas of application was analyzed in the NSF-led study and 2013 report created in collaboration with

NIH, EPA, DOD, NASA and USDA/NIFA, *Convergence of Knowledge, Technology, and Society*.[57] This report identifies convergence as a core opportunity for creating added value and progress based on five principles: interdependence, enhancing creativity and innovation through evolutionary processes of convergence that combine existing results and divergence that creates new ones; decision analysis based on system logic deduction; higher-level cross-domain languages; and vision-inspired basic research embodied in grand challenges. The process of convergence facilitates penetration of nanotechnology into various domains of knowledge and application.

NSF, NIST, and industry: The Semiconductor Research Corporation (SRC) Nanoelectronics Research Initiative (NRI) works with NIST and NSF to address the confluence of two key national priorities that are also associated with long-standing U.S. Government interagency research initiatives with special focus on future logic and memory devices beyond CMOS: (1) nanotechnology in the NNI, and (2) information technology in the Networking and Information Technology Research and Development (NITRD) Program.

USDA/FS, NNI agencies, industry, and universities: In May 2014, the Forest Service, in collaboration with NNCO, held the FS-NNI workshop, Cellulose Nanomaterials: A Path towards Commercialization. The goal of the workshop was to identify commercialization barriers from a user's perspective. Attendees included 130 people from the public and private sectors. Panelists and participants included representatives from 12 government agencies *[also applicable to Objective 1.4, Sustainable Nanomanufacturing NSI]*.

Objective 1.3 – Assess the performance of the U.S. nanotechnology R&D program.

Individual Agency Contributions to Objective 1.3

NIH: Evaluation of the impact of R&D strategic plans and scientific programs and initiatives is a standard practice for NIH institutes to justify further investments. These reviews utilize a variety of mechanisms and approaches to assess performance—scientific experts, advisory boards, analytical tools for metrics, etc.—which vary depending on the program structure and governance. The NIH Common Fund Nanomedicine Initiative underwent a program evaluation in parallel with the annual reviews of the National Network of Nanomedicine Development Centers' scientific progress since 2006–2007. Because this 10-year high-risk, high-reward pilot program was managed under the Flexible Research Authority Act, program funds and resources could be redistributed to adapt the centers' findings to translational studies by the end of the initiative in 2015.[58]

The NIH/NCI Alliance for Nanotechnology in Cancer also performed a performance assessment as part of planning exercises undertaken in 2013 to prepare a strategy for NIH/NCI's nanotechnology investment for 2015 onwards. This performance assessment combined the results of a pilot analysis of Alliance network connectivity and productivity with NIH portfolio analysis, bibliometric analysis of Alliance publications, and input from an external evaluation committee. The Alliance office also prepared an extensive report on the training and research outcomes of external Alliance support, based on published research results, U.S. patent database searches, registered clinical trials and Institutional Review Board approved studies, self-reported outcomes from training centers, and public accounts of activities by companies spun out by academic researchers in the Alliance. The results of this assessment led to the renewal in 2014 of the Alliance program for a third round of funding, maintaining both research and training centers and

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[57] M. C. Roco, W. S. Bainbridge, B. Tonn, G. Whitesides, Eds., *Convergence of knowledge, technology, and society: Beyond convergence of nano-bio-info-cognitive technologies* (Springer, Dordrecht, The Netherlands, 2013: www.wtec.org/NBIC2-Report).

[58] commonfund.nih.gov/nanomedicine/overview

individual research awards. The balance of effort between basic and translational research was slightly adjusted based on the results of this assessment, with greater emphasis placed on both the earliest and most mature stages of technology development.

The Alliance office plans to continue evaluation efforts throughout the third round of Alliance funding. The Programs of Excellence in Nanotechnology (PEN) of the NIH/NHLBI will be used for comparisons with the Alliance program. The evaluation will measure research efficacy/effectiveness, accelerated progress towards translational success, and training outputs and outcomes of these two programs. The evaluation will place a greater emphasis on assessing the potential clinical vs. scientific value of Alliance-supported technologies and analyzing roadblocks to translation. This is intended to improve the effectiveness of efforts to transfer technologies from the lab to the clinic and provide valuable feedback to researchers and their institutions regarding their development strategies.

NSF: The Center for Nanotechnology in Society (CNS) at Arizona State University has ongoing evaluation activities for research performance and nanotechnology outcomes. The CNS node at Georgia Institute of Technology evaluates trends in publications, patents, and commercialization through data mining, interviews, and other methods as part of the "Research and Innovation Systems Analysis" group. The group's main goal is to characterize the technical scope and dynamics of the nanoscale science and engineering enterprise and the linkages between it and a variety of public values and outcomes.

USDA/NIFA: NIFA regularly evaluates the performance and progress of its nanotechnology R&D projects using multiple instruments such as mandated annual progress reports, grantees meetings, workshops, symposia, and professional conferences. For example, the NIFA Agriculture and Food Research Initiative (AFRI) provided a conference grant to support an international food nanotechnology symposium, which was held in conjunction with the 17th World Congress of Food Science and Technology in Montreal, Canada, on August 17–21, 2014. U.S. scientists and NIFA grantees presented their latest research results at this conference, which attracted broad international attention. NIFA will provide funding and leadership for the first Gordon Research Conference on Nanoscale Science and Engineering for Agriculture and Food Systems, which will be held at Bentley University in Waltham, MA, on June 7–12, 2015.

USPTO: The U.S. Patent and Trademark Office contributes a variety of nanotechnology-related patent data that is used as a benchmark to analyze nanotechnology development and for trend analysis of nanotechnology patenting activity in the United States and globally. The data shows that since the start of the NNI in 2000, both the percentage of nanotechnology-related U.S. patents assigned or owned by universities and the percentage of nanotechnology-related U.S. patents with government interest statements have nearly doubled. Both of these increases are likely attributable to the increased Federal R&D funding from the NNI. Regarding international nanotechnology-related patenting activity, U.S. inventors continue to lead in the total number of nanotechnology-related patent publications globally; however, that lead has been shrinking. U.S. inventors continue to lead in the total number of nanotechnology-related patent publications in three or more countries, holding almost a third of the total, indicating their aggressive pursuit of international intellectual property protection.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 1.3

DOD/Air Force and industry: Exploring the potential impact of nanomaterial-enabled applications is essential to the AFRL nanotechnology research portfolio. Nanomaterials and nanodevice research is informed by advances in nanomanufacturing to determine where application goals can be met. Nanomanufacturing methods and analysis is a key focus area of AFRL. The Nano-Bio Manufacturing Consortium (NBMC) aims to bridge the gap between research and technology development in nanomaterials and nanotechnology by creating a shared environment for academic and industrial scientists to pursue transition opportunities. The teams executing the Air Force efforts towards this objective include academic–industrial partnerships fostered by interaction through NBMC. The specific information has been used both for comparison with technical goals in these areas and to evaluate the current overall nanomaterials engineering capability. One focus of the NBMC is nanosensors. Nanotechnology-based sensors operating on nature-inspired principles will produce unprecedented levels of sensitivity and performance for a range of applications in monitoring aerospace, medicine, and human performance aspects of interest.

NNI agencies, NNCO, National Academies, and the President's Council of Advisors on Science and Technology (PCAST): As discussed in Chapter 1 of this report, the NNI participating agencies and NNCO contribute significant background information and other resources, as appropriate, to the periodic reviews of the NNI by the National Academies and PCAST. These reviews include assessment of the performance of the nanotechnology research supported by the NNI agencies.

Objective 1.4 – Advance a portfolio of Nanotechnology Signature Initiatives (NSIs) that are each supported by three or more NNI agencies and address significant national priorities.[59]

Nanotechnology for Solar Energy Collection and Conversion

Individual agency contributions to this NSI

DOD/Air Force: AFRL's Materials and Manufacturing Directorate (AFRL/RX) continues to contribute to this NSI. Current activities are focused in three areas: (1) developing approaches to fabricate these devices on flexible and lightweight substrates to enable structural power applications (such as solar aircraft wings); (2) designing reproducible recombination layers for tandem (multilayer) devices; and (3) developing direct-write approaches for on-demand, low-cost, scalable integration of these devices onto aircraft skins. These devices are expected to have the greatest impact for applications requiring very high specific power (watt per gram) such as unmanned air vehicles and geostationary high-altitude airships.

DOE: DOE-SC supports a wide array of fundamental research related to solar energy collection and conversion in areas such as photovoltaics, solar photochemistry, and solar fuels. Funded projects include a significant fraction of the Solar Photochemistry Program, a number of Energy Frontier Research Centers and the Joint Center for Artificial Photosynthesis, an Energy Innovation Hub. Selected examples of such research include the following:

- Understanding molecular mechanisms that capture light energy and convert it into chemical and electrical energy in natural systems.
- Developing efficient artificial photosynthetic systems and a molecular-level understanding of solar energy capture and conversion in the condensed phase and at interfaces.
- Studying the elementary steps involved in light absorption and energy transfer, charge separation, and charge transport within chemical systems.
- Exploring the elementary energy conversion steps in photovoltaic materials and solar cells.
- Understanding and designing catalytic complexes or solids that generate chemical fuel from carbon dioxide and/or water, with the ultimate goal of creating transformative advances in the development of artificial photosynthetic systems for converting sunlight, water, and carbon dioxide into a range of commercially useful fuels.

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[59] For additional information on the Nanotechnology Signature Initiatives, see the 2014 NNI Strategic Plan www.nano.gov/2014StrategicPlan and www.nano.gov/signatureinitiatives.

The DOE-EERE Solar Energy Technologies Office supports a variety of projects related to nanotechnology research and development in this NSI at the intersection of scientific disciplines, such as those focused on crystal grain boundaries and nanoscale arrays of photoactive materials.

NIST: NIST is developing measurement methods needed to characterize the essential nanoscale processes in photovoltaic materials and devices. In support of this NSI, NIST developed a laser-based instrument that generates artificial sunlight to help test solar cell properties and find ways to boost their efficiencies. The instrument is based on a white light laser that uses optical-fiber amplifier technology to boost the power and a photonic crystal to broaden the spectrum. With a focused spot size below 2000 nanometers, the simulator enables researchers to optimize advanced photovoltaic materials such as quantum dots, polycrystalline semiconductors, and multijunction stacks. NIST is working to make the new simulator programmable and portable for use outside NIST. NIST also applied scanning microwave microscopy to photovoltaic (PV) materials and is refining scanning microwave probe technology for improved reliability. Transient laser spectroscopy methods are being employed to directly measure nanoscale charge carrier processes in organic PV materials to improve solar cell efficiencies. NIST developed *in situ* measurements of the nanoscale structure of organic PV materials under processing conditions that enable connections between processing methods and device performance.

NSF: NSF supports basic research and interdisciplinary efforts by groups of primarily academic researchers to address the scientific challenges of highly efficient harvesting, conversion, and storage of solar energy—projects in the Mathematical and Physical Sciences (MPS), Engineering (ENG), Computer and Information Science and Engineering (CISE), and Biological Sciences (BIO) directorates. A primary emphasis is on the education, at all levels, of a highly trained scientific and technical workforce. NSF activities that address research topics generally related to this NSI include Engineering Research Centers such as the QESST ERC and the Emerging Frontiers in Research and Innovation (EFRI) activity.

The Sustainable Energy Pathways (SEP) Program is part of the NSF-wide initiative on Science, Engineering, and Education for Sustainability (SEES). The SEP solicitation calls for innovative, interdisciplinary basic research in science, engineering, and education by teams of researchers. One example of an SEP program that addresses the goals of this NSI is the Development of Economically Viable, Highly Efficient Organic Photovoltaic Solar Cells Program, which is administered through the University of Chicago, Northwestern University, and UCLA. This program is aimed at achieving low-cost solar energy conversion to electricity through the development of organic photovoltaic (OPV) solar cells, through evaluating the sustainability of OPV technology, and through addressing the environmental and economic aspects of OPV technology.

The MPS and ENG directorates are responsible for over 80% of the NSF investment. Examples of investments relating to this NSI include research on photovoltaic energy conversion theory, modeling, surface chemistry, materials synthesis, device physics, engineering and characterization, and nanotechnology for power electronics.

USDA/NIFA: The NIFA/AFRI nanotechnology program supports a broad range of value-added uses of agricultural bionanomaterials and products to strengthen the national economy while seeking innovative technologies to provide new energy sources.

Coordinated activities with other agencies and other institutions contributing to this NSI

DOD/Army, industry, universities, and government laboratories: ARL is working with industry (MicroLink Devices, Emcore), academia (University of Texas, UCLA, University College of London) and other U.S. Government laboratories (National Renewable Energy Lab) to develop low-cost, high-efficiency gallium arsenide-based solar cells that use quantum dots, quantum wells, and surface nanostructures to enhance the spectral response and absorption properties of portable power sources for the dismounted soldier. Under internal and SBIR programs, ARL is developing special electrically conducting, antireflection coatings that work efficiently over a very large range of incident angles to eliminate the need for bulky light-tracking hardware. Nanostructured back surface reflectors are being developed to enhance absorption through light trapping and wave guiding. The goal of this research is a new generation of flexible, conformable, lightweight energy sources to lighten the burden on and extend the mission times for the soldier.

NSF and DOE: In addition to continuing participation by NSF and DOE in the Solar NSI, the two agencies are co-sponsoring the Engineering Research Center for Quantum Energy and Sustainable Solar Technologies (QESST ERC), another research center that involves industry collaboration. This center has been jointly funded by DOE's Solar Energy Technologies Program and NSF since 2011. QESST research focuses on developing a fundamental understanding of electronic excitations, relaxation, and transport in nanostructured materials, leading to materials with electric-charge collection efficiencies in excess of the single-junction solar cell limit. Under development in this research center are sophisticated new III-V quantum-scale semiconductor materials and solar designs with projected efficiencies in excess of 50%, and new photovoltaic energy concepts that will enhance planetary and deep space exploration. This center also works with companies to advance technologies toward commercialization.

NSF, DOE, and NIST: The annual "Photovoltaic Specialist Conference," which is co-sponsored by DOE, NSF, and NIST, continued to be held in each of the years following the articulation of this NSI (2010 through 2014). This conference also has included a workshop titled PV Velocity Forum: Accelerating the PV Economy that was jointly planned and implemented by DOE and NIST.

NSF, industry, and universities: Collaborative research centers have facilitated ongoing partnerships between participating agencies, industry, and academia, thereby helping to strategically focus R&D efforts and efficiently implement R&D advances. For example, the Silicon Solar Consortium Research Center is an NSF Industry/University Cooperative Research Center (I/UCRC) that involves joint NSF and industry funding. This center performs research on crystalline silicon crystal growth, impurities and defects, photovoltaic device processing, process modeling and simulation, and module issues. This center has created a multiuniversity, multicompany culture addressing the science and technology issues that the international photovoltaic silicon materials industry must solve in order to meet the future needs of advanced silicon solar cell manufacturing, while educating graduate students with photovoltaic materials/devices expertise to meet future workforce needs. As a collaborative agency-industry enterprise, this center conducts the critical research related to improving the efficiency of PV devices while addressing the manufacturing issues related to realizing the commercialization of these devices.

Sustainable Nanomanufacturing: Creating the Industries of the Future

Individual agency contributions to this NSI

DOD: A project under the Defense Production Act Title III Program, Advanced Carbon Nanotube Volume Production, is providing infrastructure for the world's first industrial-scale manufacturing facility producing carbon nanotube (CNT) yarn, sheet, tape, and slurry materials. These materials provide the warfighter with improved protection and survivability, while improving mission effectiveness and reducing operating costs. Project emphasis is on increasing output volume by expanding flexible, scalable, and modular production processes; improving product availability, quality, and yield; and reducing manufacturing costs. Carbon nanotubes exhibit extraordinary strength, unique electrical properties, and are highly efficient thermal conductors. They are the strongest and stiffest materials yet discovered in terms of tensile strength and elastic modulus, respectively. CNT materials conduct electricity, shield from electromagnetic interference and electromagnetic pulses, block flames, and enhance ballistics protection, while being impervious to corrosion, heat and cold, or sunlight degradation. CNT yarn, sheet, tape, and slurry-based products have shown that they can successfully operate in broader temperature ranges, radiation levels, or corrosive environments than conventional materials. This project initially made operational a pilot facility that has been producing CNT material for test and evaluation purposes. Tens of thousands of square feet of sheet material and thousands of kilometers of yarn made in this facility have been delivered to customers. From this contractor facility, CNT electrostatic discharge/electromagnetic interference shielding has achieved a technology readiness level (TRL) of 8/9 for spacecraft, while CNT heaters, data cables, and enhanced soft and hard ceramic armor have all achieved TRL 6. The project recently funded expansion from Pilot to Low Rate Production level, augmented by company funds, with a 2015 start date. When completed, this expanded capability will, for the first time, provide tonnage quantities of advanced CNT products sufficient for qualification and initial insertion into programs for aerospace, ballistics protection, and aircraft.

DOD/Air Force: AFRL/RX is conducting numerous research efforts toward nanoelectronics, with efforts focused on enhanced electron and phonon transport, carbon nanotubes, 2-D and 3-D electron gas structures, oxide nanostructures, thin-film processes, and predictive modeling of materials performance for applications in surveillance and electronic warfare. Significant efforts throughout the Directorate are focused on the development of metallic, organic, and carbon nanotube inks for a wide range of nanoelectronic devices, including flexible, inherently rugged electronic displays and active devices.

DOD/Army: ARL successfully engineered a new method of producing stable nanocrystalline powders with sufficient stability to resist microstructural changes during the high-temperature processing needed for full-density consolidation. Availability of advanced nanocrystalline alloys is critical to the paradigm shift mandated for future Army infantry, weapons, and vehicle performance. Thermodynamically, nanocrystalline microstructures are subject to coarsening at room temperature. Therefore, the processing and applications of these materials will be limited by the ability to create stabilized microstructures. Current users exploit state-of-the-art, atomic-level characterization techniques to identify and determine the electronic contributions responsible for reducing and minimizing the interfacial energy of high-temperature nanocrystalline alloys that are relevant to Army applications. Through this process, researchers have been able to bulk-consolidate and/or produce near-net-shaped parts, retaining nanocrystalline microstructure, potentially suitable for various Army applications. These include aluminum alloys for lightweighting ballistic applications, nanostructured steels for ultrahigh strength at high temperatures, and nanostructured materials for penetrator applications.

The STTR program provides funding to develop viable, cost-effective, industrial production techniques for carbon-nanotube-based fibers with low density and ultrahigh strength and toughness. ERDC research recently demonstrated a proof of concept for a viable, cost-effective, industrial production technique for such CNT-based fibers. Based on this research, Materials and Electrochemical Research (MER) Corporation developed a continuous industrial manufacturing process for direct spinning of carbon-nanotube-based fibers through the STTR program.

The ERDC Materials Engineering research program provided funding for research titled "Multi-Scale Understanding and Engineering of Grain Boundaries in Ceramics." The High-Performance Computing and Modernization Program provided the over 40 million CPU hours required to optimize the material design, manufacturing processes, and component design before attempting to fabricate the materials. Advances in theoretical and computational techniques to solve high-fidelity, physics-based problems coupled with high-performance computing (HPC) allow constitutive properties of materials to be determined based on their atomic and molecular structure. High-performance polycrystalline ceramics such as silicon carbide

(SiC) would have significant potential as replacements for aluminum and steel in structures, if it were not for their relatively low fracture toughness and tensile strength. Researchers are attempting to engineer state-of-the-art synthetic materials using mechanical design principles found in nature. The weak constituents found in nature are replaced with advanced synthetic engineered materials, with the goal of producing structural composite materials with mechanical properties that exceed those of both the natural materials and the state-of-the-art synthetic materials. Some underlying strategies are beginning to emerge that reflect general design concepts for achieving optimal performance from materials assembled from components with disparate and seemingly incompatible properties. A detailed understanding of the roles and relative properties of the natural materials used to achieve the desired mechanical properties and of the mechanistic behavior of natural materials is required to engineer state-of-the-art synthetic materials. Advances in micro- and nanoscale *in situ* experiments and computational techniques are shedding light on the delicate structure–property relationships required to reproduce the behaviors found in biomaterials. The results of this project demonstrate the potential benefit of an integrated computational/experimental approach to materials development. Access to HPC resources improves the quality of research by extending the size and complexity of problems that can be solved with the aid of modeling and simulation. Using simulations to optimize the material design, manufacturing processes, and component design before attempting to fabricate the materials accelerates the development process.

DOD/Navy: The Navy Nanomanufacturing Program is developing the fundamental knowledge base for high-rate nanomanufacturing of full-function hybrid flexible electronic systems and the basic science needed for building fast, power-efficient, high-density circuits on flexible substrates for a variety of applications. The proposed flexible electronic system is a wearable multifunctional distributed sensor network for brain–machine interfacing (BMI) with sensor arrays, wireless transmission, power management, and battery as components. BMI would be of DOD and commercial interest. The program is also working to fabricate efficient inorganic nanorod/polymer thin film solar cells with the nanorods vertically oriented by a magnetic field in a continuous high-rate nanomanufacturing process.

NASA: NASA continues to work with industry, universities, and other Federal agencies in the development of ultralightweight, high-strength composites based on carbon nanotube reinforcements and their application in aerospace components. This project, supported by the Space Technology Mission Directorate's Game Changing Development Program, will design, build, and flight-test in 2016 a carbon nanotube-reinforced composite overwrapped pressure vessel. Since 2013, NASA researchers, under a Center Innovation Fund project, have been exploring the use of halogen intercalation chemistries to improve the electrical conductivity of carbon nanotube yarns and fibers for use in lightweight data and power cables. In 2014, this research established a new world's record on the electrical conductivity of carbon nanotube-based wires. This work is continuing in 2015 with support from the Game Changing Development Program.

NIOSH: NIOSH is expanding its research activities that have direct connections to the NSIs. Many activities begun in 2014 and carried into 2016 are focused directly on safe and responsible development of nanomaterials, nanomanufacturing processes, and nanotechnology-enabled products. In 2015, NIOSH began to develop and disseminate case studies that demonstrate the utility of applying Prevention through Design (PtD) principles to nanomanufacturing. In 2016, NIOSH will increase its efforts to apply PtD principles to the design of safer nanomaterials by identifying physicochemical properties of nanomaterials that can be modified to decrease adverse biological responses. A research partnership with the University of Akron demonstrated that changing the structure of aluminum oxide nanowires can be used to modify their dissolution in the lung, thereby reducing the potential for damage. In 2016, similar work on TiO_2 nanowires will be published. NIOSH will use strategic partnerships with business and academia to develop and deploy effective EHS practices that can be incorporated into business and research plans. Partnerships with private nanomanufacturing companies will be expanded in 2016 to include extension of effective risk management practices into elements of the Administration's Advanced Manufacturing priority area by working directly with the emerging National Network for Manufacturing Innovation (NNMI). Many nanomaterial-enabled applications and products will realize full commercialization through advanced manufacturing technologies, and NIOSH will extend and reapply knowledge gained from nanomanufacturing into this area. *[Funding for this activity is reported by NIOSH under PCA 5; the activity also is relevant to Objective 4.4.]*

NIST: NIST continues to advance the availability of nanomanufacturing measurement technologies. The agency has developed high-throughput, microwave-based measurement methods to characterize the nanostructure of carbon nanocomposites. High-resolution tomography enables the development of material models to support microwave measurements of nanotube orientation and waviness—parameters essential to understanding the effect of processing on material performance. NIST is developing new methods to aid in understanding the long-term reliability of carbon nanocomposites, including new approaches to performing accelerated aging studies and fluorescence methods for *in situ* diagnosis of mechanical damage and aging effects. NIST began a new effort in 2015 to develop low-cost methods for multiparameter nanoparticle characterization.

NSF: The NSF Nanomanufacturing Program and other core programs fund fundamental research projects and have contributions in carbon-based nanomaterials, optical metamaterials, and cellulosic nanomaterials. A program solicitation on Scalable Nanomanufacturing has had two competitions, in 2013 and 2015; another is planned for 2016.

USDA/NIFA: NIFA's current focus in nanomanufacturing is on nanobiomaterials derived from various forest, crop, and biomass by-products. There are ongoing research efforts in synthesis of carbon-based nanomaterials; development of cost-effective production methods; functionalization and characterization of nanomaterials; and exploration of applications such as piezoelectrics, renewable nanocomposite polymers, food packaging, barrier films, and others.

Coordinated activities with other agencies and other institutions contributing to this NSI

DOD/Air Force, industry and universities: The Materials and Manufacturing Directorate's work is coordinated with other DOD and Government agencies through DOD's Reliance 21 and Communities of Interest (Advanced Materials and Energy and Power) joint planning and coordination efforts as well as through the broader-based Interagency Advanced Power Group. AFRL collaborates with many institutions and industrial partners such as the Georgia Institute of Technology, Northwestern University, and the University of Chicago.

DOD/Army, NSF, and universities: Army efforts are highly embedded within universities, including collaborations with George Mason University, MIT, Pennsylvania State University, University of North Carolina, North Carolina State University, Drexel University, and Texas A&M University. Other partners include Los Alamos National Laboratory, the ARL Sensors and Electron Devices Directorate, and the Army Armor Research, Development, and Engineering Center. There are collaborations with the Center for Computational Materials Design, an NSF-supported I/UCRC, on various aspects of phase formation and grain growth. The ARL internal mission program was instrumental in developing an ARL/Army Research Office SBIR project focused on the processing and property interrogation of high-strength nanostructured aluminum alloys. This program directly impacts the Army lightweighting capability by seeking to develop alloys that exceed the expected physical properties of current aluminum alloys. This would enable weight reduction of 65% in alloys with ultrahigh toughness.

NNI agencies: With support from the NNCO, agencies participating in this NSI collaboratively organized a symposium on Sustainable Nanomanufacturing at Nanotech 2014 (June 2014 in Washington, DC)[60] and participated in meetings of the NSI group to exchange information and coordinate nanotechnology efforts in this field. In May 2014, a wide range of experts representing industry, academia, and government were brought together at a workshop entitled Cellulose Nanomaterials: A Path toward Commercialization.[61] In September 2014, the NNI agencies, with support from NNCO, organized a technical interchange meeting, Realizing the Promise of Carbon Nanotubes: Challenges, Opportunities, and the Pathway to Commercialization.[62] Additional details on both workshops can be found in Chapter 1.

NIST, universities, and industry: Two technologies developed at NIST—microwave technology used to characterize carbon nanocomposites during manufacture, and a scalable separations technology for carbon nanotubes—are being transferred to industry via SBIR awards. NIST partnered with universities to accelerate progress in the understanding of carbon nanocomposite electrical properties, inter-nanotube interactions, and processing parameters as they affect mechanical properties and lifetime performance.

Nanoelectronics for 2020 and Beyond

Individual agency contributions to this NSI

DOD/Air Force: The AFOSR Optoelectronics and Photonics Program explores nanotechnology approaches to optoelectronic information processing, integrated photonics, and associated optical and photonic device components for air and space platforms to transform Air Force capabilities in computing, communications, storage, sensing, and surveillance. Major areas of emphasis are nanophotonics (including plasmonics, photonic crystals, metamaterials, metaphotonics, and novel sensing) and nanofabrication. Projects include (1) nanopillar-based photonic crystal lasers; (2) integration of nanopillar lasers and avalanche photodiodes (APDs) for ultrahigh-density optical interconnects; (3) nanopillar arrays for waveguides; and (4) electrical interfaces and modulation for plasmon lasers. The AFOSR Quantum Electronic Solids Program focuses on superconductors, metamaterials, and nanoscopic electronic devices based mainly upon graphene, nanotubes, and other forms of carbon with low power dissipation and the ability to provide denser nonvolatile memory, logic, and/or sensing elements that have the potential to impact future Air Force electronic systems. The program explores nanoscopic techniques to fabricate, characterize, and manipulate atomic-, molecular-, and nanometer-scale structures (including graphene and nanotubes of carbon and other elements), with the aim of producing a new generation of improved communications components, sensors, and nonvolatile, ultradense memory, resulting in the ultimate miniaturization of analog and digital circuitry. Both programs jointly sponsor the MURI, "Quantum Metaphotonics and Metamaterials: From Single Emitters to Strongly Correlated Systems," led by Brown University. The central objective of this project is to integrate quantum emitters with optical metamaterials in order to expand and redefine the range of light–matter interactions and electronic excitations for solid-state quantum optics. The program will demonstrate how the electromagnetic design freedom enabled by metamaterial cavities, waveguides, and antennas can be leveraged to enhance microscopic light–matter interactions with single emitters to realize new regimes of cavity quantum electrodynamics (cQED), and enable collective excitations in dense emitter ensembles to realize photonic analogs of strongly correlated quantum solids. Metamaterials research has expanded the range of optical materials and optical phenomena available for photonic devices. By engineering the electric and magnetic resonances of

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[60] www.techconnectworld.com/Nanotech2014/sym/Sustainable_Nanomanufacturing.html

[61] www.nano.gov/ncworkshop

[62] www.nano.gov/node/1226

patterned nanostructures, researchers have been able to tailor classical properties, including the effective permeability and permittivity of composite media.

AFRL/RX is exploring nanoelectronic materials and their synthesis processes to improve device performance and reliability and to develop additive manufacturing technologies that are less dependent on foreign foundries. Currently, most electronic materials are manufactured abroad, which places the United States at a strategic disadvantage for next-generation electronic materials. Alternative processes for electronics manufacturing are being explored to allow for cost-effective and rapid progress in advanced nanoelectronic materials, which can include 0-D (e.g., quantum dots), 1-D (e.g., nanotubes and nanowires), and 2-D (e.g., monolayer) approaches. These materials and processes are of strategic importance for both DOD applications (sensors, communications, navigation, etc.) and for commercial products in telecommunications, computation, medicine, and other fields. AFRL is actively researching these nanoscale electronic materials and their processing technologies, as well as developing strategic partnerships with U.S. academic research centers and industry for both research advancements and applications development.

DOD/Army: Emerging 2-D materials such as graphene, molybdenum disulfide, and other transition-metal dichalcogenides have been shown to exhibit excellent electrical and optical properties as well as useful physical traits such as transparency and conformability. Their two-dimensional nature allows them to be stacked in varying orientations and on varying substrates to tailor their electrical and optical properties. ARL researchers are leading a program entitled Understanding and Exploiting the Electronic Interface in Stacked 2-D Atomic Layered Materials, the goal of which is to explore and exploit the layer interaction phenomena observed between 2-D atomic layers in a heterogeneous stack. The interface and surface properties of 2-D materials are intertwined, allowing the engineering of new material systems that behave quite differently from their bulk counterparts. The program is performing research in materials growth, materials characterization, device fabrication and testing, and theoretical and computational modeling.

DOD/DARPA: Semiconductor devices are periodically “scaled” using advances in lithography and other chemical-mechanical-thermal processes. The scaling of conventional field-effect silicon devices (so-called "Moore's Law" scaling) is nearing fundamental and economic limits. The DARPA STARnet Program is exploring devices and approaches that may transcend the end of the scaled transistor. This program is also exploring other uses for new devices that can realize new types of circuits with advantages and functionalities that are not possible with conventional technologies.

Coherent collective effects in topological insulators (TIs) enable advances beyond 2020 by fundamentally altering the trade between carrier mobility and coherence time of conventional materials. DARPA is investing in a number of TI-based technologies to quantify the potential impact and rapidly mature the area. Investments include materials and fabrication while pursuing TI-based technologies for the basic building blocks of modern microsystems, including transistors, interconnects, thermoelectrics, and optical devices.

The DARPA Meso Program has been investigating a range of potentially game-changing nanoelectronic devices: piezoelectronic transistors, a handheld electronic biomolecular sensor, tunable on-chip filters and oscillators, and optomechanical information processing. Meso has developed methods to modulate states and stabilize circuits at quantum levels. This increases the spatiotemporal scales where quantum behavior can be exploited and provides the basis for robust control of nanotechnology.

DOD/Navy: For quantum information, a photonic crystal cavity coupled to control of long-lived quantum bits (qubits) provides the essential building block of a quantum network, which can be used for quantum communication or quantum computing. These can enable extremely secure communications and the processing of large data sets with superior speed, both of vital interest to the Navy and DOD. Up until now, a functional, long-lived qubit coupled to a photonic crystal cavity has not been available. NRL has developed a quantum dot spin qubit that is both long-lived and optically active, and has incorporated it into an optical cavity in a photonic crystal. Work continues to advance a universal single-qubit logic gate, as well as efficient and highly frequency-tunable photon emission.

NIST: NIST is making significant advances in developing measurements and fabrication approaches for high-performance nanoelectronics materials and devices. Programmatic efforts span a wide range of topics, including semiconductor nanowires and two-dimensional thin-film device platforms for electronic and nanophotonic applications; advancing processes to integrate molecular components into robust electronic devices with metal or silicon electrodes; measurements of the 3-D structure of directed self-assembly lithography processes for electronics manufacturing; developing new approaches to characterize topological insulators; characterizing the energy barriers at materials interfaces critical for future ultralow-powered electronics such as tunnel field-effect transistors (FETs); creating new nanoscale methods to measure and understand spin transport, dynamics, and related magnetic interactions in electronic and data storage devices; developing novel ways to measure and manipulate photons in nanophotonic applications; using photons to manipulate nanocomponents and create nanophotonic devices; characterizing the dynamics, efficiency, and stability of nanoelectromechanical resonators for advanced radio frequency communications; and coupling quantum optical and nanomechanical systems in silicon to create innovative devices for metrology and quantum communications applications. NIST is developing the technical and scientific expertise to transition quantum-information-based technologies to silicon-based platforms compatible with current silicon electronics technology. NIST is developing novel electrical characterization schemes to study the critical failure, drift, and variability mechanisms in sub-10 nm transistor structures. The NanoFab, a shared resource in NIST's Center for Nanoscale Technology (CNST) user facility, is providing support to this NSI by providing researchers access to a comprehensive commercial state-of-the-art tool set for nanoelectronics fabrication.

NSF: The primary focus of the NSF Nanoelectronics NSI investment is on upstream, exploratory research in the following areas: new alternative "state variables" for logic and memory components and suitable computer architectures; computer-based research of new devices; integration of nanoelectronic and nanophotonic components into new systems; and new quantum information system components and systems. Examples of core programs covering this thrust are the Electronic and Photonic Materials Program within MPS's Division of Materials Research; and the Electronics, Photonics, and Magnetic Devices Program within ENG's Division of Electrical, Communications, and Cyber Systems. Examples of center activities include the Materials Research Science and Engineering Centers (MRSECs), the Science and Technology Centers (STCs), the Engineering Research Centers (ERCs), and the Nanoscale Science and Engineering Centers (NSECs). Two examples are the STC on Quantum Materials and Devices at Harvard University and the MRSEC Center for Quantum and Spin Phenomena in Nanomagnetic Structures at the University of Nebraska, Lincoln. NSF has also supported the National Nanotechnology Infrastructure Network (NNIN), whose 14 universities provide capabilities that include nanoelectronics. The agency has under competition in 2015 the National Nanotechnology Coordinated Infrastructure (NNCI) with an annual budget estimated at $16 million, which will be operational in 2016 and will replace the NNIN.

Coordinated activities with other agencies and other institutions contributing to this NSI

NIST, DARPA, and industry: NIST is working with DARPA in its Unconventional Processing of Signals for Intelligent Data Exploitation (UPSIDE) program to exploit spin-based effects in nanostructures to develop non-Boolean computational methods for efficient pattern matching of complex signal inputs (e.g., video) in real time. This work is in collaboration with Intel and HRL Laboratories.

NIST, DNI, and industry: NIST is working with the Intelligence Advanced Research Projects Activity (IARPA) in its Cryogenic Computing Complexity (C3) program to assist in the development of spin-based nanoscale cryogenic memory and logic for energy-efficient exascale computing, which is critical for many national priorities and for national security. Raytheon BBN Technologies, Hypres, Northrop Grumman, and IBM are part of this program. NIST is developing state-of-the-art metrologies and benchmarks for IARPA.

NIST and industry: NIST is working with Intel under an Emerging Nanoscale Interface and Architecture Characterization (ENIAC) Program. More than 10 projects are underway to develop the new measurements needed at future nodes of semiconductor manufacturing.

NIST, industry, and universities: NIST is collaborating with several institutions to address new metrology challenges and characterize emerging research materials for advanced electronics, particularly low-dimensional electronics. Materials under investigation include carbon nanotubes, graphene, topological insulators, and atomically two-dimensional materials.

NIST, NSF, industry, and universities: Via the Nanoelectronics Research Initiative (NRI) public–private partnership, NIST, NSF, and U.S. member companies support 15 major interdisciplinary research teams at academic institutions across the Nation. A main new activity is benchmarking of new devices in order to make the best selection of future technology *[also applicable to Objective 2.2]*.

NNI agencies: With support from NNCO, agencies participating in the Nanoelectronics NSI collaboratively organized a symposium entitled Nanoelectronics for 2020 and Beyond at Nanotech 2014 (June 2014 in Washington, DC)[63] and participated in meetings of the NSI group to exchange information and coordinate nanotechnology efforts in this field.

Nanotechnology Knowledge Infrastructure (NKI): Enabling National Leadership in Sustainable Design

Individual agency contributions to this NSI

DOD/Air Force: The materials and manufacturing directorate of AFRL is focused on highly parallel experimentation to promote rapid exploration of nanomaterial growth and processing characteristics. For example, in carbon nanotubes, after two decades of work, nanotube growth is still not well understood. This has had significant industrial impact: where carbon nanotube synthesis is not well-controlled, this impedes our ability to scale production and decrease processing costs. Highly parallel and automated experimentation creates the ability to map the huge, multiparameter processing space to explore growth behavior and examine alternative processing conditions. This is the case with the system newly developed by ARES Security that has been used to perform thousands of experiments in months, dramatically expanding the understanding of growth and leading to conclusive information on catalyst form and growth processes.

NIH: NIH/NCI, NIH/NIBIB, and NIH/NIEHS have been active members of the NKI Signature Initiative since its inception. NKI activities mesh with NIH/NCI's interest in supporting nanoparticle characterization databases that provide a solid knowledge base for development of nanomaterials for use in cancer therapeutics. This knowledge base will also provide support for regulatory filings, long-term use of nanomaterials, and computational modeling of nanoparticle behavior in diagnostic and therapeutic applications. NIH/NCI supports the caNanoLab database, a web-based portal and data repository that allows researchers to submit and retrieve information on nanoparticles, including their composition, function (e.g., therapeutic, targeting, diagnostic imaging), physical (e.g., size, molecular weight), and *in vitro* experimental

[63] www.techconnectworld.com/Nanotech2014/sym/Nanoelectronics_2020_Beyond.html

characterization (e.g., cytotoxicity, immunotoxicity), along with information on the protocols used for these characterizations and links to related publications.

NIOSH: NIOSH supports the development of nanoinformatics tools for EHS practitioners. Specific activity areas include ongoing support for the Nanoparticle Information Library; migrating the GoodNanoGuide to nanoHUB at Purdue University; serving on the Nanomaterial Registry project board; and direct involvement in the planning and delivery of the Nanoinformatics workshop series. The GoodNanoGuide effort will include the collection of data on workplace exposures; experimental evidence and modeling of toxic effects from categories of nanomaterials; knowledge and data on efficacy of controls; recommended exposure limits; and tools and guidance to support sustainable nanotechnology. [*Funding for this activity is reported by NIOSH under PCA 5; it is also relevant to Objective 4.4.*]

NIST: NIST is developing a series of standard procedures to validate theoretical models and computational algorithms for use in predicting a wide variety of physicochemical properties of engineered nanomaterials. NIST efforts include validated models for direct comparison with nanomechanical property measurements of nanowires with the goal of producing predictive models; high-throughput methods to generate large quantities of processing-structure-properties data for inclusion in a new database; software to compute interactions between magnetic spins for visualization of nanoscale domain structures; and a database of computationally generated electrical properties and structures of metal nanoparticles. Testing of the nanoparticle database will begin in 2015, and the deployment of the database is planned for 2016.

NSF: NSF continues its participation in the NKI Signature Initiative through investments in nanoscale modeling and simulation, database networking, the computer user facility Network for Computational Nanotechnology (or in brief, nanoHUB), and Cyber-Enabled Discovery and Innovation initiatives within its Cyberinfrastructure Framework for 21st Century Science and Engineering—activities such as Software Infrastructure for Sustained Innovation. NSF will also contribute to the foundations of this NSI by means of specific databases for nanoscale materials and processes, transformative thinking about models for linkage of properties and behaviors at different scales, extension of computational and statistical techniques to support development and use of the nanotechnology cyber toolbox to accelerate discovery and manufacturing of nanomaterials and nanodevices, advances in fundamental theory and modeling, techniques across ranges of scales (from first principles to coarse-graining and phase-field modeling), and education by integrating the cyber toolbox into the fabric of next-generation science and the training of the next-generation modeling community.

Coordinated activities with other agencies and other institutions contributing to this NSI

NIH, NIOSH, universities, and industry: NIH/NCI and NIH/NIEHS have jointly supported the Nanomaterial Registry with NIH/NIBIB since 2012. The goal of the Nanomaterial Registry is to become the definitive cross-disciplinary resource for nanoparticle characterization data for health, toxicity, and industrial concerns. It draws inputs from existing curated databases, including caNanoLab, and currently includes over 1,300 particle entries. Entries are populated on the web portal through curated data extraction using a Minimal Information About Nanomaterials (MIAN) characterization vocabulary architecture. MIANs capture the physicochemical characteristics, biological interactions, and environmental interactions of the given particle. This homogenized vocabulary enables searches and comparisons based on MIAN similarity.

Outreach to scientific publishers has led to multiple publishing companies (including Nature Publishing Group, the American Chemical Society, and Elsevier) joining discussions on the implementation of shared policies for the deposition of nanoparticle characterization data into federally supported databases. The collection of these data as part of the publication submission policy will streamline data collection and increase use of nanoparticle information databases.

NCI's National Cancer Informatics Program supports the Nanotechnology Working Group, an interest group comprised primarily of external and academic researchers who develop and promote adherence to best practices in nanoinformatics. Working group members are working on a series of consensus papers focused on "nanocuration" as part of a Nanomaterial Data Curation Initiative.[64] These papers are a community-driven effort set to provide a snapshot of current curation practices and concerns that will provide recommendations for moving toward increasingly standardized curation practices.

NIOSH, NNI agencies, industry, and universities: NIOSH will continue collaborations that started in 2014 and 2015 with the Nanoinformatics consortium that includes Federal partners NCI, NIH, NIST, Pacific Northwest National Laboratory (PNNL), and DOD, and many public and private sector partners: UCLA, the National Nanomanufacturing Network, nanoHUB, RTI International, MIT, and the NanoBusiness Commercialization Association [*also relates to Goal 4*].

NIST, other NNI agencies, industry, universities, and international organizations: Multiple NNI agencies are participating in several international forums that are developing ontologies and nomenclatures for engineered nanomaterials. Federal agency participation in these efforts helps to facilitate data sharing and ensure that agency perspectives and positions are well represented in the resulting documentary standards.

NNI agencies: The agencies participating in the NKI NSI are working with NNI-funded collaborators to examine data sharing needs and mechanisms within the research enterprise. This includes the development of a Data Readiness Levels (DRLs) draft discussion document[65] in 2013 and a compiled response document in 2014. More information on this activity is discussed in Chapter 1.

With support from NNCO, agencies participating in the NKI NSI collaboratively organized a town hall discussion and participated in a symposium on Modeling, Simulation, and Informatics at Nanotech 2014 (June 2014 in Washington, DC).[66] The agencies also participated in meetings of the NKI NSI group to exchange information and coordinate nanotechnology efforts in this field.

Nanotechnology for Sensors and Sensors for Nanotechnology: Improving and Protecting Health, Safety, and the Environment

Individual agency contributions to this NSI

DOD/Air Force: AFRL/RX is continuing the development of nontraditional sensors to detect biomarkers that indicate fatigue, cognition, and other indicators of human performance. Work is focused on identifying binding agents for these biomarkers and the transducer devices that would indicate a binding event and thereby signal the detection of the biomarker. Carbon nanomaterials such as graphene and carbon nanotubes have been demonstrated as potential transducer devices. Efforts are also focused on formulating inks of the binding agents for simple device fabrication.

DOD/DARPA: Nanotechnology and nanofabrication advances are being used in DARPA's Meso Program to develop nanoengineered electrochemical charge transfer interfaces for transduction of chemistry-specific and biomolecular structural information to readable electrical signals, realizing ultralow-noise, low-power electronic biomolecular sensors. This would result in a handheld device that could provide a novel capability to rapidly detect toxins from blood or other fluids in austere environments, improving portability compared to existing optical sensors. Recently, a prototype of such a sensor successfully demonstrated

[64] nciphub.org/groups/nanotechnologydatacurationinterestgroup

[65] www.nano.gov/node/1015

[66] www.techconnectworld.com/Nanotech2014/sym/Modeling_Simulation_Nanoscale.html

electronic biomolecular detection of minimum-injury concentrations of the neurotoxin botulinum-A, and discriminated among mass isotopes at the resolution of nuclear magnetic resonance (NMR).

FDA: FDA staff participated in the planning and execution of the Sensor Fabrication, Integration, and Commercialization Workshop held on September 11–12, 2014. FDA plans to continue supporting the Sensors NSI in 2015 and 2016.

NASA: NASA supports work in the development of sensors for the detection of chemical and biological species for use in planetary exploration, vehicle performance monitoring, and astronaut health management. In 2013, NASA Glenn researchers utilized porous tin oxide nanorods, with multiwall carbon nanotubes as templates, in sensors for the detection of methane over a temperature range of 20–500 °C. In 2015, this sensor technology will be tested in a Vehicle Integrated Propulsion Research (VIPR) engine test for the study of vehicle health management capabilities. Work on the development of autonomous chemical-biological sensor platforms based on carbon nanotube and nanofiber sensing elements was initiated at NASA Ames in 2014 with funding from the Space Technology Mission Directorate's Game Changing Development Program. It demonstrated the ability of carbon nanofiber sensors to detect biomarkers for cardiac disease at low concentrations that exceed medical requirements.

NIH: NIH/NCI has a wide portfolio in *in vitro* diagnostic grant support focused on development of devices for detection of blood-borne cancer biomarkers, including circulating tumor cells, cell-free DNA, and proteins. NIH/NCI worked with NNCO to help organize the 2014 NNI Sensor Fabrication, Integration, and Commercialization Workshop. NIH/NCI also supports the Nanotechnology Characterization Laboratory, which provides characterization protocols and data valuable for Thrust 2 of the Nanosensors NSI.[67] In addition to the NIH/NCI-specific portfolio, other institutes such as NIH/NHLBI also support nanosensor-related R&D through hallmark programs like the Programs of Excellence in Nanotechnology. For instance, Massachusetts General Hospital investigators have developed a magnetic nanosensor for detection and profiling of erythrocyte-derived microvesicles.[68] They have shown that increasing numbers of microvesicles as blood ages contributes to decreased quality of blood, and so their device could help to assess blood quality before it is given to patients.

NIOSH: In 2016, NIOSH will continue its investment in the development, testing, and evaluation of direct-reading instruments capable of detecting and measuring airborne nanoparticles. NIOSH will continue to support the development of guidelines and voluntary consensus standards for identification of sensor needs specific to realizing the objective of developing realistic applications in complex workplace situations. One particle detection instrument has already been patented and licensed by NIOSH and is being manufactured by an instrument company. An advanced version of that instrument capable of elemental analysis is under development by NIOSH. Prototypes are anticipated in 2016. *[Funding for this activity is reported by NIOSH under PCA 5; this activity is also relevant to Objective 4.1.]*

NIST: NIST is developing chemical and biochemical measurement methods to characterize nanosensors, and is fabricating engineered nanomaterials and nanosensors for a variety of applications, including low-power, portable semiconductor nanowire sensors for environmental and biomedical applications and advanced chemical and biochemical sensors enabled by nanostructured materials. NIST is developing metrology to exploit nanotechnology for wearable devices, such as those that utilize carbon-based nanostructures to detect and disarm chemical weapons.

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[67] More information on the Nanosensors NSI and its thrust areas can be found at www.nano.gov/node/847.

[68] www.ncbi.nlm.nih.gov/pubmed/24295203

NSF: Through its Nano-Biosensing, Biophotonics, and other programs, NSF supports development of novel sensitive, discriminative, low-cost, and easy-to-operate biosensing systems; innovative ideas in the development of novel biorecognition strategies; multifunctional nanomaterials and interfaces with predefined physical, chemical, or biological characteristics for biosensing applications; and fundamental study of biomacromolecule confinement and orientation at the micro- and nanoscale interfaces for biosensing applications. NSF also supports the development of sensors to detect engineered nanoparticles in a variety of environmental matrices.

USDA/NIFA: The agency utilizes multiple funding authorities to support development of nanobiosensors for more sensitive, specific, and robust detection of pathogens, toxins, and contaminants in food to ensure food safety and biosecurity. NIFA also continues to support the development of sensors for monitoring the environmental stresses in crop and livestock production, and the distribution of agricultural chemicals in fields to provide critical information for precision agriculture. NIFA has been supporting and providing leadership to a multistate research committee (NC1194: Nanotechnology and Biosensors). The committee has been effective in advancing nanoscale science and engineering for nanosensor development and commercialization. NIFA was a member of the planning committee for the September 2014 NNI-sponsored Sensor Fabrication, Integration, and Commercialization Workshop, and identified a keynote speaker from a leading agricultural machinery company that has developed and employed many sensor technologies.

Coordinated activities with other agencies and other institutions contributing to this NSI

DOD/Air Force, industry, and universities: The Materials and Manufacturing Directorate activities in nanotechnology for sensors are highly coordinated with the AFRL Human Effectiveness and Sensors Directorates as well as the AFRL-sponsored Nano-Bio Manufacturing Consortium. Numerous universities including Northeastern University, University of Cincinnati, and others contribute to the work in addition to several companies including MC10, General Electric, and Brewer Science.

NIOSH, NIH, FDA, NIST, DOD, NASA, NSF, and EPA: NIOSH participates with other agencies on an initiative to develop nanotechnology-enabled sensors and sensors for nanomaterials for EHS research applications. The objective of the initiative is to identify opportunities for the development and commercialization of sensors that will enable more specific tracking of engineered nanomaterials throughout their life cycles. This detection and measurement capability will support the efforts of private-sector companies to demonstrate responsible development. By early 2016, NIOSH plans to extend its efforts in detection of airborne nanoparticles into specific applications in the areas of detection of nanomaterials in biologic systems to evaluate and predict biological behavior and translocation between organ systems. An aligned effort is the reapplication of more sensitive and specific detection technology to evaluate worker exposures to nanomaterials, with an ultimate goal of real-time detection. Starting in 2016, NIOSH will evaluate the feasibility of applying advanced sensing technology to biomarkers as a means of evaluating nanomaterial exposure and possible early response in support of ongoing nanomaterial worker surveillance. *[These activities also relate to Objective 4.1.]*

NNI agencies, universities, and industry: Agencies participating in the Nanosensors NSI released a Request for Information (RFI)[69] on October 1, 2013, to gather input from the public on specific needs for the accelerated development and commercialization of nanosensors. The RFI focused on the following themes: standards, testing, manufacturing, commercialization, and regulation. Common themes were identified based on these inputs. For example, the need to improve communication and collaboration among stakeholders was a common response. There was agreement that, as sensors become the backbone of the

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[69] federalregister.gov/a/2013-23916

"Internet of Things" and software development continues to play a crucial role in sensor performance, data security is necessary for the acceptance of ubiquitous sensing. Responses indicated that access to test conditions beyond standard laboratory environments and closer to field use is critical for sensor development, and that transition of prototype sensors from research to commercial use depends on the availability of realistic test beds. Agencies participating in this NSI also hosted sessions on nanosensing and a town hall meeting at the June 2014 TechConnect World Innovation Conference,[70] an annual event designed to accelerate the commercialization of innovations out of the lab and into industry. With support from NNCO, these community-building efforts were used to inform planning for the September 2014 NNI Sensor Fabrication, Integration, and Commercialization Workshop. This event focused on identifying key challenges faced by sensor developers and determining the critical needs of the nanosensor development community, especially with respect to necessary standards, testing facilities, and advances in manufacturing. The workshop is being used as the basis for a report and a redesigned website intended to provide information and guidance to the community regarding sensor fabrication and test facilities.

Goal 2: Foster the transfer of new technologies into products for commercial and public benefit.

The purpose of Goal 2 is to establish processes and resources to facilitate the responsible transfer of nanotechnology research into practical applications and capture its benefits for national security, quality of life, economic development, and job creation. Several factors are necessary to successfully commercialize any new technology. Scalable, repeatable, cost-effective, and high-precision manufacturing methods are required to move the technology from the laboratory into commercial products. Investments by both the public and private sectors are needed to shepherd technologies to maturity. Maximizing the benefits of nanotechnology developments to the U.S. economy requires efforts to remove barriers to global commercialization and an understanding of the potential markets for a given product. Goal 2 encompasses four objectives that detail how the NNI will focus its resources and broaden its engagement with academia, industry, and the international community to reach this goal.

The NNI member agencies also have a number of activities uniquely targeting technology transfer and commercialization, for example, workshops to obtain input from industry and academia, SBIR and STTR programs to fund innovations in small businesses, and cutting-edge research infrastructure for use by all nanotechnology researchers, including those from industry.

Objective 2.1 – Assist the nanotechnology-based business community in understanding the Federal Government's R&D funding and regulatory environment.

Individual Agency Contributions to Objective 2.1

DOC/BIS: The Bureau of Industry and Security (BIS) advances U.S. national security, foreign policy, and economic objectives by ensuring an effective export control and treaty compliance system and by promoting continued U.S. leadership in strategic technologies, including nanotechnology. BIS accomplishes its mission by maintaining and strengthening adaptable, efficient, and effective export control and treaty compliance systems. BIS export control outreach and education activities constitute the first stage in the bureau's contact with U.S. exporters and provide guidance and transparency to new and experienced exporters regarding the Export Administration Regulations (EAR). BIS's activities include

[70] www.techconnectworld.com/Biotech2014/sym/Nanotechnology_Sensors_Sensors_Nanotechnology.html#WE4.11

seminars, webinars, teleconferences, and on-location panel sessions at various conferences. Additionally, one-on-one counseling assistance is provided for extended hours of daily operation. Over the past few years, BIS has developed capabilities to offer training online and via interactive webinars. Through these programs, BIS provides guidance on regulations, policies, and practices and helps to increase businesses' compliance with U.S. export control regulations. BIS has also developed an introductory series of easy-to-use training modules. This service offers exporters and re-exporters a cost-saving mechanism to learn about U.S. dual-use export controls. BIS services are particularly useful for small and medium-sized businesses that operate with limited compliance resources.

FDA: FDA routinely presents its scientific considerations and regulatory approach on nanotechnology to stakeholders, including the nanotechnology-based business community, through participation in various public forums. For example, FDA issued three final guidances and one draft guidance in 2014 providing greater regulatory clarity for industry on the use of nanotechnology in FDA-regulated products. All four guidance documents encourage manufacturers to consult with the agency before taking their products to market. Consultations with FDA early in the product development process help to facilitate mutual understanding about specific scientific and regulatory issues relevant to the nanotechnology product, and help address questions related to safety, efficacy, public health impact, and/or regulatory status of the product. FDA plans on finalizing the draft guidance to industry in 2015 and 2016.

NASA: NASA's internal TechPort (technology portfolio) website was established in 2012 to manage NASA's advanced technology investments and make information on them more accessible first to employees and contractors and eventually to the public. The website currently contains information on NASA's efforts in nanotechnology R&D, including work funded at NASA Centers, grants and contracts with industry, and the products of these activities. TechPort continues to be updated regularly and is being beta-tested internally at NASA prior to public release.

NSF: The agency supports programs to promote university–industry interaction (Grant Opportunities for Academic Liaison with Industry or GOALI, Industry/University Cooperative Research Centers or I/UCRCs, and Partnerships for Innovation or PFI), translational research (Engineering Research Centers or ERCs and the Innovation Corps or I-Corps), and small business innovation (SBIR/STTR) in nanotechnology.

USPTO: The transfer of new technologies into products for commercial and public benefit depends on effective mechanisms that protect new ideas and investments in innovation and creativity. USPTO is at the cutting edge of the Nation's innovation system, providing intellectual property policy advice and guidance to the Executive Branch. The agency has put in place several initiatives to keep pace with the rapid advances being made in nanotechnology. The agency continues to provide in-depth nanotechnology-specific training events for patent examiners as well as to foster communication among examiners across multiple disciplines. USPTO has a subset of patent examiners across all technology disciplines who serve as points of contact to assist other examiners with nanotechnology issues related to patent examining.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 2.1

NSF and NNI agencies: NSF will continue to co-sponsor nanotechnology regional alliance conferences together with other agencies by providing additional funding for academic participants and by setting a long-term perspective. Among the conferences supported is the annual National Nanomanufacturing Network conference.

Objective 2.2 – Increase focus on nanotechnology-based commercialization and related support for public–private partnerships.

Individual Agency Contributions to Objective 2.2

DOD/Air Force: AFRL/RX supports nanotechnology-based commercialization through partnerships and collaborations with small businesses as well as through the public–private Nano-Bio Manufacturing Consortium, which has continued to develop since its launch in 2013. This three-year effort is based on government-industry-university cost-sharing, with technical efforts selected by a team representing member institutions. The initial platform being developed is a wearable human performance assessment patch. The institute will integrate manufacturability early in the development process by fostering common design tools and techniques; metrology, validation, and standards; and interface requirements and modules.

DOD/Army: Commercialization of nanotechnologies must consider the potential liabilities associated with nanoparticle releases throughout the product life cycle. The Army is collaborating with military industry partners to develop environmental life cycle analysis approaches for nanotechnologies. These approaches are used to identify areas of potential nanoparticle release during production and future product liabilities during use and end of the technology life. Cooperative partnerships between Army and industry will result in more rapid transition of technology to production and use and environmentally sustainable practices *[also applicable to Objective 4.1]*.

ERDC STTR research recently demonstrated a proof of concept for a viable, cost-effective, industrial production technique for carbon nanotube-based fibers with low density and high strength and toughness. The STTR program is providing Phase II funding to transfer this technology to the private sector to support innovative manufacturing technologies to fabricate a lightweight, ultrahigh-strength flexible CNT-based material. Based on this research, Materials and Electrochemical Research (MER) Corporation has developed a continuous industrial manufacturing process for direct spinning of CNT-based fibers.

DOD/DARPA: The private companies and universities participating in the DARPA's STARnet Program, a public-private partnership funding breakthrough research to understand nanoscale physics and materials science, have all agreed to the same intellectual property (IP) rights. (DARPA has usual and customary IP rights for DOD.) STARnet participants are encouraged to collaborate and to work with university researchers under the program, sharing the research with all, and gaining knowledge and expertise along the way.

DOD/Navy: Under two separate Navy programs to advance development and commercialization of nanomaterials with unprecedented properties, universities and industry are conducting cooperative research and development. In the first program, Raytheon has teamed with several universities to develop a new generation of infrared (IR) transparent ceramics for extreme environments, such as those experienced by IR missile domes. This work has resulted in the development of thermal-shock-resistant domes with unprecedented optical properties, which have been accepted for transition to use in AIM 9-X missiles. A pilot plant is being constructed, and further development is being funded by ONR, the Office of the Secretary of Defense ManTech (manufacturing technology) programs, and the Air Force. Under the second program, Integran, Inc., has teamed with Rutgers University to develop hybrid structures consisting of graphene-reinforced polymers coated with electrodeposited nanostructured alloys. The structures exhibit remarkable strength, toughness, and ballistic properties and are being tested by Pratt & Whitney for aircraft engine applications.

DOE: In order to transfer new technologies into the market, the DOE Office of Energy Efficiency and Renewable Energy supports the SunShot Incubator Program, which provides early-stage assistance to help startup companies cross technological barriers to commercialization while encouraging private sector investment. Additionally, DOE-EERE funds three manufacturing development centers through the Photovoltaic Manufacturing Initiative and the National Renewable Energy Laboratory's Process Development Integration Laboratory.

DOE-EERE supports research and development of promising solid-state lighting technologies through annual competitive solicitations. Manufacturing R&D projects accelerate SSL technology adoption through manufacturing improvements that reduce costs and enhance the quality of LEDs and OLEDs. Research includes the development of high-speed, high-resolution, nondestructive test equipment with standardized test procedures and appropriate metrics within each stage of the value chain for semiconductor wafers, epitaxial layers, LED dies, packaged LEDs, modules, luminaires, and optical components. Also included is the development of manufacturing equipment enabling high speed, low cost, and uniform deposition in state-of-the-art OLED structures and layers.

NASA: NASA continues to support the development and commercialization of nanotechnology-related products through the SBIR and STTR programs. In 2014, this included funding of R&D related to the development of advanced nanoscale materials, electronics, sensors, propulsion systems, and propellants.

NIH: NIH/NCI continues to participate in the Translation of Nanotechnology in Cancer (TONIC) consortium it initiated in 2012. This consortium brings together representatives from the NIH/NCI Alliance for Nanotechnology in Cancer research centers and awards, pharmaceutical and biotechnology companies, and patient advocacy groups to promote collaboration between academia and industry and share knowledge across groups about best practices in translating nanotechnology from the lab to the marketplace. TONIC members meet regularly by phone and at national meetings to discuss the potential clinical and commercial value of nanotechnologies currently under development. A nanodrug working group is developing clinical protocols to test nanoparticle drugs in patients, with the intention of addressing limitations and gaps specific to nanoparticle therapeutics arising from their distinct mechanisms of action and *in vivo* behavior.

The NIH/NCI Alliance for Nanotechnology in Cancer remains focused on promoting clinical translation and commercialization of research results. Eight Alliance-developed therapeutics are being tested in 17 cancer-related clinical trials, and five devices and instruments have started clinical trials or received Institutional Review Board (IRB) approval for human studies. Alliance researchers are partnering with more than 70 companies to translate their discoveries to the clinic or marketplace.

NIST: NIST's Technology Partnerships Office continues to promote commercialization, technology transfer, and entrepreneurship in nanotechnology broadly across NIST's laboratory programs and through leadership of the Federal Laboratory Consortium for Technology Transfer. Over the past year, NIST hosted two technology transfer events (at NIST's Gaithersburg and Boulder campuses, respectively) that showcased new nanotechnology-related developments in microfluidic, nanofabrication, and ion beam technologies for attendees from local companies and economic development organizations. Several recent NIST patents issued or pending in nanotechnology-related areas have potential industrial applications. For example, a new technology developed under a cooperative R&D agreement (CRADA) by researchers from NIST CNST and zeroK NanoTech Corporation generates ion beams with high brightness and resolution for use in nanoscale fabrication and measurement applications. The patented technology, initially developed at NIST by the research team, is now under license to zeroK NanoTech.

NSF: NSF sponsors public–private partnerships (e.g., the Nanoelectronics Research Initiative and I-Corps) and centers that advance collaboration with industry (e.g., the Nanosystems ERCs and NSECs). NSF sponsored the Nanotechnology Undergraduate Education (NUE) project NanoTRA–Texas Regional Alliance to Foster Nanotechnology Environment, Health, and Safety Awareness in Tomorrow's Engineering and Technology Leaders. NSF also has supported a survey on nanomanufacturing through sponsorship of a study entitled Nanotechnology and Commercialization—Achieving Sustainable Nanoproducts. This study, conducted by the National Center for Manufacturing Sciences, is a follow-up to previous similar studies sponsored by NSF. It is a 30-question online survey and includes interviews.[71]

USDA/NIFA: The USDA SBIR program housed in NIFA has continued to support nanotechnology R&D aiming at commercialization and involving the business community. Examples of the NIFA SBIR projects include nanotechnology-enabled sensor technologies for detection of microbial pathogens and insects and crop environmental stresses, nanoscale delivery of antimicrobial agents, and nanocellulose composites to improve polymer functionalities.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 2.2

CPSC and NSF: In 2016, the CPSC staff, in collaboration with NSF, proposes to develop centers of excellence to assist stakeholders, including manufacturers, on understanding risk-based approaches for product evaluation, and to develop testing methods (e.g., exposure assessment) that will be used to identify and mitigate potential product hazards. Research will target the development of methods for quantifying and characterizing the presence, release, and mechanisms of consumer exposure to nanomaterials. The center will also have other benefits to society by developing scientists with expertise in nanomaterials and consumer product safety research who will be able to further our basic understanding of this technology and develop innovative methods for the responsible use of nanomaterials in products. The center will also serve as a resource for manufacturers and distributers of nanotechnology-enabled products for approaches to ensuring the safe use of this technology in products, as well as for the consumer groups and others in the general public with a desire to learn more about nanomaterial use and implications *[also relevant to Objectives 2.3 and 4.3]*.

DOD/Air Force, industry, and universities: The Nano-Bio Manufacturing Consortium is a collaboration between 10 industrial and academic members, in addition to the AFRL Materials and Manufacturing, Sensors, and Human Effectiveness Directorates, and the FlexTech Alliance, which manages efforts on behalf of AFRL.

DOD/Army, EPA, and CPSC: Cooperative partnerships between Army and industry will result in a more rapid transition of environmentally sustainable technology throughout the life cycles of nanomaterial-based products. Partnerships with industry, EPA, and CPSC facilitate the mitigation of environmental, safety, and health risks of nanomaterial-based products in commercialization.

DOE and NSF: NSF (Directorate for Engineering) and DOE (EERE-SETP) co-sponsor the Quantum Energy and Sustainable Solar Technologies (QESST) Engineering Research Center, which works with companies to advance technologies toward commercialization.

NIST, NSF, industry, and universities: NSF and NIST continue their support of the Nanoelectronics Research Initiative, which in 2013 announced a second major phase and annual funding for three multiuniversity research centers *[also relevant to Objective 2.3]*.

[71] www.usnanosurvey.org

USDA/FS and industry: In 2013, the Forest Service and its partner the U.S. Endowment for Forestry and Communities formed a public–private partnership named P^{3}Nano to advance forest-based nanomaterials for a wide range of applications. In 2014, P^3 Nano issued a request for proposals for a total of $3 million. From the proposals received, the Science Advisory Committee of P^{3}Nano selected for funding eight proposals in the areas of building materials, composites, wood adhesives, design and engineering of cellulose nanomaterials production plant, and biopackaging. *[These activities also relate to Objective 1.4.]*

Objective 2.3 – Promote broader accessibility and utilization of user facilities, cooperative research centers, and regional initiatives to accelerate the transfer of nanoscale science from lab to market.

Individual Agency Contributions to Objective 2.3

DOE: DOE-SC continues to operate five Nanoscale Science Research Centers (NSRCs), national user facilities for interdisciplinary research at the nanoscale, serving as the basis for a national program that encompasses new science, new tools, and new computing capabilities. These are Center for Functional Nanomaterials (CFN) at Brookhaven National Laboratory, the Center for Integrated Nanotechnologies at Los Alamos and Sandia National Laboratories, the Center for Nanoscale Materials at Argonne National Laboratory, the Center for Nanophase Materials Sciences at Oak Ridge National Laboratory, and the Molecular Foundry (MF) at Lawrence Berkeley National Laboratory. Each center has particular expertise and capabilities in selected theme areas, such as synthesis and characterization of nanomaterials; catalysis; theory, modeling, and simulation; electronic materials; nanoscale photonics; soft and biological materials; imaging and spectroscopy; and nanoscale integration. For example, the CFN conducts energy-related research on electronic nanomaterials and soft and bio-nanomaterials, with emphasis on block co-polymer and DNA-mediated self-assembly of nanostructures; and the MF emphasizes combinatorial synthesis of nanomaterials, multimodal *in situ* imaging and spectroscopy, interfaces in nanomaterials, "single digit" nanofabrication, and high-resolution electron scattering.

DOE-EERE supports solar energy activities at the National Renewable Energy Laboratory though an annual operating plan that contains a collection of efforts related to nanotechnology. One example is research utilizing nanomaterials to enhance transparent conducting materials and efforts to increase the resolution of measurement techniques to electrically and optically probe grain boundaries, interfaces, and structures.

NIST: With the implementation of the new NanoFab website complete, CNST is expanding its accessibility to industry, academic, and government users. CNST is also expanding the range and depth of its documented nanofabrication processes and process documentation, making it easier to maintain and distribute the latest nanofabrication processes among the nanotechnology R&D community. The NanoFab has recently initiated a program to host at least two nanofabrication tool vendor workshops per year to bring together government, industry, and academic researchers to discuss technologies of mutual interest.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 2.3

NIH, FDA, NIST, industry, and universities: The Nanotechnology Characterization Laboratory (NCL) is a formal interagency collaboration between NIH/NCI, FDA, and NIST. NCL continues to regularly engage with the nanotechnology research and development community by attending and presenting at conferences, publishing trends and research results, and providing substantial and valuable information on nanoparticle characterization and behavior on its website ncl.cancer.gov. Over the past ten years, NCL has performed characterization of over 300 different nanoparticle-based formulations originating from academic, government, and industrial laboratories. The results contributed to nine nanotechnology-enabled technologies that have gone on to receive Investigational New Drug (IND) approval from FDA.

NCL makes its assays freely available to the public[72] and has compiled its methods into a book, *Characterization of Nanoparticles Intended for Drug Delivery*. NCL's three-tiered assay cascade includes physicochemical, *in vitro*, and *in vivo* characterization. The NCL's physicochemical characterization of nanomaterials goes well beyond basic measurements of size and surface charge. NCL's routine physicochemical characterization also includes batch-to-batch consistency evaluation, measurement of drug loading, confirmation of targeting ligand conjugation, quantitation of surface ligands, and nanoformulation stability assessment. NCL's *in vitro* analysis includes sterility and endotoxin quantification, something many researchers often overlook, and analysis of hematological compatibility and immune cell functions using human whole blood. NCL's *in vivo* capabilities include toxicology, immunotoxicology, drug metabolism, pharmacokinetics, efficacy, and imaging studies.

NSF, DOD, NIST, and industry: NSF supports the National Nanomanufacturing Network (NNN), which includes the NSF NSECs and non-NSF centers in collaboration with DOD, NIST, and industry partners in an alliance to advance U.S. strength in nanomanufacturing.

Objective 2.4 – Actively engage in international activities integral to the development and responsible commercialization of nanotechnology-enabled products and processes.

Individual Agency Contributions to Objective 2.4

DOC/BIS: BIS has developed and published two comprehensive documents on its Export Management and Compliance Programs (EMCPs), which are programs that can be established to manage a business's export-related decisions and transactions to ensure compliance with the Export Administration Regulations and license conditions. Specifically, BIS has published "Compliance Guidelines: How to Develop an Effective Export Management and Compliance Program and Manual" and "EMCP Audit Module: Self-Assessment Tool." Additionally, BIS conducts regularly scheduled outreach seminars dedicated to the topic "How to Develop an Export Management and Compliance Program" and continues to offer the webinar "Elements of an Effective Export Compliance Program" to its menu of online training offerings.

DOD/Air Force: To seed innovation in areas that are relevant to Air Force capabilities and that can potentially benefit from research and technology development in nanomaterials and devices, Air Force researchers have engaged the international community to encourage work in specific areas that indicate technology potential. In areas such as graphene nanodevices, nanomagnetic materials, and bio-inspired nanosensors, the Materials Directorate has established recognized metrics that can facilitate wide technical evaluation on the part of researchers and both guide and identify research with technological potential in these areas. This process can also identify classes of materials that may provide unique advantages over a technology area, such as nanomaterial hair sensors and carbon nanotube biomolecule sensors, and allow for focused nanomanufacturing capability development to support broad-based commercialization.

USDA/NIFA: The NIFA staff has actively engaged with the international food and agriculture scientific community and has provided leadership in fostering information exchange and R&D cooperation. As mentioned earlier in this report, NIFA provided a conference grant and leadership to support an international food nanotechnology symposium that was held in conjunction with the 17th World Congress of Food Science and Technology in Montreal, Canada, on August, 17–21, 2014. A new initiative for capacity building in developing countries and emerging economies emerged and was enthusiastically embraced by the scientists present. A plan to move forward was jointly considered by other organizations including the

[72] ncl.cancer.gov/working_assay-cascade.asp

International Union of Food Science and Technology, the International Council for Science, and the International Society of Food Applications of Nanoscale Sciences.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 2.4

DOD/Army, EPA, NIST, industry, and international organizations: The U.S. Army Corps of Engineers has been working with EPA and NIST on methods and approaches to support science-based management and regulatory decisions to assess the environmental safety of nanotechnology. Starting in 2014, in response to the 2013 National Academies assessment of progress on EHS research and the NNI 2013 Workshop on the Perception, Assessment, and Management of the Potential Risks of Nanotechnology, the Army has been collaborating with EPA, NIST, Germany, Austria, Canada, the United Kingdom, and industry to develop standardized testing decision trees and screening methodologies to assess release, fate and transport, and toxicity of nanoparticles. Methods for assessing release of nanoparticles are being developed through ASTM International, the International Life Sciences Institute (ILSI), and the Organisation for Economic Co-operation and Development (OECD).

DOD/Navy, DOD/Army, industry, and international organizations: In March 2014, researchers from ONR and NRL visited Israel to meet with its Ministry of Defense and present at NanoIsrael 2014, as well as to conduct many site visits to small businesses and universities to explore opportunities for collaborations in nanotechnologies. The trip was coordinated by and included participants from the Air Force Research Laboratory and the Army Research Laboratory.

NIOSH and international organizations: In 2016, NIOSH will extend research efforts started in 2015 through partnerships with INRS (the National Research and Safety Institute, France), HSL (the Health and Safety Laboratory, United Kingdom), TNO (Organisation for Applied Scientific Research, the Netherlands), IGF (the Institute for the Research on Hazardous Substances, Germany), CIOP-PIB (the Central Institute for Labour Protection, National Research Institute, Poland) and NRCWE (the National Research Centre for the Working Environment, Denmark) on the European Union (EU) Dustinano project, comparing “dustiness” (i.e., particle release with respect to inhalation exposure) evaluation methods for a limited set of nanomaterials. The collaborating organizations will explore the utility of dustiness as a metric for risk management decision making.

NIOSH, NIST, and international organizations: NIOSH is collaborating with NIST and the National Research Council of Canada (NRC-Canada) to develop and qualify nanoscale reference materials to support measurement quality for established and emerging nanomaterials. In 2014, NIOSH collaborated with NIST on surface area measurements for NIST Standard Reference Material 1898: Titanium Dioxide Nanomaterial, which is now commercially available. In 2015, collaborations with NRC-Canada continued on qualification of two cellulose nanocrystal reference materials and one single-wall carbon nanotube reference material, representative of an emerging nanomaterial and a high-value material proposed for multiple applications. NIOSH and other agencies will use these reference materials to improve measurement quality, which enables new areas of research and strongly supports the critical and necessary intersection of materials measurement scientists with toxicology and occupational health professionals.

NIOSH and other NNI agencies: NIOSH, in collaboration with other NNI agencies, contributes in the areas of human health, exposure assessment, risk assessment, and risk management and controls by participating in multiple communities of research (CoRs) as part of the U.S.–EU effort to bridge EHS research efforts. In addition to active participation in the CoRs, NIOSH has actively engaged research institutes in Canada, Brazil, Japan, China, Sweden, the United Kingdom, and Russia in several areas of nanotechnology EHS research collaboration.

NIOSH and standards developing organizations: NIOSH will continue to play an active role in the International Organization for Standardization (ISO) Technical Committee (TC) 229 Nanotechnologies and ASTM International Technical Committee E56 on Nanotechnology, both of which focus on development of consensus standards for industry and commerce. A key ISO TC 229 project led by NIOSH will create a strategy for the development of categorical occupational exposure limits (OELs) for nanomaterials. This project was started in 2014 and will carry into 2016. NIOSH will participate in an international inter-laboratory study to develop methods for determination of nanomaterial size for high production volume nanomaterials including titania and carbon black. The output of this effort will have broad applications in nanomanufacturing and will provide improved tools for more robust material characterizations in EHS research. Aligned with this effort is collaboration with ASTM International, in which NIOSH is working to develop a standard guide on sample preparation for particle sizing and a standard guide on detection and characterization of silver nanomaterials in commercial products.

NIST and standards developing organizations: NIST continues its active participation and leadership in the development of international consensus standards. Many of these standards are foundational for the development and responsible commercialization of nanotechnology-enabled products and processes. NIST provides physical, chemical, structural, and electrical property measurement and characterization expertise relating to a broad range of nanomaterials and nano-objects. NIST engagement for developing nanotechnology standards in ASTM International, the International Electrotechnical Commission (IEC), and ISO has led to measurement protocols, EHS-related standards, and terminology standards. NIST participation has also ensured that international standards support the competitiveness of U.S. industry and do not adversely impact global trade and commerce. NIST has also contributed expertise gained through the research efforts in developing physical standards (such as Reference Materials and Standard Reference Materials) to support U.S. Government agency participation in organizations such as the OECD Working Party on Manufactured Nanomaterials (WPMN).

NIST continues to raise awareness of standards development activities and their impact through engagement with other agencies and in interagency groups such as the NSET Subcommittee, the NEHI Working Group, and the nanotechnology subgroup of the White House Emerging Technologies Interagency Policy Committee.

NSF and international organizations: NSF continues to participate in OECD and other international forum activities.

USDA/FS and standards developing organizations: In 2014, the Forest Service submitted a new work item proposal to ISO TC229 to develop an international standard for cellulose nanomaterials terminology. Forest Service experts also are participating in the development of an ISO TC229 cellulose nanomaterials characterization technical report.

USPTO and other nations' patent offices: USPTO is moving to a new patent classification system, the Cooperative Patent Classification (CPC), which is jointly managed by USPTO and the European Patent Office (EPO). This new classification system is based on an internationally used patent classification system (IPC), which contains most of the world's patent documents. As USPTO completes its initial transition to this new classification system in January 2015, there will be a more harmonized, internationally consistent classification of nanotechnology-related patent documents.

Goal 3: Develop and sustain educational resources, a skilled workforce, and a dynamic infrastructure and toolset to advance nanotechnology.

Fundamental to the successful development of nanotechnology is the continued development of the infrastructure necessary to support this effort. A substantial investment, strengthened by interagency cooperation and collaboration through the NNI, is needed to develop the talent and facilities necessary to achieve the other NNI goals of advancing a world-class R&D program (Goal 1), fostering the transfer of new technologies into products for commercial and public benefit (Goal 2), and supporting responsible development of nanotechnology (Goal 4).

This goal encompasses three objectives[73] that detail how the NNI will responsibly engage and educate the public and the workforce regarding the opportunities that nanotechnology offers and the skills it requires, along with providing the needed access to advanced facilities and tools. Education is among the chief objectives of NNI-funded university research. In addition, specific programs target K–16 education, improve nanotechnology curricula in U.S. schools and universities, and educate the public about nanotechnology. The NNI continues to sustain, maintain, and upgrade its extensive network of research centers, user facilities, and other infrastructure for nanotechnology research, a key element of the original NNI strategy.[74]

Objective 3.1 – Sustain outreach and informal education programs in order to inform the public about the opportunities and impacts of nanotechnology.

Individual Agency Contributions to Objective 3.1

DOD/DARPA: Under DARPA's STARnet Program, six multiuniversity centers have been formed, providing numerous formal and informal efforts for education and outreach. The program establishes a vibrant academic environment with frequent technical exchanges through seminars and webcasts that are open to the public. Research results are frequently published in technical and nontechnical journals, magazines, and books. Center directors and researchers have outreach to companies and government labs, and present their work in public meetings.

NIH: Community and public outreach about cancer nanotechnology are built into the award structures for the research and training centers of the NIH/NCI Alliance for Nanotechnology in Cancer. Alliance research and training centers have dedicated funds for outreach to the general, patient, and medical communities. Alliance members participate in the National Science Foundation's Nanoscale Informal Science Education Network (NISE-Net) "Nano Days" either by developing their own outreach activities or by participating in activities organized in their areas. Alliance members have also developed courses and symposia on nanotechnology that are eligible for Continuing Medical Education credits. Training and education at the middle and high school level is also an integral component of the grants funded by NIH/NHLBI through three different programs:

- *NanoCarD Summer Internships and Student Dyads*: The NanoCarD Summer Internship and Student Dyad Programs were ongoing in summer 2014. Six high school students were paired in dyads and spent four hands-on research sessions in the laboratories of NanoCarD (Nanomedicines for Cardiovascular Disease) investigators. In addition, three undergraduate student interns from Rensselaer Polytechnic Institute, Northwestern University, and the Rutgers University Honors

[73] For the full descriptions of the objectives of this NNI goal, see the 2014 National Nanotechnology Initiative Strategic Plan, www.nano.gov/2014StrategicPlan or www.nano.gov/about-nni/what/vision-goals.

[74] For more information on NNI-supported research infrastructure see www.nano.gov/centers-networks.

Program had 10-week summer research experiences working on NanoCarD-related research projects studying human cardiac tissue engineering, cardiac stem cells, and cardiovascular cell nanomechanics. Fiscal support for supplies was provided through the NanoCarD Skills Core.

- *Introduction to Nanotechnology for High School Students*: Through an ongoing partnership with the Center for Excellence in Youth Education (CEYE) at Mount Sinai School of Medicine, the NanoCarD Skills Core has helped to support the Introduction to Nanotechnology Summer High School Course[75] for 18 students in 2014, most from disadvantaged backgrounds that are underrepresented in science and medicine. The course was structured around in-class lectures, demonstrations, and hands-on exercises including model building. Themes covered in the lectures included “Understanding Nanoscale,” “Concepts of Nanotools,” “Nanotechnology in Nature,” and “Nanotechnology in Medicine.” A textbook, *Nanotechnology for Dummies,* was provided to all students. The nano-model-building component initiated in 2013 was continued in 2014. Mount Sinai NanoCarD investigators and postdoctoral researchers participated in the 2014 program. The six-week 2014 summer course culminated in a two-day CEYE symposium of student presentations, and a final awards ceremony. Fiscal support for supplies was provided through the NanoCarD Skills Core.
- *Washington University Community Outreach*: In March 2014, NIH/NHLBI worked with the Washington University Institute for School Partnership in St. Louis to organize a nanotechnology in-reach event for a diverse group of middle school students. Forty students recruited from Marian Middle School came to the Washington University campus to be introduced to nanoscience and to carry out experiments at the university chemistry laboratories. The curriculum included a didactic approach to presenting the experiments and challenged the students to write up their own experimental plans and reports. This was the first in-reach with Marian Middle School, an all-girls middle school in the city of St. Louis. In addition, a nanomedicine workshop on Nanotechnology and Imaging of Lung was held at Washington University on July 10, 2014, for middle and high school students. The workshop included presentations by known academic professors as well as by postdoctoral scholars and graduate students from the Washington University Program of Excellence in Nanotechnology.

NSF: Two Centers for Nanotechnology in Society with significant educational components are funded at Arizona State University (ASU) and the University of California, Santa Barbara (UCSB). CNS-UCSB supports interdisciplinary education across its research activities in various ways. Graduate students and postdoctoral researchers associated with one or more of the center's research thrusts are being mentored by their CNS advisors. Previous graduate students and postdoctoral researchers received jobs in academia and in the private sector in areas related to societal implications of nanotechnology. CNS outreach activities include engaging with the Centers for Environmental Implications of Nanotechnology at UCSB and with policy groups and nongovernmental organizations (NGOs); these activities promote increased awareness of societal issues within the nanoscale science and engineering community. Public engagement efforts include media interviews, speaker series, NanoDays, web-based materials, and public presentations. CNS-ASU has been offering an immersive training session for nanoscale science and engineering graduate students in Washington, DC, called Science Outside the Lab. CNS-ASU has established an annual, two-week “Winter School” for doctoral students and postdoctoral scholars. Looking ahead, CNS-ASU plans to focus recruiting, funding, and other resources on students from underrepresented groups for the Winter School. It also plans to develop and implement targeted recruiting efforts for a new Graduate Certificate in Responsible Innovation and a minor in Science and Technology Policy, and it will organize and host

[75] Link to course application: icahn.mssm.edu/static_files/MSSM/Files/Education/CMCA/nanoapplication.pdf.

recruiting events with the Hearing Research Center, the ASU American Indian Studies Program, and the American Indian Policy Institute, among others.

The NSF-supported Nanotechnology Applications and Career Knowledge (NACK) Network and the Nanoscale Informal Science Education Network (NISE Net) are two national networks serving the nanotechnology technological community and informal science community. NSF has supported the Nanotechnology Undergraduate Education program since 2003, with the last competition in 2015, and plans to have another proposal solicitation in 2016. NSF also supported a workshop on education needs and approaches for nanotechnology in December 2014.

USDA/NIFA: NIFA's higher education programs support competitive grants to universities for developing nanotechnology curricula for undergraduate and graduate students in agriculture and food science and technology including food engineering, food security, food safety, bioenergy, and sustainability. For example, NIFA has provided funding to support the School of Veterinary Medicine at Tuskegee University, an 1890 land-grant institution, to enhance the infrastructure needed for teaching nanobiotechnology to veterinary and graduate students and to help support in a 2013–2015 grant an Interdisciplinary Pathobiology PhD program that started in the fall of 2013.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 3.1

CPSC and NIH: CPSC established an interagency agreement with the National Library of Medicine (NLM) in previous fiscal years to develop and post information on nanotechnology targeted to the general public. The CPSC staff will continue to collaborate with NLM to develop information that will provide current information on nanomaterials to a nontechnical audience.

NIH, NSF, and universities: Community and public outreach about cancer nanotechnology is a systemic function of the NCI Alliance for Nanotechnology in Cancer. Alliance research and training centers have dedicated funds for outreach to the general, patient, and medical communities. As noted above, Alliance members participate in the NSF NISE Net "Nano Days." Other efforts include "Nanotechnology Town Halls" hosted by Northwestern University for a lay audience; a free one-day mini-symposium, Nanobiomotors: Structures, Mechanisms and Clinical Implications, hosted by the University of Kentucky, which was open to the public; and "The Art of Systems Biology and Nanoscience Days for Kids and Evenings for Grownups" events hosted by the University of New Mexico. Alliance members also have developed courses and symposia on nanotechnology that are eligible for continuing medical education credits.

Objective 3.2 – Establish and sustain programs that assist in developing and maintaining a skilled nanotechnology workforce.

Individual Agency Contributions to Objective 3.2

DOD/Air Force: AFOSR sponsors research assistantship programs, faculty programs, and graduate school programs. These programs support graduate education; encourage development of research excellence in critical technological areas such as nanotechnology, where research facilities and qualified researchers are lacking; train personnel to conduct high-quality research; and stimulate mutual research interests between the Air Force and institutions of higher education. Other collaborative efforts with universities include the National Defense Science and Engineering Graduate Fellowship Program, the USAF National Research Council Resident Research Associateship Program, the USAF Summer Faculty Fellowship Program, the Visiting Scientist Program, and the Window on Science Program.

Through the Research Collaboration Program, AFRL is reaching out to students nationwide and sponsoring summer internships and research at laboratories and home institutions. The focus of this work in nanomaterials and devices allows for greater exposure of these students to topics in both nanoscience and nanosafety. This initial contact with AFRL leads to ongoing relationships between students and AFRL researchers. Return interns, fellowship candidates, co-op employees, and new hires have resulted from this program, which bolsters both the overall workforce familiarity with nanotechnology issues and renews the AFRL workforce. Projects in nano-optical coatings for improved performance in imaging systems, nanomaterial biosensing systems, tunable nano-optical devices, and nanotechnology-modified fabrics for wearable electronics are among the projects that have shown promising results based on the efforts of student researchers. The experience gained by these students, both in the technical content of their work and in exposure to nanoscience laboratory practices, will augment their skills throughout their careers. *[This work is also relevant to Objective 4.4.]*

DOE: By supporting fundamental and applied R&D, DOE supports students at both the undergraduate and graduate levels, as well as postdoctoral researchers, to gain expertise in nanotechnology. Additionally, the businesses supported by programs such as the SunShot Incubator and SBIR/STTR help create a skilled nanotechnology workforce.

FDA: FDA workforce training focuses on lectures by experts in science issues concerning nanotechnology and hands-on laboratory training with analytical equipment used to characterize the physical and chemical properties of engineered nanomaterials relevant to FDA-regulated products. FDA also sponsors postdoctoral fellows, graduate students, and student interns for fellowships in nanotechnology to support the development of a trained workforce. FDA will continue to support these activities in 2015 and 2016.

NASA: NASA continues to support the training of the next generation of scientists and engineers, including those working in nanotechnology. NASA funds graduate student research through research grants and fellowships such as the Space Technology Research Fellows, student internships, and postdoctoral fellowships. In 2013, NASA awarded two new grants in nanotechnology research for a total of $1.5 million under the Experimental Program to Stimulate Competitive Research (EPSCoR) program. In late 2012, the Space Technology Research Grants Program initiated the Space Technology Early Career Faculty Awards; of the seven grants awarded in 2014, two were in areas related to nanotechnology.

NIH: The NIH/NCI Alliance for Nanotechnology in Cancer supports Cancer Nanotechnology Training Centers that are establishing innovative research education programs supporting the development of a cadre of investigators capable of pursuing cancer nanotechnology research. The training programs are focused on mentored laboratory-based training in multidisciplinary research projects, but each training center also develops seminars, workshops, and short courses to teach the cross-cutting skills and knowledge necessary for successful research in cancer nanotechnology. The training centers also support career development activities for their participants. They have trained 125 graduate students and postdoctoral researchers in multidisciplinary research, with a focus on cross-training in medical and physical sciences and engineering. More than 800 people, ranging from undergraduates to mid-career researchers, have participated in training center-organized or hosted symposia, workshops, and conferences.

The Alliance also supports the transition of a cohort of seven young researchers in cancer nanotechnology from postdoctoral to independent faculty positions, through Pathway to Independence in Cancer Nanotechnology Career Development Awards. These researchers are now in tenure track positions at research universities across the United States, and are beginning to receive their first independent research funding from NIH, other Federal agencies, and private foundations. One Alliance R00 award holder, Dr. Andrew Goodwin of the University of Colorado, recently received an NIH New Innovator Award for his project "Rapid, Multiscale Sensing Using Acoustic Detection Mechanisms."[76] In addition, the National Institute of Child Health and Human Development established a summer educational program on pediatrics and nanotechnology, and NIDCR is requiring U01 grantees involved in the novel dental restorative program to train postdoctoral fellows, graduate students, undergraduate students, and high school students to develop and maintain a skilled nanotechnology workforce.

NIOSH: Direct training of graduate students, postdoctoral fellows, and visiting scientists in NIOSH research laboratories has been offered in the areas of toxicology, aerosol characterization, and analytical measurements. Beginning in 2015, NIOSH entered into research agreements with three academic institutions to incorporate EHS training into their nanomaterial research curriculum. By 2016 NIOSH hopes to have specific examples of nanomaterial safety and Prevention through Design (PtD) principles being transferred into the private sector as part of the program to provide trained technologists. Training courses developed and delivered by NIOSH at several levels for professional industrial hygienists and EHS practitioners are a direct output in support of responsible development of the technology. NIOSH will increase collaborations between the Institute's nanotoxicology program and the materials science and engineering departments at West Virginia, Pittsburgh, Carnegie Mellon, and North Carolina State universities to demonstrate the effectiveness of safety-by-design principles at the materials synthesis stage.

NSF: NSF supports education-related activities such as the development of educational materials for schools, curriculum development for nanoscience and engineering, development of new teaching tools, undergraduate programs, technical training, and public outreach. Two networks for formal and informal nanotechnology education (led by Penn State and the Museum of Science, Boston) with national outreach will continue to be supported.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 3.2

DOE and NSF: DOE and NSF co-sponsor the Quantum Energy and Sustainable Solar Technologies Engineering Research Center, which has a primary goal of creating educational resources and a skilled workforce in solar technology.

NIH and NIST: NIST, in addition to providing training for any interested participants from the NIH U01 projects with respect to instrumentation and standards development, has its own series of postdoctoral fellows receiving training in nanotechnology.

NIST and NSF: The NIST Center for Nanoscale Science and Technology (CNST) and the NSF Advanced Technological Education program are conducting a joint program to provide extended internships at NIST for community college students being trained in semiconductor manufacturing technology. The first students have "graduated" from the 12-week internship, which provides an opportunity to gain hands-on, practical experience in a nanotechnology facility working in nanofabrication, processing, characterization, and tool maintenance—areas specifically targeted to meet the needs of U.S. manufacturers for skilled technicians. The experience gained from this internship at CNST helps qualify the students to compete for highly skilled jobs working as engineering technicians in semiconductor manufacturing. The starting pay for these jobs is in the range of $50,000 to $60,000 per year.

The NIST/NSF jointly funded Summer Undergraduate Research Fellowship (SURF) program provides nanotechnology research opportunities throughout NIST's laboratories and user facilities at both the Gaithersburg, MD, and Boulder, CO, campuses. In 2014, NIST hosted 180 students for a variety of research activities, including nanotechnology-related projects.

[76] projectreporter.nih.gov/project_description.cfm?projectnumber=1DP2EB020401-01

Objective 3.3 – Provide, facilitate the sharing of, and sustain the physical R&D infrastructure, notably user facilities and cooperative research centers.

Individual Agency Contributions to Objective 3.3

DOE: The Office of Science's five Nanoscale Science Research Centers (NSRCs) are housed in custom-designed laboratory buildings near one or more other major DOE facilities for x-ray and neutron scattering, which complement and leverage the capabilities of the NSRCs. For example, at the Argonne National Laboratory, the Center for Nanoscale Materials and the Advanced Photon Source (APS) share operation of a hard x-ray nanoprobe beamline that allows for unprecedented views deep within nanomaterials. Similarly, at Oak Ridge National Laboratory, the capabilities at the Center for Nanophase Materials Sciences are closely tied to neutron scattering capabilities at the national laboratory, integrating synthesis science, theory/modeling/simulation, and advanced approaches for functional and structural imaging. The NSRC laboratories contain cleanrooms, nanofabrication resources, one-of-a-kind signature instruments, state-of-the-art electron microscopy, and other instruments not generally available except at major user facilities. These facilities are available to the academic, industry, and government research community for successfully peer-reviewed research projects. The NSRCs provide training for graduate students and postdoctoral researchers in interdisciplinary nanoscale science, engineering, and technology research.

FDA: FDA has established two state-of-the-art nanomaterial characterization facilities, at the White Oak Campus in Silver Spring, MD, and at the Jefferson Laboratories in Jefferson, AR. These facilities support FDA research scientists by providing the equipment and knowledge to characterize nanomaterials. These facilities also serve to provide hands-on training for FDA review and enforcement staff. FDA will continue to maintain these facilities and has plans to add additional equipment in 2015 and 2016.

NIST: NIST continues to sustain and update the capabilities and capacity in its nanotechnology user facility, the CNST, providing industry, academia, NIST, and other Government agencies with rapid access to world-class nanoscale measurement and fabrication methods and technology. Access is provided in two ways. First, in the NanoFab, users access a commercial state-of-the-art tool set at economical hourly rates, supported by a dedicated, full-time technical support staff. Second, in the NanoLab, users access the next generation of tools and processes through collaboration with the multidisciplinary research staff. The NanoFab continues to enhance its capabilities and capacity, with notable upcoming additions, including state-of-the-art substrate cleaning systems; rapid thermal processing; a wafer-scale thin-film resistivity mapping system; and a new field-emission scanning electron microscope (FESEM) capable of nondestructive imaging of features on 200 mm wafers, the wafer size most in demand by industrial researchers. New capabilities in the NanoLab include methods and instrumentation for *in situ* characterization of nanomaterials and nanodevices functioning in realistic operating environments, and innovative measurement methods that combine Raman spectroscopy with atomic-scale imaging electron microscopy to measure catalytic processes on the nanoscale. In addition to CNST, NIST maintains the Precision Imaging Facility (PIF) at the NIST campus in Boulder, CO, with staff expertise in nanoscale characterization in an ever-growing range of materials, from metal welds to semiconductor nanowire LEDs to complex aerospace coatings and conducting oxides. The PIF promotes collaborative research with local universities and DOE national laboratories.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 3.3

NIST, industry, and universities: The NIST CNST user facility is collaborating with industry and universities to develop and make available to users new nanoscale measurement and fabrication methods. For example, in the past year using the CNST NanoFab user facility, scientists from NIST and the University of Maryland collaborated to build a silver, glass, and chromium metamaterial-based nanostructure that can all but stop visible light traveling in one direction while allowing it to pass through in the other direction. The device could someday play a role in optical information processing and in detecting tiny particles for biosensing applications.

Goal 4: Support responsible development of nanotechnology.

Realizing the potential benefits of nanotechnology for human, social, and economic well-being, and for the environment, requires that responsible development of nanotechnology—assessment and management of potential risks—be integrated into all aspects of the field, from world-class nanotechnology R&D (Goal 1) to commercialization of nanotechnology-enabled products (Goal 2). Responsible development is a fundamental component of all three objectives in nanotechnology-focused education, workforce, and infrastructure development (Goal 3). Research in support of Goal 4 addresses the recognized issues and opportunities surrounding the protection of humans and the environment that are shared by many stakeholder groups.

In 2011, the NNI developed, with input from stakeholders, a nanotechnology-related environmental, health, and safety (nanoEHS) research strategy with a broad, multiagency perspective.[77] That document fully supports the Goal 4 objectives and details specific research needs in six interrelated and synergistic nanoEHS areas: (1) a *nanomaterial measurement infrastructure* coupled with (2) *predictive modeling and informatics* that provides accurate and reproducible data on (3) *human exposure*, (4) *human health*, and (5) *the environment*, all of which are essential for science-based *(6) risk assessment and management* of engineered nanomaterials and nanotechnology-enabled products. The NNI agencies, individually and collaboratively, will continue to provide information on progress toward addressing these research needs.

Consideration of life cycle issues is a key component of all four objectives described below. Advances in these objectives require coordinated efforts involving multidisciplinary, multistakeholder national and international teams.

Objective 4.1 – 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.

Individual Agency Contributions to Objective 4.1

DOD/Air Force: Using core funding, AFRL scientists are accomplishing a multitude of nanotechnology research projects geared towards investigating the biological interaction of engineered nanomaterials (ENMs), including potential toxicity arising from resultant physicochemical and structural properties. This research will facilitate a better understanding of nano–bio interaction mechanisms and provide in-depth analysis of their corresponding effects and aid researchers in devising appropriate ways to monitor exposure levels and develop control strategies to enhance Air Force force-protection efforts. While the Air Force is working to minimize risks concerning the production, handling, and disposal of nanomaterials as they relate to future mission requirements, a significant knowledge gap remains with respect to the human and ecological health implications of increasing nanomaterial usage. It is critical to understand the transport and transformation of nanomaterials channeled through the environment and the human body, including their significant avenues of access and potentially adverse effects. Two key areas of immediate military relevance include propulsion and munitions systems, which employ nanomaterials not only in reducing the sensitivity of munitions to accidental initiation during storage and delivery, but also in

[77] www.nano.gov/you/environmental-health-safety

generating more energetic propulsion/explosions and ensuring long-term storage stability. Research in the Human Effectiveness Directorate focuses on understanding the toxicological properties of ENMs based on size, charge, shape, and functionalization.

EPA: In 2014, EPA integrated research supported under its Chemical Safety for Sustainability program,[78] including research on emerging materials, focused on engineered nanomaterials. A key scientific issue is the complexity of relating nanomaterial features directly to risks. An important avenue of investigation focuses on identifying critical intermediate properties of ENMs that are predictive of potential risks. Another key issue is understanding the interactions between ENMs and biological or other complex media. Methods are required to characterize nanomaterials in simple and complex media and to evaluate the release of nanomaterials from consumer products, and alternative testing approaches are needed to evaluate adverse outcome pathways of nanomaterials. Predicting impacts of ENMs used in real-world conditions will depend on properties of both the ENMs and the matrix. Research will evaluate nanomaterials across a life cycle of product use ranging from manufacture to use and end-of-life disposal and will consider the release, fate, transport, and transformations of nanomaterials as they age.

EPA has also funded the creation of The EPA STAR Center for Organotypic Culture Models at the University of Washington, a Predictive Toxicology Center for Organic Culture Models and Assessment of AOPs (adverse outcome pathways) for engineered nanomaterials. The overall goal of this center is to develop innovative organotypic culture systems to better evaluate the potential for cellular and organ toxicity following exposure to ENMs within an AOP model. EPA funded this center in 2014 and plans to continue its support in 2015 and 2016.

FDA: In 2014, FDA centers provided funding for regulatory science projects related to the products under their purview such as medical products, foods, and feeds. In addition, the FDA Office of the Chief Scientist funded projects focused on cross-agency issues through the Collaborative Nanotechnology Grants (CORES) program. With funding beginning in 2006, these projects have led to the development of vital regulatory science tools such as assays, assessment methodologies, and test protocols that FDA staff use when reviewing the safety and efficacy of nanotechnology in FDA-regulated products. For example, FDA collaborated with NCL to develop a panel of *in vitro* assays, which appear in the *Handbook of Immunological Properties of Engineered Nanomaterials*, for evaluating the effects of nanomaterials on blood platelets and endothelial cells. Findings from these projects also serve in drafting guidance to industry and in helping to provide sound and scientifically based responses to inquiries from stakeholders. In 2015 and 2016, FDA will continue to fund projects on an as-needed basis in areas where knowledge gaps exist.

NIH: The major focus of the NIH National Institute of Environmental Health Sciences nanotechnology research effort is broadly associated with this goal. Gaining knowledge on fundamental interaction of ENMs with biological matrices as dictated by their physicochemical properties is critical in assessing potential health risks associated with accidental or incidental exposure to nanomaterials or nanotechnology-enabled products [*see also Objectives 1.4 and 2.2*]. NIH/NIEHS investments address all of the six research needs in the human health core research area identified in the 2011 NNI EHS Research Strategy.[79] Current NIH/NIEHS nanoEHS investments specifically focus on research needs 1–5 in the human health core research area through the efforts of a consortium of research centers, the NIH/NIEHS Centers for Nanotechnology Health Implications Research (NCNHIR), established in 2010; good laboratory practices studies carried out by National Toxicology Program (NTP); and intramural research at the clinical research

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[78] http://www2.epa.gov/aboutepa/about-chemical-safety-sustainability-research-program

[79] *The National Nanotechnology Initiative Environmental, Health, and Safety Research Strategy* (NSTC, Washington, DC, 2011; www.nano.gov/2011EHSStrategy).

facility. These programs are evaluating the toxicity of dozens of ENMs with diverse physical and chemical properties. The ENMs being characterized by these centers represent a majority of the ENMs commercially produced in large quantities. The toxicology data from these investigations are utilized in developing computational predictive models.

NIH/NIEHS is currently developing plans to continue support for research efforts in five research needs areas identified in the 2011 NNI EHS Research Strategy to gain comprehensive understanding of toxic effects of ENMs to predict potential health effects and development of tools to assess exposure to ENMs from diverse routes. These efforts will focus on expanding efforts to assess the toxicity of ENMs from multiple routes of exposure and human exposure to nanomaterials in different media (air and water). This research will also assess the potential contributions of susceptibility factors in human health effects assessment; such factors include underlying disease, genetics, age, and gender. These new NIEHS initiatives for 2015 are being developed in consultation with member agencies of the NEHI Working Group.

NIOSH: NIOSH continues its efforts to develop more complete hazard and safety assessments using key classes of ENMs: carbon nanotubes; metal oxides; silver; the nanowire forms of silver, silica, and titania; graphene and graphene oxide; and cellulose nanocrystals and nanofibers. In 2016 NIOSH will increase efforts to develop a more realistic, "real world" evaluation of hazard and risk represented by various nanomaterials through their life cycles. In 2014 NIOSH expanded its field investigation efforts to include a focused effort on developing risk management practices that support responsible development of nanotechnology. In 2016, that particular element of the NIOSH field research effort will focus on outputs that support the Sustainable Nanomanufacturing Signature Initiative. Carbon nanotubes are the nanomaterial to be evaluated as a class. The intent is to couple toxicology dose levels to those that have been observed in occupational exposure assessments conducted by NIOSH. In 2015, NIOSH published a summary of the principles outlined in the 2012 NIOSH-sponsored Safe Nano Design Workshop.[80] In 2016, NIOSH will move forward with development and dissemination of key areas identified by workshop attendees and stakeholders, which include (1) demonstrating change in nanomaterial toxicology through material design changes, and (2) disseminating case studies developed with private companies that demonstrate the effectiveness of incorporating facility and process design into the organization's EHS strategy. Impact in this key program area has already been realized through NIOSH partnering with private sector companies to conduct on-site research that will result in the development and implementation of effective risk management practices that will ultimately result in safer, more efficient nanomanufacturing processes.

NIST: NIST is developing measurement tools to determine the physicochemical, human-toxicological, and ecotoxicological properties of key ENMs in relevant media (e.g., air, water, and biological matrices); to characterize transformations, transport, and fate of ENMs in such media; and to evaluate potential exposures to airborne ENMs. NIST is also developing transferable methods to detect the presence of ENMs in nanotechnology-enabled products and to assess life-cycle releases of ENMs from such products. Key highlights of work conducted in 2015 and planned for 2016 include the following:

- Make available the world's first silver nanoparticle (75 nm and 10 nm diameter) reference materials.
- Design *in vitro* toxicology assays to enable evaluation of nine quality metrics that describe assay performance, and identify sources of assay variability and demonstrate robustness through pilot interlaboratory testing.
- Develop methods that utilize ^{14}C-labeled carbon nanotubes to track the location and fate of carbon nanotubes in biological and environmental systems.

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[80] www.cdc.gov/niosh/topics/PtD/nanoworkshop/default.html

- Complete comparative studies of various methods to detect the presence of silver nanoparticles in textiles and carbon nanotubes in polymer composites, including instrument detection limits for each method.
- Develop and evaluate novel nanoparticle-based fire retardant layer-by-layer coatings that have been demonstrated to reduce the fire hazards associated with polyurethane foam by 30%. The decreased flammability of polyurethane foam, used in many home furnishings, is expected to lead to significant reduction in residential fire losses.

NRC: The Nuclear Regulatory Commission (NRC) is an independent agency created by Congress. NRC's mission is to license and regulate the Nation's civilian use of by-product, source, and special nuclear materials to ensure adequate protection of public health and safety, to promote the common defense and security, and to protect the environment. As a regulatory agency, NRC does not typically sponsor fundamental research or product development; rather it is focused, in part, on confirmatory research to verify the safe application of new technologies in the civilian nuclear industry. Currently, the agency's focus with nanotechnology is to monitor developments that might be applied within the nuclear industry in order for NRC to carry out its oversight role.

USDA/NIFA: The NIFA nanotechnology programs have been and will continue supporting the EHS research targets that are most relevant to agricultural production and food applications. For example, a new project funded in the most recent funding cycle will investigate the fate and transport of zinc and silver nanoparticles in livestock manure and their impact on the complex ecological environment.

Coordinated Activities with other Agencies and Institutions Contributing to Objective 4.1

CPSC, DOD, FDA, NIOSH, and NIST: The CPSC staff will continue its significant efforts to develop methods and data to identify and mitigate potential hazards from nanotechnology-enabled products. The staff signed several interagency agreements in 2014 with DOD, FDA, NIOSH, and NIST, with the work planned to continue into 2015 and beyond. These research studies will primarily focus on the application of nanomaterials to consumer products, the mechanisms that impact release of nanomaterials from a range of matrices, and approaches to quantify and characterize exposure to consumers and the general population.

CPSC has developed several research projects through interagency agreements made in 2013 through 2015 that will continue through 2016. The objective of this work is to develop robust methods to characterize nanomaterials in products and understand releases and exposure potential. NIOSH provides direct support in the following areas: toxicology testing and physical characterization of aerosols generated by several products that have consumer and commercial application; toxicology testing and physical characterization of several nanomaterial-containing products during the machining (cutting, sanding, drilling) of those products; characterization of nanoparticulate emissions from laser printers; and work with manufacturers to understand how emissions might be reduced. The results of these studies are disseminated to the public through reports, presentations at technical meetings, and publication in peer-reviewed journals.

DOD/Army and Air Force: AFRL coordinates with the U.S. Army Corps of Engineers, which provides its expertise in life cycle analysis to help determine the risk of exposure to nanomaterials during different stages of development. The organizations will use predictive and computational modeling approaches to identify potential release of nanoscale particles from nanostructured materials and technologies.

DOD/Army, other NNI agencies, industry, and universities: The Army invests in understanding the potential nanoparticle release, fate, transport, and toxicity processes that are required to understand and proactively manage risks to the environment and human health. The Army is developing tools, methods, and approaches to provide accurate and reliable information and data supporting risk assessment and management. These studies focus on the life cycles of nanotechnologies developed by the Army, other DOD agencies, the Institute for Soldier Nanotechnologies at MIT, academic partners, and industry. For example, the Armament Research, Development and Engineering Center (ARDEC) has partnered with the Engineer Research and Development Center (ERDC) to begin a comprehensive program to understand the environmental consequences of nanomaterials. ARDEC will be providing ERDC with the necessary nanomaterials to support environmental testing and to help develop the database for materials that might impact DOD. Further, ERDC nanoscale research includes risk assessment research on specific materials and technologies that are priorities for partner institutions. Risk-based processes to quantitatively assess the benefit and impact of nanomaterial-based products in the environment and computational approaches for the smart design of functional nanomaterials provide technical guidance on evaluating nanoEHS impacts during development, transition, and acquisition. Through partnerships with EPA, CPSC, NIST, and NIOSH, results of these studies will be used to support safe development of the nanotechnologies, enable more rapid fielding and commercialization, and meet regulatory requirements.

DOD, EPA, NIST, and CPSC: ERDC coordinates research activities directly with the Army Research Laboratory; the Army Armament Research, Development and Engineering Center; the Air Force Research Laboratory, the Air Force Civil Engineer Center; the Defense Advanced Research Projects Agency; the Defense Threat Reduction Agency; the Environmental Protection Agency; the National Institute of Standards and Technology; the Consumer Product Safety Commission; and industry partners to develop environmental life cycle analysis approaches for nanotechnologies *[also relevant to Objective 1.2]*.

EPA and CPSC: EPA and CPSC are nearing completion of a collaborative research project evaluating potential release of copper from copper-treated commercial wood products. The composition, particle size distribution, leaching, bioavailability, and exposure to micronized copper have been evaluated. Reports are being developed and will be available in the near future.[81]

EPA, NSF, USDA/NIFA, CPSC, United Kingdom, and OECD: EPA's Science to Achieve Results (STAR) Program has issued joint solicitations with NSF and USDA. In addition, EPA, CPSC, and the United Kingdom awarded six grants in 2010 under a joint international solicitation.

FDA and CPSC: In 2014, FDA collaborated with CPSC through an interagency agreement on assessing whether current methods for determining migration of conventional additives are applicable to the evaluation of nanomaterials used in consumer products that contact food. Results from this work were presented at the June 2014 TechConnect World Innovation Conference, on June 18, 2014, in Washington, DC.[82] This work is planned to continue through 2016.

NIH, EPA, NSF, FDA, and NIOSH: Federal agencies such as NIH, EPA, NSF, FDA, and NIOSH have ongoing efforts and collaborations to share knowledge and materials on the topic of EHS. In 2016, NIH/NIEHS will continue to work with other interested agencies to develop NIH and/or interagency initiatives, as appropriate, in areas identified in the NIH section of Objective 4.1 above.

NIH, NSF, CPSC, the European Union, and universities: In 2015, NIH/NIEHS participated in a joint solicitation[83] with NSF and CPSC for international collaborative efforts to support nanoEHS research with European Union countries. This program will support participation of investigators at U.S. universities in

[81] nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100LJWI.txt

[82] www.techconnectworld.com/World2014

[83] http://www.siinn.eu/en/joint-calls/2014-third-siinn-call/,161

U.S.–EU consortium efforts to address nanoEHS research needs identified in the 2011 NNI EHS Research Strategy. *[This program is also relevant to Objective 2.4.]*

NIOSH, CPSC, and NIH: NIOSH has continued formal collaborations with CPSC and the NIH/NIEHS National Toxicology Program to deliver research results that provide basic knowledge in two fronts: (1) work done with CPSC that continues to characterize the exposure potential and biological responses to inhalation of select nanomaterials from consumer products in support of human exposure risk assessments, and (2) continued NIOSH collaboration with NTP to investigate actual worker exposure potential during manufacture and use of engineered nanomaterials. NTP also collaborates with NIOSH to investigate potential hazards associated with exposure to cellulose nanomaterials. *[This work is also relevant to the Nanomanufacturing NSI in Objective 1.4.]*

NIOSH and DOD/Army: Throughout 2014 and 2015, NIOSH has supported efforts in the Army to develop tools, methods, and approaches to provide accurate and reliable information and data supporting risk assessment and management of nanomaterials used in a variety of applications. Direct collaboration with the U.S. Army Center for Environmental Health Research (USACEHR) resulted in risk assessment guidance that was applied in 2015 to identify and prioritize nanomaterials for more detailed evaluation. Starting in 2015 and continuing into 2016, NIOSH is supporting USACEHR efforts to identify priority nanomaterials that serve as models for computational approaches to predicting human and environmental health risks. This program effort will have application through the Engineer Research and Development Center (ERDC) and the Armament Research, Development and Engineering Center (ARDEC). ARDEC will be providing ERDC with the necessary nanomaterials to support environmental testing and will help develop the database for materials that might impact DOD. Through additional NIOSH partnerships with EPA, CPSC, and NIST, results of these studies will be used to support safe development of the technologies, enable more rapid fielding and commercialization, and meet regulatory requirements.

In 2015, NIOSH extended an interagency agreement with the Navy Medical Research Unit to explore correlations between laboratory toxicology testing, high-throughput screening techniques, and potential human health impacts of exposure to engineered nanomaterials. In 2016, NIOSH will use the results of this research collaboration to evaluate its strategy for using a categorical approach to classify nanomaterials into hazard classes as a starting point for more effective risk assessment and management.

NIST and CPSC: In collaboration with CPSC, NIST is developing testing and measurement procedures for determining the quantities and properties of nanoparticles released from consumer products such as flooring coatings and interior paints. This joint work is developing instrumentation and analytical methods to measure particles released during abrasion in air (dry conditions) from floor coatings and interior paints containing a known amount of nanoparticles, as well as developing methods to measure and identify the particles remaining on the coating surface and in cleaning liquids. Additional work in 2016 will involve the study of nanoparticles released from coatings during ultraviolet (UV) degradation processes.

NIST, EPA, NIOSH, CPSC, OSHA, NRC-Canada, industry, and non-governmental organizations: U.S. and Canadian federal agencies are working with industry on the NanoRelease Project, coordinated by the Research Foundation of the International Life Sciences Institute, to develop methods for evaluating the release of carbon nanotubes from polymer-based composites and to use these methods in interlaboratory testing studies.

NIST and industry: NIST coordinated and participated in an interlaboratory comparison study with the Advanced Materials and Systems Research Division of BASF on protocols that simulate nanocomposite aging, as well as procedures for the detection of released particles and fragments. With a focus on the mechanism of nanoparticle release via mechanical shear after weathering, the study is expected to result in a combined method that will assist in the characterization of released fragments as they relate to fate, transport, and ecotoxicological testing.

NSF, EPA, and universities: NSF and EPA joint research on environmental implications of nanotechnology, including development of new measurement methods for nanoparticle characterization and toxicity of nanomaterials, will continue to be investigated in the two dedicated multidisciplinary Centers for Environmental Implications of Nanotechnology (CEIN) at UCLA and Duke University (the awards are approximately $5 million each). Essential elements of these investigations will be research on methods and instrumentation for nanoparticle detection, characterization, monitoring, and environmental risk analysis, including interactions of nanomaterials with cellular constituents, metabolic networks, and living tissues; bioaccumulation and its effects on living systems; and the impacts of nanostructures dispersed in the environment.

USGS and NIOSH: USGS and NIOSH are working on approaches for analysis of low-level dissolution of nanomaterials in biological fluids.

USGS and universities: USGS is conducting research on the influence of environmental transformations on the bioaccumulation and toxicity of metal-based nanoparticles, including Ag, Ni, CuO, and ZnO nanoparticles, to aquatic organisms. Stable isotopic tracers are being employed in novel ways to quantify biological uptake and delineate ion and nanoparticle uptake. Collaborating organizations include the University of South Carolina, the University of Kentucky, the University of Birmingham (UK), Roskilde University (Denmark), and the University of California, Davis. These research activities are planned to continue in the coming years.

Objective 4.2 – Create and employ means for timely dissemination, evaluation, and incorporation of relevant EHS knowledge and best practices.

Individual Agency Contributions to Objective 4.2

DOD/Air Force: AFRL is evaluating potential health risks of engineered nanomaterials and identifying appropriate exposure limits, contributing to timely dissemination, evaluation, and incorporation of relevant EHS knowledge and best practices.

DOD/Army: The Army is developing tools, methods, and approaches to provide accurate and reliable data supporting risk assessment and management. Among these is a tiered, user-friendly conceptual framework for adaptive screening and evaluation of the potential for nanomaterial-unique EHS impacts associated with acquisition and use of military-relevant nanotechnologies, as well as step-by-step scientific testing procedures needed to acquire all the information to make informed EHS determinations. These tools and methods and relevant information will be made accessible through a webpage, allowing for their easy dissemination.

EPA: Since 2013, EPA intramural research on engineered nanomaterials has been published in over 55 peer-reviewed manuscripts or book chapters, and EPA research has been presented at numerous national and international scientific meetings.

FDA: Internal to FDA, select groups of staff meet regularly to review and discuss internal FDA research on assessing the safety and efficacy of nanotechnology in FDA-regulated products. For example, the charter for the FDA Nanotechnology Task Force was revised and endorsed by the FDA Commissioner in 2014, underscoring the continued importance of this forum. Likewise, FDA staff who review the safety and efficacy of FDA-regulated products meet regularly to discuss products using nanotechnology and consult with FDA experts on nanotechnology.

External to FDA, the projects funded by FDA result in peer-reviewed journal articles as well as scientific contributions to standards development. In 2014, FDA issued three final guidances and one draft guidance providing greater regulatory clarity for industry on the use of nanotechnology in FDA-regulated products.[84]

NIOSH: NIOSH will continue to disseminate the results of research from its nanotechnology research program in the form of publication of progress reports of all NIOSH Nanotechnology Research Center projects, e-newsletters, the NIOSH Science Blog, technical meeting and symposia presentations, formal peer-reviewed journal publications, and NIOSH publications. The NIOSH Workplace Safety and Health Nanotechnology Topic webpage[85] is one of the top pages visited on the agency website. In 2015, NIOSH continued a multifaceted initiative focused on delivering knowledge and training to industrial hygiene and EHS practitioners, private sector nanomanufacturing companies, engineering students, and international research partners. NIOSH refined the content and delivery of a higher-level exposure measurements and assessment strategy training course for EHS professionals and delivered the course nationally and internationally in 2015. Plans for 2016 include follow-up on the effectiveness of a 2015 publication on nanotechnology health and safety strategies for small to mid-sized nanomaterial producers and users. Starting in 2015 and continuing through 2016, NIOSH will disseminate to companies individual process-based control strategies that draw from the broader 2013 NIOSH guidance document, *Current Strategies for Engineering Controls in Nanomaterial Production and Downstream Handling Processes*.[86]

NIST: Based on nanoEHS programmatic research efforts, NIST will continue to grow the number of laboratory protocols available for wide utility by the nanoscience community (e.g., protocols for measurement and dispersion of nanoparticles[87]). In the next year, NIST intends to make publicly available a series of protocols, e.g., validated procedures for preparing control samples with specified concentrations of engineered nanomaterials in product matrices; single-particle inductively coupled plasma mass spectrometry measurement methods with validated data; and experimental design principles to avoid artifacts and misinterpretations in nanoecotoxicology testing.

NSF: Research on the safety of manufacturing nanoparticles is already included in four Nanoscale Science and Engineering Centers and the National Nanotechnology Infrastructure Network. Environmental implications of nanotechnology, including development of new measurement methods for nanoparticle characterization and toxicity of nanomaterials, will continue to be investigated in the two Centers for Environmental Implications of Nanotechnology at UCLA and Duke University, as described in the Coordinated Activities section of Objective 4.1.

Coordinated Activities with other Agencies and Institutions Contributing to Objective 4.2

CPSC, NIOSH, and NIST: The CPSC staff, through a number of interagency agreements with agencies including NIOSH and NIST, has developed methods for characterizing the release of nanomaterials from a wide range of products and product matrices. These methods have been published in peer-reviewed scientific journals, and the data are being used to support the development of voluntary standards. For example, CPSC and NIST have been developing methods to evaluate abrading of coatings and finishes for floors and walls, and have proposed that these methods be incorporated into an international ASTM E56 standard. Methods used for characterizing nanosilver releases from textiles will support another ASTM standard for nanosilver release, as part of an interagency agreement with NIST.

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[84] www.fda.gov/ScienceResearch/SpecialTopics/Nanotechnology/ucm301093.htm

[85] www.cdc.gov/niosh/topics/nanotech

[86] www.cdc.gov/niosh/docs/2014-102/pdfs/2014-102.pdf

[87] www.nist.gov/mml/np-measurement-protocols.cfm

DOD/Air Force, NNI agencies, universities, and industry: To examine potential toxicity, health, and environmental issues in the DOD community, Air Force personnel organized and led the first Air Force Workshop on Biological Interactions of Engineered Nanomaterials: Environmental, Safety and Health Issues of Military Concern.[88] This workshop brought together participants from industry, academia, and government agencies, including EPA and NIOSH, to communicate and discuss current controls associated with the use of nanomaterials. AFRL scientists participate in the DOD Nanomaterials Environment Safety and Occupational Health (ESOH) Working Group. In coordination with the DOD Emerging Contaminants Governance Board, this working group provides technical, policy, and legal information relating to the safety and health issues associated with ENMs.

DOD/Army, DOD/Air Force, and CPSC: Tools and methods are being developed and validated using specific materials and technologies that are priorities to partner agencies and institutions to ensure work is relevant to the current state of Army nanotechnology development and the overall Army need. ERDC is currently working with different nanomaterials provided by ARL, ARDEC, and CPSC to provide relevant EHS knowledge and best practices.

NNI agencies and OECD: The OECD Working Party on Manufactured Nanomaterials (WPMN) organized four meetings or workshops during 2014 with emphasis of various aspects of international approaches and cooperation to evaluate ENMs. These included a general meeting of the WPMN (June 2–5 in Paris) and individual meetings hosted by EPA in the Washington, DC, area targeted to chemical and physical characterization of ENMs (June 18–19), aquatic toxicity (July 1–2), and categorization of ENMs (September 17–19). The meetings included participation of multiple Federal partners, including EPA, FDA, CPSC, NIOSH, NIST, and ERDC, as well as international delegates from OECD member countries and representatives of industrial trade organizations and nongovernmental organizations. Follow-up work is anticipated in 2015.

EPA and universities: A workshop organized by the University of California Center for Environmental Implications of Nanotechnology and EPA was held at the Woodrow Wilson Center in Washington, DC, May 19–20, 2014. The workshop involved participants from academia, industry, NGOs, and Government agencies. The discussion involved how categorization and alternative testing strategies could be used to aid in risk assessment of ENMs, with a special focus on carbon nanotubes, which represent about half of the ENM premanufacture notices received by EPA.

FDA, NNI agencies, and international organizations: FDA coordinates with other U.S. Government agencies and international agencies as well as other stakeholders through international organizations such as ISO, ASTM, and OECD.

NNI agencies: NNI agencies, with support from NNCO, released in June 2014 the NNI's *Progress Review on the Coordinated Implementation of the NNI 2011 Environmental, Health, and Safety Research Strategy*, a document that demonstrates the wide range of research activities, accomplishments, and collaborations of Federal agencies working toward the responsible development of nanotechnology.[89] The NNI also sponsored a webinar for the general public on July 31, 2014, that featured a discussion of the EHS Progress Review. The webinar included a brief overview presentation followed by a Q&A session with questions directed to representatives of several Federal agencies, including EPA, OSHA, NIOSH, NIST, NIEHS, ERDC, CPSC, and NNCO. Over 400 individuals logged in to participate in the webinar, demonstrating substantial public interest in the topics covered. An archived webcast is available at www.nano.gov/node/1166.

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[88] www.denix.osd.mil/cmrmd/upload/Nano-Flyer-Issue-1.pdf

[89] www.nano.gov/2014EHSProgressReview

NSF and EPA: The Centers for the Environmental Implications of Nanotechnology at UCLA and at Duke University will increase dissemination of information to government regulators at State and Federal levels and to industry stakeholders, with a focus on decision support tools, nanosafety training, and consumer product safety.

NSF, NIH, CPSC, and the European Union: NSF, CPSC, NIH, and the EU are continuing collaboration on a joint U.S./EU solicitation for nanotechnology EHS. A focus will be on implications of the next generation of nanotechnology products and productive processes, as well as public participation in nanotechnology-related activities. Research on both implications and applications of nanotechnology will address the sources of nanoparticles and nanostructured materials in the environment (in air, water, soil, biosystems, and working environments), as well as the nonclinical biological implications. These activities will support the ongoing efforts to leverage knowledge and resources between researchers in the United States and the EU.[90] The results will be disseminated via the participating agencies websites, the NSF Grantees Conference, peer-reviewed journal publications, and presented at professional meetings in the United States as well as abroad.

Objective 4.3 – Develop the national capacity to identify, define, and responsibly address concepts and challenges specific to the ethical, legal, and societal implications (ELSI) of nanotechnology.

Individual Agency Contributions to Objective 4.3

NIOSH: NIOSH is working to foster the responsible development of nanotechnology and the realization of its societal and commercial benefits. Workers are among the first in society to have potential exposures to any new material, including nanomaterials, and thus the protection of the worker can be seen as the core of responsible development. Occupational safety and health criteria for responsible development of nanotechnology should be developed at the societal level (by government agencies, trade and professional associations, unions, NGOs, and insurers) first, and then promoted for use at the business enterprise level (employers, suppliers, and business customers).

NSF: NSF supports research directed at identifying and quantifying the broad implications of nanotechnology for society, including social, economic, workforce, educational, ethical, and legal implications. The application of nanoscale technologies will stimulate far-reaching changes in the design, production, and use of many goods and services. NSF also supports a project to embed humanists and social scientists in laboratories for greater collaboration in nanoscience around the world, providing a model for future integration of ethicists and social scientists into nanotechnology R&D laboratories broadly.

The Centers for Nanotechnology in Society at University of California, Santa Barbara and Arizona State University are among the very few social science centers in the world looking at nanotechnology ELSI issues and operating on a large scale to involve multiple institutions and multiple disciplines. The overarching goal of both centers is to foster the integration of social science research with nanoscale science and engineering (NSE) to promote socially responsible innovations. CNS-UCSB does so by focusing on the broad range of individuals' perceptions of risks—including their beliefs, values, and ideologies—where risk perception is not regarded as a problem to be handled but rather as a factor that needs to be understood, constituted by multiple stakeholder groups having multifaceted, complex, and evolving relationships. CNS-ASU does so by focusing on the unifying framework of anticipatory governance, which

[90] us-eu.org

involves promoting the involvement of multiple stakeholders in deliberations about plausible future technological developments.

These two CNS centers promote increased awareness of societal issues within the nanoscale science and engineering community. They continue to inform policy via presentations to key State, national, and international regulators and policymakers. They also continue to engage in various public outreach engagements via media interviews, speaker series, NanoDays, web-based materials, and public presentations. CNS-ASU also studies the ways in which NSE contributes to increasing or decreasing social and economic inequalities in different national contexts, and it explores ways to ensure that NSE can contribute to equity, equality, and responsibility as public values. Over the last year, CNS-ASU has shifted its work to analyzing the unequal conditions and consequences of emerging nanotechnology applications in developed and developing countries. The decision was made to focus these efforts on case studies of two countries, the United States and South Africa.

USDA/NIFA: NIFA's Agriculture and Food Research Initiative nanotechnology program solicits research proposals on assessment and analysis of the perceptions and social acceptance of nanotechnology and nanotechnology-based food or non-food products by the public, the agriculture community, and food stakeholders, using appropriate social science approaches. For example, a new project funded in 2015 will use advanced eye-tracking methodologies to obtain a greater understanding of the important characteristics of consumer acceptance of food and agricultural products affected by nanotechnology.

Coordinated Activities with other Agencies and Institutions Contributing to Objective 4.3

CPSC and NSF: The CPSC staff, in coordination with NSF, is proposing for 2016 a center of excellence that will develop methods to characterize exposures and risks to consumers and the general population, and address the societal implications of nanomaterial use in consumer products. Research will target the development of methods for quantifying and characterizing the presence, release, and mechanisms of consumer exposure to nanomaterials. The center will provide other benefits to society by developing scientists with expertise in nanomaterials and consumer product safety research who will be able to further the public's basic understanding of this technology and develop innovative methods for the responsible use of nanomaterials in products. The center will also serve a resource for manufacturers and distributers of nanotechnology-enabled products for approaches to ensuring the safe use of this technology in products, as well as for consumer groups and others in the general public that have a desire to learn more about nanomaterial use and implications. *[Also relevant to Objectives 2.2 and 2.3.]*

DOD/Air Force and EPA: AFRL has contributed substantial comments and assessments to EPA on rule development for nanomaterial reporting and information-gathering in relation to health effects, the technology research environment, and impacts on manufacturing development.

Objective 4.4 – Incorporate sustainability in the responsible development of nanotechnology.

Individual Agency Contributions to Objective 4.4

DOD/Air Force: AFRL scientists are conducting focused research to establish the possible effects of nanoparticle exposure on biological systems.

DOD/Army: The ARL is conducting a multiscale research program to investigate low-cost, high-performance reinforcement of transparent composites using cellulose-based nanomaterials derived from renewable bioresources. Target applications include lightweight films and composites for use in ballistic protection and structural applications, with particular interest in reducing mechanical failure of transparent laminates. Significant accomplishments include development of cellulosic nanoarchitectures with tunable mechanical properties by using metal ions to bridge the fibrils; capability to generate well-dispersed silver nanoparticles *in situ* in nanocellulose gels, aerogels and thin films; development of nanocellulose-reinforced poly(methyl methacrylate) nanofibers with improved modulus; development of new processes for drying; and dispersing nanocellulose particles to facilitate their use in nonpolar and transparent engineering polymers. ARL is also examining a new method of transforming plastic waste materials into value-added nanofibrous products with specific focus on water filtration membranes. Significant accomplishments include fabricated nanofibers from expanded polystyrene packaging and polyethylene terephthalate water bottles using solvent-based electrospinning.

NIOSH: NIOSH is working with industry to implement effective controls and handling practices to significantly reduce worker exposure. Throughout 2016, NIOSH will work with partner companies along their material life cycles and supply chains to identify where and how effective health and safety contributes to the overall sustainability of their processes and products. NIOSH is also collaborating with nanomaterial manufacturers to evaluate the bioactivity of nanoparticles produced by these companies and to evaluate the effectiveness of surface modification in reducing this bioactivity.

NSF: NSF supports several programs under this objective, including the NSF-wide initiative for Science, Engineering, and Education for Sustainability (SEES), and the establishment and development of the Sustainable Nanotechnology Organization (SNO) since 2012. An international SNO conference will be held in 2015 in Europe, and a U.S. conference will be held in 2016.

USDA/NIFA: Sustainability is recognized as one of the key challenges facing agriculture and food systems. NIFA's AFRI nanotechnology program has supported research projects that aim at enhancing sustainability of agricultural production and utilization of agriculturally based biomaterials and value-added novel products. For example, a new project funded in 2015 will develop an electrospinning technology to produce reinforced and functionalized starch nanofibers for various packaging applications such as antimicrobial films.

Coordinated Activities with other Agencies and Institutions Contributing to Objective 4.4

DOD/Army, USDA/FS, NIST, and universities: The Army Research Laboratory has coordinated its nanocellulose activities with relevant leaders in preparation and processing, especially focusing on critical challenges in developing optimized nanocellulose-based composites. ARL collaborates with the USDA Forest Products Laboratory in probing the effects of nanocellulose surface chemistry and microstructure on composite properties; with Northwestern, Penn State, Purdue, and other universities on better understanding and manipulating fundamental properties of cellulose nanocrystals as well as developing improved materials and techniques for secondary processing; and with applied Army engineering laboratories and NIST to test and evaluate new materials.

EPA and NSF: The EPA and NSF have co-funded a grant entitled "Network for Characterizing Chemical Life Cycle: Life Cycle of Nanomaterials" with Arizona State University. This project will evaluate the trade-offs between using nanomaterials to improve the functionality of consumer products and the potential risk to humans and the environment.

Appendix A. Abbreviations and Acronyms

AFOSR	Air Force Office of Scientific Research
AFRI	Agriculture and Food Research Initiative (USDA/NIFA)
AFRL	Air Force Research Laboratory
AFRL/RI	Air Force Research Laboratory Information Directorate
AFRL/RX	Air Force Research Laboratory Materials and Manufacturing Directorate
ARDEC	Armament Research, Development and Engineering Center (DOD/U.S. Army)
ARL	Army Research Laboratory
ARO	Army Research Office (DOD)
ARS	Agricultural Research Service (USDA)
BIS	Bureau of Industry and Security (DOC)
CDC	Centers for Disease Control and Prevention (DHHS)
CEMMSS	Cyber-Enabled Materials, Manufacturing, and Smart Systems (NSF program),
CMOS	complementary metal-oxide semiconductor
CN	cellulose nanomaterial(s)
CNS	Centers for Nanotechnology in Society at Arizona State University and University of California, Santa Barbara (CNS-ASU and CNS-UCSB) (NSF)
CNST	Center for Nanoscale Science and Technology (DOC/NIST)
CNT	carbon nanotube
CoR	Community of Research
CPSC	Consumer Product Safety Commission
DARPA	Defense Advanced Research Projects Agency
DHHS	Department of Health and Human Services
DHS	Department of Homeland Security
DNI	Director of National Intelligence
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOEd	Department of Education
DOE-SC	DOE Office of Science
DOJ	Department of Justice
DOL	Department of Labor
DOS	Department of State
DOT	Department of Transportation
DOTreas	Department of the Treasury
DTRA	Defense Threat Reduction Agency (DOD)
EERE	(Office of) Energy Efficiency and Renewable Energy (DOE)
EHS	environment(al), health, and safety
ELSI	ethical, legal, and societal implications
ENG	Engineering Directorate of NSF
ENM	engineered nanomaterial
EPA	Environmental Protection Agency
ERC	Engineering Research Centers (NSF)
ERDC	Engineer Research and Development Center (DOD/U.S. Army)
EU	European Union
FDA	Food and Drug Administration (DHHS)
FHWA	Federal Highway Administration (DOT)
FOA	Funding Opportunity Announcement
FS	Forest Service (USDA)
HFCT	Hydrogen and Fuel Cells Technology program (DOE)
IC	Intelligence Community
ISO	International Organization for Standardization
I/UCRC	Industry/University Cooperative Research Center (NSF)
LED	light-emitting diode
MEMS	microelectromechanical systems
Meso	Mesodynamic Architectures (program) (DOD/DARPA)
MPS	Mathematical and Physical Sciences Directorate of NSF
MRSEC	Materials Research Science and Engineering Centers (NSF)
nanoEHS	nanotechnology environment, health, and safety (research, etc.)
NASA	National Aeronautics and Space Administration
NCI	National Cancer Institute (DHHS/NIH)
NCL	Nanotechnology Characterization Laboratory (DHHS/NIH/NCI)
NEHI	Nanotechnology Environmental and Health Implications Working Group of the NSET Subcommittee
NERC	Nanosystems Engineering Research Centers (NSF)
NGO	nongovernmental organization
NHLBI	National Heart, Lung, and Blood Institute (DHHS/NIH)

NIBIB	National Institute of Biomedical Imaging and Bioengineering (DHHS/NIH)
NIDCR	National Institute of Dental and Craniofacial Research (DHHS/NIH)
NIEHS	National Institute of Environmental Health Sciences (DHHS/NIH)
NIFA	National Institute of Food and Agriculture (USDA)
NIH	National Institutes of Health (DHHS)
NIOSH	National Institute for Occupational Safety and Health (DHHS/CDC)
NIST	National Institute of Standards and Technology (DOC)
NITRD	Networking and Information Technology Research and Development Program
NKI	Nanotechnology Knowledge Infrastructure (Nanotechnology Signature Initiative)
nm	nanometer(s)
NNCO	National Nanotechnology Coordination Office
NNI	National Nanotechnology Initiative
NNIN	National Nanotechnology Infrastructure Network
NNMI	National Network for Manufacturing Innovation
NRC	Nuclear Regulatory Commission
NRC-Canada	National Research Council of Canada
NRI	Nanoelectronics Research Initiative
NRL	Navy Research Laboratory
NRO	National Reconnaissance Office (IC/DNI)
NSE	nanoscale science and engineering
NSEC	Nanoscale Science and Engineering Centers (NSF)
NSET	Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC
NSF	National Science Foundation
NSI	Nanotechnology Signature Initiative
NSRC	Nanoscale Science Research Centers (DOE)
NSTC	National Science and Technology Council
NTP	National Toxicology Program (DHHS/NIH/multiagency)
OECD	Organisation for Economic Co-operation and Development
OLED	organic light-emitting diode
OMB	Office of Management and Budget (Executive Office of the President)
ONR	Office of Naval Research
OSHA	Occupational Safety and Health Administration (DOL)
OSTP	Office of Science and Technology Policy (Executive Office of the President)
PCA	Program Component Area of the National Nanotechnology Initiative
PCAST	President's Council of Advisors on Science and Technology
PV	photovoltaic
QESST	Quantum Energy and Sustainable Solar Technologies (NSF/DOE Engineering Research Center)
RFA	request for applications
RFI	request for information
SBIR	Small Business Innovation Research Program
SETP	Solar Energy Technology Program (DOE/EERE)
SI	International System of Units
SSL	solid-state lighting
STAR	Science to Achieve Results (EPA)
STARnet	Semiconductor Technology Advanced Research Network (AFRL, DARPA, industry, universities)
STEM	science, technology, engineering, and mathematics
STTR	Small Business Technology Transfer Research Program
TAPPI	Technical Association of the Pulp and Paper Industry
TONIC	Translation of Nanotechnology in Cancer
USAF	U.S. Air Force
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USITC	U.S. International Trade Commission
USPTO	U.S. Patent and Trademark Office (DOC)
WMD(s)	weapon(s) of mass destruction

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