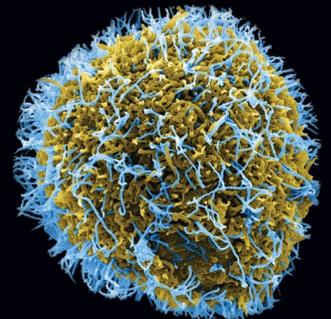
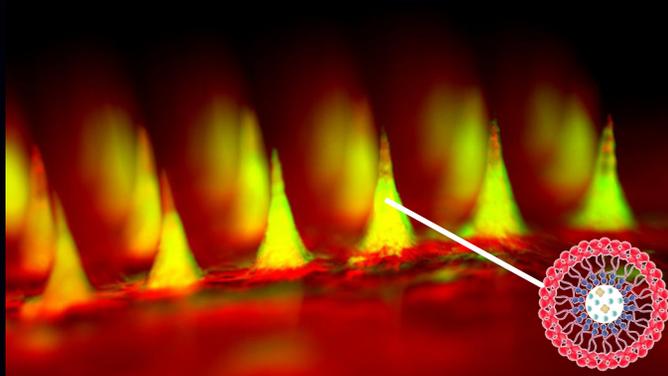
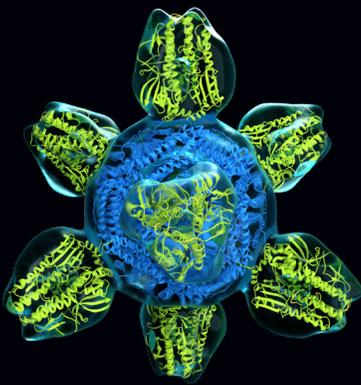


THE NATIONAL NANOTECHNOLOGY INITIATIVE

Supplement to the President's 2017 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 2017 Budget request submitted to Congress on February 9, 2016, and serves as the Annual Report for the National Nanotechnology Initiative (NNI) called for under the provisions of the 21st Century Nanotechnology Research and Development Act of 2003 (Public Law 108-153, 15 USC §7501). The report also addresses the requirement for Department of Defense reporting on its nanotechnology investments, per 10 USC §2358. Additional information regarding the NNI is available on the NNI website at www.nano.gov.

About the cover

Front cover: Images illustrating three novel nanomedicine applications. *Center:* microneedle array for glucose-responsive insulin delivery imaged using fluorescence microscopy. This "smart insulin patch" is based on painless microneedles loaded with hypoxia-sensitive vesicles ~100 nm in diameter that release insulin in response to high glucose levels. Dr. Zhen Gu and colleagues at the University of North Carolina (UNC) at Chapel Hill and North Carolina State University have demonstrated that this patch effectively regulates the blood glucose of type 1 diabetic mice with faster response than current pH-sensitive formulations. The inset image on the lower right shows the structure of the nanovesicles; each microneedle contains more than 100 million of these vesicles. The research was supported by the American Diabetes Association, the State of North Carolina, the National Institutes of Health (NIH), and the National Science Foundation (NSF). *Left:* colorized rendering of a candidate universal flu vaccine nanoparticle. The vaccine molecule, developed at the NIH Vaccine Research Center, displays only the conserved part of the viral spike and stimulates the production of antibodies to fight against the ever-changing flu virus. The vaccine is engineered from a ~13 nm ferritin core (blue) combined with a 7 nm influenza antigen (green). Image credit: NIH National Institute of Allergy and Infectious Diseases (NIAID). *Right:* colorized scanning electron micrograph of Ebola virus particles on an infected VERO E6 cell. Blue represents individual Ebola virus particles. The image was produced by John Bernbaum and Jiro Wada at NIAID. When the Ebola outbreak struck in 2014, the Food and Drug Administration authorized emergency use of lateral flow immunoassays for Ebola detection that use gold nanoparticles for visual interpretation of the tests.

Back cover: Images illustrating examples of NNI educational outreach activities. *Center:* Comic from the NSF/NNI competition, *Generation Nano: Small Science Superheroes*. Illustration by Amina Khan, NSF. *Left of Center:* *Polymer Nanocone Array* (biomimetic of antimicrobial insect surface) by Kyle Nowlin, UNC-Greensboro, winner from the first cycle of the NNI's student image contest, EnvisioNano. *Right of Center:* *Gelatin Nanoparticles in Brain* (nasal delivery of stroke medication to the brain) by Elizabeth Sawicki, University of Illinois at Urbana-Champaign, winner from the second cycle of EnvisioNano. *Outside right:* still photo from the video *Chlorination-less* (water treatment method using reusable nanodiamond powder) by Abelardo Colon and Jennifer Gill, University of Puerto Rico at Rio Piedras, the winning video from the NNI's Student Video Contest. *Outside left:* Society of Emerging NanoTechnologies (SENT) student group at the University of Central Florida; photo by Alexis Vilaboy. See www.nano.gov/2017BudgetSupplement for more information on these images, including hyperlinks to relevant websites.

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SUPPLEMENT TO THE PRESIDENT'S BUDGET FOR FISCAL YEAR 2017

THE NATIONAL NANOTECHNOLOGY INITIATIVE



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

March 2016

Report prepared by
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† An independent commission that is represented on NSET but is non-voting

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

March 31, 2016

Dear Members of Congress:

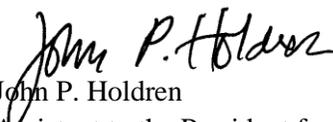
I am pleased to forward this annual report on the multiagency National Nanotechnology Initiative (NNI) in the form of the NNI Supplement to the President's Budget for Fiscal Year 2017. This document highlights the programs and coordinated activities taking place across the many departments, independent 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 \$1.4 billion NNI budget for Fiscal Year 2017 will continue to advance U.S. understanding of nanoscale phenomena and the Nation's ability to engineer nanoscale devices and systems that address national priorities and global challenges. The 2017 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. Proposed NNI investments in research facilities and infrastructure in 2017 are \$235 million, a 7 percent increase from 2015 levels. Nanotechnology environmental, health, and safety activities again account for approximately 10 percent of the NNI budget request. Over its lifetime, the NNI has successfully fostered the transition of nanotechnology discoveries from lab to market and has enabled the growth of new industries that have exploited the unique properties of the nanoscale to make products that have enhanced our way of life. Over one-third of this budget request is focused on activities that further these efforts.

The Obama Administration has maintained strong fiscal support for the NNI throughout the two terms and has endeavored to engage the entire NNI innovation ecosystem in new ways to ensure the broad stakeholder community continues to support the NNI vision of a future in which applications of nanotechnology will lead to a revolution in technology and industry that benefits society. Examples of such efforts abound in this supplement, including: the launch of the first Nanotechnology-inspired Grand Challenge; awards to support a nationwide network of nanofabrication facilities; a new phase in the national effort to harness the power of nanotechnology to radically change the way we diagnose, treat, and prevent cancer; plans for a new center to study and assess the use of nanomaterials in consumer products; and contests, challenge prizes, and new teacher resources to educate and inspire the next generation of scientists and engineers.

It is essential that the United States continue to lead the way in innovation 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
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

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EXECUTIVE SUMMARY

This Supplement to the President’s Budget is the annual report of the National Nanotechnology Initiative (NNI), 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 in 2001,¹ participating agencies have invested nearly \$24 billion² (including the President’s 2017 Budget request) in fundamental and applied nanotechnology R&D; technology transfer; 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 2015, Federal agencies invested a total of \$1.5 billion in nanotechnology-related activities. The 2017 request calls for a total investment of over \$1.4 billion, affirming the important role nanotechnology continues to play in the Administration’s innovation agenda. This report highlights accomplishments over the past year, discusses activities currently underway, and outlines plans for how agencies will work both individually and collectively in 2017 to build upon these accomplishments and further advance the goals of the NNI.

As the NNI approaches its sixteenth year, participating agencies, together with the White House Office of Science and Technology Policy (OSTP) and the National Nanotechnology Coordination Office (NNCO), are working aggressively to chart the future directions of the NNI (“NNI 2.0”). In its biennial assessment of the NNI in 2014, the President’s Council of Advisors for Science and Technology (PCAST) provided suggestions on effecting the transition to NNI 2.0 and emphasized the need for greater focus on commercialization activities and broader engagement of the nanotechnology community in setting the future goals and directions of the Initiative. Over the past year, NNI agencies, OSTP, and NNCO have been working to address many of PCAST’s recommendations, including the establishment of Nanotechnology-Inspired Grand Challenges, which are ambitious but achievable goals that will harness nanotechnology to solve national or global problems and that have the potential to capture the public’s imagination. Based upon inputs from NNI agencies and ideas from the broader nanotechnology community solicited under a Request for Information (RFI), the first Nanotechnology-Inspired Grand Challenge (for future computing) was announced by OSTP on October 20, 2015. This Grand Challenge calls on the scientific community to collaborate to “create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain.”³ This Grand Challenge has generated broad interest within the nanotechnology community—not only NNI agencies, but also industry, technical societies, and private foundations—and planning is underway to address how the agencies and the broader community will work to achieve this goal. Topics for additional Nanotechnology-Inspired Grand Challenges are under review.

While investments in fundamental research continue at a significant level—comprising 42% of the total 2017 request—NNI agencies also recognize the need to move nanotechnology research from fundamental discovery to nanotechnology-based applications, and to transition discoveries from lab to market. This recognition is reflected in the fact that 35% of the 2017 request is for R&D for the Nanotechnology Signature Initiatives (NSIs) and R&D for nanotechnology-enabled applications, devices, and systems—both areas that

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

² Plus an additional \$1 billion in cumulative funding through the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs between 2004 and 2014; see Chapter 2 of this report.

³ www.nano.gov/grandchallenges

aim to accelerate this transition. NSIs are multiagency initiatives designed to provide an increased emphasis and focus on technology areas of national importance that may be more rapidly advanced through enhanced interagency coordination and collaboration. Each of the five NSIs⁴ underwent internal reviews in 2015 to assess their impact and progress and to identify changes, if necessary, to keep the goals and objectives current. For example, updates to the white papers that discuss the goals and objectives of the Nanomanufacturing and Nanoelectronics NSIs are being made in 2016. The internal review of the Nanotechnology for Solar Energy Collection and Conversion NSI concluded that a robust portfolio of research is now being funded by Government and industry such that the additional focus afforded by the NSI mechanism is no longer required. Accordingly, this NSI was retired in late 2015, and agencies will not report funding or activities against it beyond 2015. Discussions are underway among NNI agencies on for the development of a new NSI.

Significant accomplishments in solar energy capture and conversion, nanomanufacturing, nanoelectronics, nanoinformatics, and sensors have been made under the NSIs, attesting to the impact that enhanced coordination and collaboration can have on accelerating technology development and transition to applications. Investments by the Department of Defense (DOD) in support of the goals of the Nanomanufacturing NSI have enabled the commercial-scale production of carbon nanotube (CNT) sheets and yarns, which are now being evaluated in several DOD and National Aeronautics and Space Administration (NASA) advanced development programs. In the fall of 2016, NASA is planning a sounding rocket flight test of a CNT yarn composite overwrap pressure vessel, the first flight test of CNT yarn-reinforced composites in an aerospace structural component. Close collaboration with industry through public-private partnerships such as the Nanoelectronics Research Initiative (NRI) and the Semiconductor Technology Advanced Research Network (STARnet) has ensured that research advances in new nanoelectronic materials, devices, and architectures transition to commercial applications as quickly as possible. Nanotechnology is having a significant impact on advanced sensor technology. For example, DOD-funded research has led to the development of a portable sensor based on chemically modified carbon nanotubes⁵ that can be read by a smartphone to detect hazardous gases or food spoilage. The NSIs have made effective use of webinars and the NNI website to provide information to and strengthen interactions with all sectors of the nanotechnology community. In calendar year 2015, the Sensors NSI, in collaboration with the Nanotechnology Knowledge Infrastructure (NKI) NSI, hosted a series of webinars that enlisted experts from participating agencies, industry, and academia to discuss topics ranging from an introduction to nanosensors and their applications to the use of various techniques to improve data quality and reliability.

Transitioning nanotechnology-based discoveries from lab to the market continues to be an NNI priority. In 2014 (the most recent year reported), nearly \$97 million was provided to small businesses engaged in nanotechnology R&D and commercialization through the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, in addition to the funding reported under the NNI Program Component Areas (PCAs, see Chapter 2). NNI agencies continue to promote technology transfer and entrepreneurship through such programs as the National Science Foundation (NSF) Innovation Corps (I-CorpsTM) program, the National Institutes of Health (NIH) Translation of Nanotechnology in Cancer consortium, and the Nano-Bio Manufacturing Consortium 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. Planning is underway for additional

⁴ Nanotechnology for Solar Energy Collection and Conversion; Sustainable Nanomanufacturing; Nanoelectronics for 2020 and Beyond, Nanotechnology Knowledge Infrastructure (NKI); and Nanotechnology for Sensors and Sensors for Nanotechnology. See Chapter 1 for full titles and abbreviations.

⁵ www.pnas.org/content/111/51/18162/F1.expansion.htm

webinars. In addition, OSTP and NNCO released an RFI on February 2, 2016, to gather examples of commercialization successes arising from the nanotechnology resources and investments made under the auspices of the NNI. Planning efforts are in progress for a workshop to highlight the commercial impact of the NNI, share best practices, and identify challenges faced in the commercialization of nanotechnology that could be addressed by the Government.

Proposed NNI investments in research facilities and infrastructure in 2017 are \$235 million, a 7% increase over actual 2015 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 Nanoscale Science Research Centers (NSRCs), the Center for Nanoscale Science and Technology (CNST) at the National Institute of Standards and Technology, NSF's National Nanotechnology Coordinated Infrastructure (NNCI), and two state-of-the-art nanomaterial characterization laboratories established by the Food and Drug Administration. The 2017 request includes funding for the Consumer Product Safety Commission (CPSC) for a new nanotechnology center at NIH's National Institute of Environmental Health Sciences (NIEHS) to conduct research in exposure and risk assessment of engineered nanomaterials in consumer products.

Continued progress in nanotechnology research, development, and commercialization requires a skilled workforce from the laboratory to the shop floor and a public that understands the benefits and risks of nanotechnology. NNI agencies provide support for a diverse array of nanotechnology-based educational activities covering K-12, community college, undergraduate, and graduate programs. In 2015, NNCO worked with NNI agencies, academia, and State and local governments to promote incorporation of nanotechnology concepts into science, technology, engineering, and mathematics (STEM) education and to provide ready access to instructional resources. NNCO expanded the educational resources available on the NNI's website, www.nano.gov, and worked with nanoHUB (funded by NSF) on the development of a searchable nanotechnology education resource portal. NNCO has also worked with NNI agencies, in particular NSF, to use contests and challenges, videos, and social media to educate the public and stimulate student interest and excitement in nanotechnology. In 2015, NSF and NNCO collaborated with NBC Learn to produce a series of six videos, "Nanotechnology: Super Small Science," which explain how nanotechnology has had a significant impact on areas such as electronics, renewable energy, and human health. These videos, released in January of 2016, have the potential to reach more than 9 million students and over 200 NBC affiliates. In 2015, NSF and NNCO partnered to launch the contest, "Generation Nano: Small Science Superheroes," challenging high school students to imagine and illustrate how nanotechnology could be used to empower a new superhero. Semifinalists will be invited to attend the 2016 USA Science and Engineering Festival to present their projects, where the final winners will be selected and announced.

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 activities incorporated in the NSIs, account for about 10% of the NNI budget request in 2017. In 2015, CPSC partnered with the NNI to host the Quantifying Exposure to Engineered Nanomaterials from Consumer Products (QEEN) workshop to bring experts together to assess the state of understanding in exposure science related to engineered nanomaterials and identify knowledge gaps and technology needs. A report from this workshop is being finalized, and information gained from this workshop will be used by CPSC in planning the proposed new nanoEHS research center at NIH/NIEHS mentioned above. In 2016, the Nanotechnology Environmental and Health Implications (NEHI) Working Group⁶ will host a series of webinars

⁶ A working group of the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council; the NSET Subcommittee coordinates the NNI.

to increase awareness of resources available to promote safe and responsible nanotechnology research, development, and commercialization. A key component of the NNI's nanoEHS strategy is extensive communication and coordination with academic, industrial, and international nanoEHS communities, including the U.S.–EU (European Union) Communities of Research;⁷ collaboration with dedicated multidisciplinary academic centers such as the NSF- and EPA-funded centers focusing on the environmental implications of nanotechnology at the University of California, Los Angeles, and at Duke University; and strong U.S. participation in the development of nanoEHS-related international standards. The NNI participating agencies and NNCO will continue to engage with the stakeholder community and leverage international efforts to establish a broad and readily accessible EHS knowledge base in support of science-based regulatory decision making and responsible development of nanotechnology.

Setting the future course of the NNI and ensuring its continued vitality and relevance requires the development of a compelling strategic plan that addresses future national needs and those of NNI agencies, and that defines how the Federal Government's investments in fundamental and applied nanotechnology R&D and in efforts to transition nanotechnology from lab to market can best meet those needs. In 2015, the NSET Subcommittee, with the support of NNCO, initiated the process to update the February 2014 NNI Strategic Plan. As part of this process, a stakeholder workshop and a series of webinars are being planned to gather public input on various aspects of the plan and on potential future directions for the NNI.

⁷ www.us-eu.org

1. INTRODUCTION AND OVERVIEW

Overview of the National Nanotechnology Initiative

The National Nanotechnology Initiative (NNI), established in 2001,⁸ is a U.S. Government research and development (R&D) initiative involving 20 Federal departments, independent agencies, and commissions⁹ 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.”¹⁰ 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 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 list 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. To illustrate, a sheet of paper is about 100,000 nanometers thick. 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.

⁸ General note: In conformance with Office of Management and Budget style, references to years in this report are to fiscal years unless otherwise noted.

⁹ Hereafter within this document the Federal departments, independent agencies, and commissions participating in the NNI are referred to collectively as “agencies.”

¹⁰ *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

1. Introduction and Overview

The NSET Subcommittee has identified critical issues that require focused interagency attention and activity, facilitated 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 Nanotechnology Innovation and Commercialization Ecosystem (NICE) Working Group¹¹—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.¹²

The 2014 NNI Strategic Plan sets out the vision for the NNI stated previously 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 these 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,¹³ the strategic plan also identifies R&D investment categories, known as Program Component Areas (PCAs). The five 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. Nanotechnology-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 portfolio is intended to be dynamic. NSIs will be retired when it is determined that focus on a given topical area is no longer necessary. New NSIs will be established when it is determined that spotlighting R&D efforts on new topics is required. The technical content of each NSI is reviewed on a regular basis and updated, as appropriate, to address changing needs and research progress. NSI topics for 2015 through 2017 are as follows:

- Nanotechnology for Solar Energy Collection and Conversion: Contributing to Energy Solutions for the Future (Solar NSI—retired at the end of 2015).
- 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).

¹¹ Chartered in 2015 as an update to the prior Nanomanufacturing, Industry Liaison, and Innovation Working Group.

¹² *National Nanotechnology Initiative Strategic Plan* (NSTC, Washington, DC, 2014, www.nano.gov/2014StrategicPlan), p. 51.

¹³ 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.

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- 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.¹⁴ This strategy supports all four NNI goals but is most closely aligned with NNI Goal 4 and PCA 5.

NNI funding represents the sum of the nanotechnology-related investments 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. NNI agencies collaborate closely, facilitated through the NSET Subcommittee and its working groups and coordinators, to create an integrated R&D program that leverages investment, knowledge, and expertise, as well as equipment and other infrastructure to advance NNI goals and meet individual agency mission needs and objectives. Detailed highlights of these activities can be found in Chapter 4, organized by the four NNI goals and their respective objectives. Provided below is a brief summary of the activities for each goal, followed by a summary of activities in support of each of the Nanotechnology Signature Initiatives.

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

Even as the results of previous Federal investments in nanoscience transition into commercial products, NNI agencies remain committed to strong and sustained support for research and development that will lead to the next generation of nanotechnology-enabled innovations. These continued investments enable future discoveries that build upon and expand the body of knowledge developed under the auspices of the NNI and ensure that the United States remains at the forefront of nanotechnology. The aim of Goal 1 is to advance nanoscience and nanotechnology by expanding the boundaries of understanding and by developing technologies through groundbreaking, 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 both on the availability of a skilled workforce, infrastructure, and tools (Goal 3), and on laying a strong foundation for responsible incorporation of nanotechnology into commercial products (Goals 2 and 4).¹⁵ NNI agencies support a wide range of foundational research and other activities advancing Goal 1, including the more focused and coordinated activities of the NSIs. Examples of coordinated activities under Goal 1 include industry, university, and government consortia on nanotechnology-based approaches to reduce the cost of water treatment; improve the efficiency of low-cost gallium arsenide-based solar cells; produce new optoelectronic fibers and textiles for multifunctional warfighter combat uniforms; develop conformal coatings for sutures, surgical sponges, and bandages that enable unprecedented wound healing; create imaging technologies for detection and characterization of pathogenic, toxic, and bacterial threats to food safety; and promote international efforts to develop standards to accelerate regulatory review of nanotechnology-enabled products and processes.

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

The research and development advanced under Goal 1 serves as the foundation for innovative new products. Although nanotechnology products are already in the marketplace, many observers perceive the NNI to be

¹⁴ *National Nanotechnology Initiative Environmental, Health, and Safety Research Strategy* (NSTC, Washington, DC, 2011; www.nano.gov/2011EHSStrategy).

¹⁵ See Table 4 in the *National Nanotechnology Initiative Strategic Plan* (NSTC, Washington, DC, 2014, www.nano.gov/2014StrategicPlan), p. 49.

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at a tipping point. There is a significant potential in the near term to broaden the utilization of novel properties that exist at the nanoscale in more complex devices and systems. In order to realize this potential, the focus of Goal 2 is to establish processes and resources that facilitate the transfer of nanotechnology research into applications that benefit society, national security, and the economy. Investments by both the public and private sectors are needed to shepherd these nanotechnologies to maturity. 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.¹⁶

As with any new technology, scalable, repeatable, cost-effective, and high-precision manufacturing methods are required to move discoveries from the laboratory into commercial products. These requirements are addressed for specific application areas in the institutes of the National Network for Manufacturing Innovation (NNMI), several of which involve aspects of nanotechnology. Federal participants in the NNMI and the NNI actively communicate with each other to leverage resources and exploit knowledge gained from their respective manufacturing and technology development activities. NNI member agencies also have a number of activities uniquely targeting technology transfer and commercialization. These include workshops to obtain input from industry and academia; Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs to fund innovations in small businesses; and the development and maintenance of a cutting-edge research infrastructure for use by all nanotechnology researchers, including those in industry.

In addition to the NNI agency activities, the NNCO Director and Deputy Director, NNCO's dedicated industrial liaison staff member, and the OSTP Assistant Director for Nanotechnology and Advanced Materials conduct outreach activities to engage with and learn from the commercial sector with respect to commercialization of nanotechnologies. As a point of contact for industry, the NNCO industrial liaison not only responds to routine requests from companies for assistance, but also actively engages industry with nearly 400 phone conversations, in-person meetings, and site visits per year, and attends industry workshops and conferences to keep abreast of developments and concerns. During these interactions, key private-sector issues such as funding, partnerships, intellectual property, and the regulatory environment are discussed and monitored, and information gained from these discussions is relayed to NNI agencies and OSTP. In 2015, the NNCO Director and Deputy Director attended several industry-focused workshops, and OSTP held two events at the White House to discuss NNI activities and interact with attendees to learn more about both the successes and challenges that companies are experiencing.

In calendar year 2015, NNCO initiated a series of webinars focused on identifying challenges faced by companies in the commercialization of nanotechnology and on providing information to help address some of these challenges.¹⁷ New webinars are being planned for 2016. In addition, OSTP and NNCO, have reached out to the nanotechnology community with a Request for Information (RFI) to gather nanotechnology commercialization success stories.¹⁸ Feedback from this RFI will help inform the NNI agencies about the current state of nanotechnology commercialization and the impact of Federal research investments. Planning is underway for a workshop to highlight the success stories, share best practices, and seek ways that NNI agencies can facilitate future successes.

¹⁶ 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.

¹⁷ www.nano.gov/SMEwebinars2015

¹⁸ www.federalregister.gov/articles/2016/02/02/2016-01521/nanotechnology-commercialization-success-stories

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

The advancement of nanotechnology research, development, and commercialization requires a robust research infrastructure, with state-of-the-art facilities for characterization and fabrication and a highly skilled workforce prepared via a broad spectrum of instructional and workforce training programs across the educational continuum. A substantial investment, strengthened by interagency cooperation and collaboration through the NNI, is required to develop the facilities and talent 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). Goal 3 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 access to advanced facilities and tools.

Education is among the chief objectives of NNI-funded university research, especially at the graduate level. Specific NNI programs have targeted K–12 and undergraduate-level education, focused on improving and expanding nanotechnology curricula in U.S. schools and universities. There are also a number of NNCO activities that aim to promote and support nanotechnology education. For example, 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 response to the needs identified in a December 2014 Nanoscale Science and Engineering Education (NSEE) Workshop, NNCO has developed, in collaboration with nanoHUB, a searchable web portal of teaching resources, including lesson plans, demonstrations, and laboratory exercises.¹⁹ NNCO will showcase many of these resources at the 2016 National Science Teacher Association (NSTA) annual conference, in addition to highlighting the web portal during teacher training programs, lectures, and webinars. Furthermore, two educational video series have been developed for classroom use—“Nanotechnology: Super Small Science,”²⁰ created under a collaboration between NSF and NBC Learn, and “Innovation Workshop: Nanotechnology,”²¹ produced by the Fairfax County (Virginia) Public School District in collaboration with NNCO and NIST—that have the potential to reach a broad audience. For example, NBC Learn has an audience of more than 9 million students, and highlights from these videos are distributed to more than 200 NBC affiliates for use in news and other on-air segments.

NNCO is supporting NNI agencies in utilizing contests, social media, and other tools to spark student interest in nanotechnology and other science, technology, engineering, and mathematics (STEM) subjects. In 2015, multimedia image (“EnvisioNano”) and video (“Tiny Science. Big Impacts. Cool Videos.”) contests were launched to encourage college students to share information about their research and create a greater awareness of the NNI. “Generation Nano: Small Science Superheroes,” a contest developed by NSF and NNCO, is challenging high school students to explore how nanotechnology can make a hero super. This contest has caught the attention of legendary comic book creator Stan Lee, who is actively promoting the contest to help reach students beyond those already focused on science and technology. NNCO is also facilitating a network of college student groups devoted to raising awareness of and promoting opportunities in nanotechnology and other emerging technologies. Representatives from these groups plan to meet annually at a student leaders’ conference to be held in conjunction with the TechConnect World Innovation Conference and Expo.

¹⁹ nanohub.org/publications/118/1

²⁰ www.nsf.gov/news/special_reports/nanotechnology

²¹ www.fcps.edu/fairfaxnetwork/innovation_nanotechnology

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Community colleges across the country are developing programs to support the increasing need for a trained, highly skilled nanotechnology workforce, often in collaboration with local industry. More information about these programs, including the NSF-funded Nano-Link Center for Nanotechnology Education and the Nanotechnology Applications and Career Knowledge (NACK) Network, can be found at www.nano.gov/education-training-workforce. At least two States have now incorporated nanotechnology into their K–12 science standards, which will help promote nanoscience literacy for their students and citizens. NNCO will continue to work with State departments of education to facilitate access to existing resources and provide technical guidance. Educational resources and lessons learned will be made available nationwide to assist States as they develop or expand their nanotechnology-related education offerings, and venues such as the National Science Teacher Association’s National Conference on Science Education will be used to provide enhanced visibility of NNI resources to STEM educators.

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 better appreciate and assess the opportunities and potential impacts presented by nanotechnology. The NNI agencies partner 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, NSF’s Nanoscale Informal Science Education Network (NISE Net) worked over a period of eight years to create engaging physical and digital instructional kits to support NanoDays,²² a nationwide, week-long annual festival of educational activities about nanoscale science and engineering. Although this NSF grant has officially ended, many of the over 250 sites that hosted NanoDays have indicated they will continue the event—a testament to the strong public interest in nanotechnology and the collaborative network developed under this program. NNI outreach also takes the form of public lectures, science cafes, and the development of print and video content.

The toolkit required for successful nanotechnology research, development, and commercialization includes broad access by researchers to specialized physical infrastructure such as instrumentation for fabrication and characterization, and to models, simulations, and data. The NNI continues to support cyber and physical infrastructure for nanotechnology through its extensive network of research centers and user facilities, including the DOE Nanoscale Science Research Centers (NSRCs) and the NIST Center for Nanoscale Science and Technology (CNST). In addition to these user facilities, the new NSF-supported National Nanotechnology Coordinated Infrastructure (NNCI) network has 16 sites across the country that give academic, small business, and industry researchers access to leading-edge tools and experience. More information on NNI-supported infrastructure can be found in Chapter 4. The NNI also leverages activities of other Federal programs and initiatives such as the Materials Genome Initiative (MGI), National Robotics Initiative (NRI), National Strategic Computing Initiative (NSCI), and National Network for Manufacturing Innovation (NNMI).

Goal 4. Support Responsible Development of Nanotechnology

Since its inception, a primary goal of the NNI has been the responsible development of nanotechnology. Well-coordinated nanotechnology-related environmental, health, and safety (nanoEHS) research is essential to ensure a future in which responsible development of nanotechnology provides maximum benefit to society and the environment. These efforts are pivotal in contributing to American innovation and to advancing 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

²² www.nisenet.org/nanodays

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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. NEHI, the NNI EHS coordinator, and NNCO, as appropriate, support interactions between agencies and the diverse stakeholder communities to enhance the value of NNI efforts and provide a collaborative approach to examining the public health and environmental aspects of nanomaterials. These efforts continue to be guided by the 2011 NNI EHS Research Strategy.²³

Over the years, considerable investment has been focused on nanoEHS research through extramural programs as well as intramural activities within agencies, resulting in significant advances in the state of knowledge and the tools available to understand and mitigate risks. To share some of these advances, NEHI is planning a webinar series to raise awareness of available resources, such as the NIOSH Current Intelligence Bulletins on nanomaterials, and to share best practices for laboratory safety. Other regions in the world have been making significant investments in nanoEHS as well. NEHI and NNI agencies are working to identify opportunities to collaborate and leverage these efforts to maximize the impact of the collective investment and to ensure that shared knowledge informs science-based regulation to protect human health and the environment without unnecessarily impacting commerce. The U.S.–EU (European Union) Communities of Research (CoRs)²⁴ are one mechanism for collaboration and information exchange among nanoEHS researchers. The CoRs are researcher-led groups of experts who communicate via regular conference calls, a shared website, and annual workshops to develop work products such as white papers and database protocols. In the annual CoR workshops (which alternate between venues in the United States and Europe), the participants engage in analyzing a nanoEHS scenario and reporting on their CoR progress and plans. The CoR workshops also provide a forum for U.S. and EU policy makers to meet and discuss critical issues and opportunities.

Goal 4 is also advanced by activities within the Sensors, NNI, and Nanomanufacturing NSIs, as well as activities supported by the NNI coordinators for global implications and standards development, and by community-led activities. Ongoing communication and coordination among these many efforts are critical and are facilitated by the NNI and NNCO. Examples of these efforts include the U.S.–EU CoRs; collaborations with dedicated multidisciplinary academic centers such as the NSF- and EPA-funded centers at the University of California, Los Angeles (UCLA) and Duke University focusing on the environmental implications of nanotechnology; and the coordination of nanoEHS-related standards development among various standards organizations (e.g., the Organisation for Economic Co-operation and Development (OECD), the American Society for Testing and Materials, and the International Organization for Standardization). Additionally, the NNI's www.nano.gov website provides an FAQ page for businesses²⁵ 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

²³ *National Nanotechnology Initiative Environmental, Health, and Safety Research Strategy* (NSTC, Washington, DC, 2011; www.nano.gov/2011EHSSStrategy).

²⁴ www.us-eu.org

²⁵ www.nano.gov/bizfaqs

the international stakeholder community to expand a broad and readily accessible EHS knowledge base in support of regulatory decision making and responsible development of nanotechnology.

Overview of the Nanotechnology Signature Initiatives

In 2010, the Federal agencies participating in the NNI launched the Nanotechnology Signature Initiatives (NSIs) as a new mechanism for interagency coordination and collaboration intended to accelerate nanotechnology development in support of the President's priorities and innovation strategy. The NSIs became a Program Component Area (PCA) in the 2014 NNI Strategic Plan. The NSIs provide a spotlight on areas of national importance and define the shared vision of the participating agencies for accelerating the advancement of nanoscale science and technology from research through commercialization in those identified areas. 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. The NSI portfolio is intended to be dynamic, and the areas of focus will change. New topic areas will be introduced and some topics will be retired as the spotlight provided by the NSI mechanism is no longer necessary to advance research and development in those areas. The technical content of each NSI is reviewed on a regular basis and updated, as appropriate, to address changing needs and research progress. While specifically described as Objective 1.4 of Goal 1, the focused goals and outcomes of each signature initiative are 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

The Solar NSI²⁶ was one of the first three signature initiatives launched in 2010, based upon the realization that the levelized cost of energy of solar technology was not yet economically competitive with conventional fossil fuel technologies and that nanotechnology had a strong potential to reduce this cost. The white paper for this initiative²⁷ identified new innovations and fundamental breakthroughs that were expected to overcome the limits of existing technologies and help accelerate the development of economically viable solar energy technologies. The goals identified for the Solar NSI were 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 formation of the Solar NSI brought together representatives from participating agencies to address strategically important technical areas identified in the 2010 white paper. Enhanced cross-agency communication 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.

Examples of research advancement during the course of the Solar NSI can be found in "A Progress Review of the Nanotechnology for Solar Energy Collection and Conversion NSI."²⁸ An early example of progress is the

²⁶ www.nano.gov/NSISolar

²⁷ www.nano.gov/sites/default/files/pub_resource/nnisiginit solarenergyfinaljuly2010.pdf

²⁸ www.nano.gov/sites/default/files/pub_resource/nsi_status_report_solar_12_2015.pdf

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National Renewable Energy Laboratory (NREL) demonstration in 2011 of “black silicon” that set a world record for energy conversion efficiency by black silicon solar cells, and was licensed to industry. Another example is the transition of Government-funded quantum dot solar cell technology to a major U.S. manufacturer of commercial solar cells to increase the efficiency of space-based solar cells and provide increased power for U.S. satellites. In the area of solar thermal conversion, flat-panel solar thermoelectric generators have been reported with electric conversion efficiencies seven to eight times higher than previously reported. Significant advances have also been made in the area of solar-to-fuel conversion; for example, researchers funded by USDA/NIFA developed a thin-film prototype device that combines the natural process of photosynthesis, based on the nanoscale protein found in leafy vegetables, with silicon to provide power through solar energy to drive a small handheld device.

The Solar NSI has provided a valuable focus on critical scientific challenges facing solar energy technologies and on the programs within the participating agencies that address these issues. The strength of these interactions and the active community that has developed—composed of researchers and program managers across the Federal Government and federally funded external researchers—make the continued focus of a signature initiative unnecessary. Although research activities and interagency collaboration in these important areas will continue, 2015 is the last year they are reported under the NSI mechanism. The NSI spotlight will transition to other high-priority areas for the NNI and will be reported under other PCAs as appropriate.

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 NSI²⁹ was launched in 2010 to establish manufacturing technologies for economical and sustainable integration of nanoscale building blocks into complex, large-scale systems.

The agency representatives participating in the Nanomanufacturing NSI met in 2015 to evaluate progress and consider future directions for their collaborative efforts. Participants agreed that nanomanufacturing remains a high-priority area that continues to benefit from the spotlight afforded by the signature initiative mechanism; they are currently in the process of updating the NSI white paper to define new goals and objectives. The updated document will be informed by ongoing interactions with representatives from the National Network for Manufacturing Innovation Institutes.

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. As detailed in a forthcoming progress review of the Sustainable Nanomanufacturing NSI,³⁰ the two-, four-, and eight-year goals identified in the 2010 Nanomanufacturing NSI white paper for carbon-based nanomaterials have been met ahead of schedule. Consortia have been formed for coordinating research on manufacturing methods and metrology for high-performance nanomaterials; material systems and processes have been demonstrated for scalable, sustainable, efficient, and safe nanomanufacturing; and engagement with industrial partners to identify materials and processes appropriate for production has led to technology transfer and adoption by U.S. manufacturers.

²⁹ www.nano.gov/NSINanomanufacturing

³⁰ www.nano.gov/NSIProgressReview

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A focused effort involving several NNI agencies in partnership with the Office of the Secretary of Defense, Defense Production Act (DPA) Title III, for the production of carbon nanotube (CNT) yarn, sheet, tape, and slurry materials has resulted in significant advancements at Nanocomp Technologies in Merrimack, New Hampshire. Tens of thousands of square feet of sheet material and thousands of kilometers of yarn made in this facility have been delivered to customers. CNT electrostatic discharge/electromagnetic interference shielding from this contractor facility has achieved a technology readiness level³¹ (TRL) of 8/9 for spacecraft, and CNT heaters, data cables, and enhanced soft and hard ceramic armor all have achieved TRL 6. 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. Nanocomp's CNT-based products are currently being utilized in DOD and NASA advanced development programs for important applications including lightweight body and vehicle armor; improved structural components for spacecraft, satellites, and aircraft; and lightweight cable and wiring.

Public-private partnerships have also been formed to accelerate the research and development of cellulose nanomaterials. The USDA Forest Service (FS) Forest Products Laboratory (FPL) is working in partnership with the Agenda 2020 Technology Alliance and universities to develop the precompetitive science and technology critical for the commercialization and economic use of cellulose nanomaterials. P³Nano is a partnership between USDA/FS and the U.S. Endowment for Forestry and Communities to rapidly advance the commercialization of cellulose nanomaterials. These efforts are supported by materials produced at FPL's cellulose nanocrystal pilot plant in Madison, Wisconsin, and the ton-a-day cellulose nanofibril pilot plant at the University of Maine.

Other significant efforts supporting the Nanomanufacturing NSI include the development by NIST of high-throughput measurement methods to characterize nanomaterial composites and the efforts by NIOSH to apply Prevention through Design principles, working closely with fabrication facilities and laboratories to ensure safe practices. NIOSH also has released several guidance documents detailing safe handling procedures and current intelligence related to nanoEHS. 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 further miniaturization of conventional devices. Recognizing this challenge, the Nanoelectronics NSI³² was launched in 2010 to discover and use novel nanoscale fabrication processes and innovative concepts to produce revolutionary materials, devices, systems, and architectures.

The agency representatives participating in the Nanoelectronics NSI met in 2015 to evaluate progress and consider future directions for their collaborative efforts. Participants agreed that nanoelectronics remains an area that can benefit from the focus and attention afforded by the signature initiative mechanism. However, significant advances have been made since the launch of the signature initiative, including the development of an entirely new class of 2D materials with the potential to impact future electronics. In light of this, agency representatives are in the process of updating the NSI white paper to define new goals and objectives.

³¹ www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

³² www.nano.gov/NSINanoelectronics

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Over the course of the Nanoelectronics NSI, broad efforts across the Federal Government, including strong collaboration with academia and industry, have addressed the five thrust areas identified in the 2010 Nanoelectronics NSI white paper: (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.³³

For example, the Nanoelectronics Research Initiative (NRI) is a public–private partnership to collaboratively prioritize and fund university research relevant to the semiconductor industry.³⁴ NRI, a program within the Semiconductor Research Corporation, leverages expertise and resources from industry, Federal agencies, and State governments. NRI supports long-range research toward the discovery of the fundamental building blocks for tomorrow’s nanoscale electronics—new devices and circuit architectures for computing—that are viewed as essential to continuing performance advances in information technology. The Semiconductor Technology Advanced Research Network (STARnet) Program,³⁵ which leverages resources from industry (Semiconductor Industry Association and member companies) 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.

A forthcoming progress review of the Nanoelectronics for 2020 and Beyond NSI³⁶ notes that several advances have occurred since the launch of the signature initiative. For example, researchers have demonstrated that ferroelectric polarization can be used to stabilize spin crossover molecules in either the high-spin or low-spin state over a wide temperature range including room temperature, providing a possible path toward low-power nonvolatile magneto-electric logic operations at GHz clock speeds. A novel technology also has been demonstrated for constructing large-scale electronic systems based on graphene/molybdenum disulfide heterostructures grown by chemical vapor deposition. High-performance devices and circuits based on these heterostructures have been fabricated.

With respect to thrust area 5, the NSF-supported NNCI network—the successor to the National Nanotechnology Infrastructure Network—consists of 16 regional open nanotechnology laboratory user facilities and over 20 laboratory and education partners. The NNCI user facility sites include capabilities and instrumentation that specifically address current and anticipated user needs across the broad areas of nanoscale science, engineering, and technology.

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 NSI³⁷ 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. Agencies participating

³³ www.nano.gov/sites/default/files/pub_resource/nni_siginit_nanoelectronics_jul_2010.pdf

³⁴ www.src.org/program/nri

³⁵ www.src.org/program/starnet

³⁶ www.nano.gov/NSIProgressReview

³⁷ www.nano.gov/NKIPortal

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in the NKI NSI recognize that the development of a robust and functional informatics infrastructure requires broad communication and collaboration among the various nanotechnology communities. As such, these agencies engage, leverage resources, and collaborate with vibrant groups from the nanoinformatics community—including the National Cancer Institute’s National Cancer Informatics Program Nanotechnology Working Group, the EU 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 interacted with the nanoinformatics community by organizing and participating in a wide range of relevant events, including a webinar series in the fall of 2015. The series covered three topics: (1) “Introduction to Nanoinformatics,” with presentations by Mark Hoover (NIOSH), Christina Lu (NIH), Robert Hanisch (NIST), and Daryl Hess (NSF); (2) “Applications of Nanoinformatics,” with presentations by Christine Hendren (Duke University) and Bruce Lippy (Center for Construction Research and Training); and (3) “All Hands on Deck for Improving Data Quality,” in collaboration with the Sensors NSI agencies, with presentations by Paul Weiss (UCLA and *ACS Nano*) and Ewan Birney (European Bioinformatics Institute).

During the annual review of the NKI NSI, agency participants agreed that the general framework outlined in the 2012 white paper document remains representative of the needs for this initiative. Continued interaction with community groups, as noted above and in the forthcoming progress review of the NKI NSI,³⁸ is critical to growing and promoting the knowledge infrastructure. Ongoing collaboration with other data-rich NSIs—for example, Nanomanufacturing and Sensors—and other efforts such as the Materials Genome Initiative, enable sharing of best practices in common areas and ensure that the informatics infrastructure being developed broadly serves the needs of the research and development community. The pages of www.nano.gov/NKIPortal highlight many of the resources that make up the cyber-toolbox and identify a number of the community partners critical to the success of the NKI NSI.

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 both on earth and in space. The Sensors NSI³⁹ addresses both the opportunity of using nanotechnology to advance sensor development and the challenges of developing sensors that keep pace with the increasingly widespread use of engineered nanomaterials.

Engaging with stakeholders remains an important priority to identify the barriers researchers face in the development and commercialization of nanosensors. The Sensors NSI serves as a focal point for relevant communities and the public to address opportunities and barriers through the RFI mechanism, town hall discussions, technical sessions and panels at conferences, and community meetings. A Sensors NSI Web Portal was recently launched via a webinar⁴⁰ to serve as a ready source of information for the nanosensor community regarding sensor fabrication and test facilities, funding opportunities, regulatory information, standards, and other relevant resources. In the fall of 2015, the Sensors NSI organized a series of three technical webinars. “Nanosensor Technologies and Applications,” the first in the series, was a tutorial provided by Meyya Meyyappan (NASA). In the second webinar, Kim Sapsford (FDA) presented “A Regulatory Case Study

³⁸ www.nano.gov/NSIProgressReview.

³⁹ www.nano.gov/SensorsNSIPortal

⁴⁰ www.nano.gov/sites/default/files/sensors_nsi_webinar_nco_for_archive_final.pdf

for the Development of Nanosensors.” The final event in the series was “All Hands on Deck for Improving Data Quality,” presented as noted above in collaboration with the NKI NSI.

During the annual review of the Sensors NSI, agency participants agreed that the general framework of the white paper remains relevant. As detailed in the forthcoming progress review of the Sensors NSI,⁴¹ there are many examples of nanosensor advancements supported by the participating agencies. For example, DOD-funded research has led to the development of a portable sensor based on chemically modified carbon nanotubes⁴² that can be read by a smartphone to detect hazardous gases and food spoilage. Another example is the industry-wide exposure assessment study, led by NIOSH in collaboration with U.S. manufacturers and users of carbon nanotubes and nanofibers.⁴³ Continued emphasis afforded by the signature initiative spotlight will accelerate further advancements in nanosensors. One area of focus, highlighted by the community as a near-term need, is the identification of testing procedures and facilities. The agencies are currently working together to catalog both existing and highly needed facilities, in addition to engaging in the Sensors NSI-related activities detailed in Chapter 4.

Setting the Course for NNI 2.0—Responding to the Recommendations of the 2014 PCAST Assessment

As required by law under the 21st Century Nanotechnology R&D Act, the President’s Council of Advisors for Science and Technology (PCAST) performed its biennial assessment of the NNI in 2014 and released a report of its findings and recommendations.⁴⁴ An emphasis of this report was on defining the future of the NNI (“NNI 2.0”) with a focus on improving efforts to support lab-to-market transitions and on effecting broader engagement of the nanotechnology community in setting the goals and directions of the Initiative. In 2015, NNI agencies, OSTP, and NNCO worked to address many of the PCAST recommendations and put in motion efforts to chart the future course of the NNI, in keeping with the Administration’s recently updated Strategy for American Innovation.⁴⁵

A major recommendation in the 2014 PCAST assessment is that the NNI should establish Grand Challenges as an “effective means for focusing and amplifying the impact of Federal nanotechnology activities.” In response to this recommendation, a Request for Information was released by OSTP on June 17, 2015, for public input on potential topics for *Nanotechnology-Inspired Grand Challenges for the Next Decade*, ambitious but achievable goals that will harness nanotechnology to solve national or global problems and that have the potential to capture the public’s imagination. Over 100 responses were received covering a wide range of topics including nanomedicine, energy, nanomanufacturing, and the environment. After careful review of the responses and further discussions, the first Nanotechnology-Inspired Grand Challenge was announced on October 20, 2015, calling on the scientific community to collaborate to “*Create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain.*”⁴⁶ DOD, DOE, NIST, and the Intelligence Advanced Research Projects Activity (IARPA) have expressed support for this Grand Challenge and are in the process of developing agency plans for addressing it. Agencies are also working together to develop plans for

⁴¹ www.nano.gov/NSIPProgressReview

⁴² www.pnas.org/content/111/51/18162/F1.expansion.htm

⁴³ www.ncbi.nlm.nih.gov/pubmed/25851309

⁴⁴ www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/pcast_fifth_nni_review_oct2014_final.pdf

⁴⁵ www.whitehouse.gov/sites/default/files/strategy_for_american_innovation_october_2015.pdf

⁴⁶ www.nano.gov/grandchallenges

1. Introduction and Overview

coordinating their research efforts in this area. This planning will continue through 2016. Support for this Grand Challenge has also been expressed by industry, technical societies, and private foundations that are exploring mechanisms, including public–private partnerships, to engage their communities in addressing this Grand Challenge. Topics for potential future Nanotechnology-Inspired Grand Challenges are under review.

The PCAST report also expressed the need for the development of a set of evaluation metrics to assess the impact of future NNI research and commercialization programs on workforce, productivity, and scientific knowledge. The NNCO Director has joined the newly established Task Force for Measurement and Impact (TFMI) under the OECD Working Party for Nanotechnology, Biotechnology, and Convergent Technologies, which is working to develop and measure a set of standards, indicators, and metrics to assess impact and trends in these emerging technologies. The development of a globally harmonized set of metrics and indicators will allow for identification of global trends in research, development, and commercialization; assessment of the effectiveness and vitality of international collaborations; and more valid comparisons between countries on the impacts of their investments in these emerging technologies. A list of indicators for both nanotechnology and biotechnology, developed by TFMI in 2015, will be tracked in 2016. In 2016, TFMI also will compile an inventory of science, technology, and innovation policies that are relevant to bio-, nano-, and convergent technologies with an eye to developing a global tool kit for performing impact assessments. As discussed previously under Goal 2, OSTP and NNCO released an RFI in early 2016 to collect examples of commercialization success stories arising from NNI investments and resources. Planning is underway for a workshop to publicize the success stories, identify best practices that can aid in the successful commercialization of nanotechnology, and pinpoint areas and needs that the NNI can address to foster commercialization.

Setting the future course of the NNI and ensuring its continued vitality and relevance requires a compelling strategic plan that addresses national needs and those of NNI agencies and identifies how the Federal Government’s future investments in fundamental and applied nanotechnology research and development, and in efforts to transition nanotechnology from lab to market, can best meet those needs. The 21st Century Nanotechnology R&D Act requires the development of a revised NNI Strategic Plan every 3 years. In 2015, the NSET Subcommittee, with support from NNCO, initiated the process to update the 2014 NNI Strategic Plan with the goal of releasing the new plan in the fall of 2016. As part of this process, the NNI will host a stakeholder workshop and a series of webinars in 2016 to gather public input on various aspects of the plan and potential future directions for the National Nanotechnology Initiative.

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Budget Summary

The President's 2017 Budget provides over \$1.4 billion for the National Nanotechnology Initiative (NNI), a continued investment in support of a key component of the Administration's priorities and innovation strategy. Cumulatively totaling nearly \$24 billion since the inception of the NNI in 2001 (including the 2017 request), this support reflects the continued importance of investments 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 and the 2011 NNI Environmental, Health, and Safety Research Strategy.⁴⁷ These documents guide how NNI agencies address the full range of nanotechnology research and development, technology transfer to the commercial marketplace, infrastructure, and education, as well as the societal issues that accompany an emerging technology. The NNI investments in 2015 and 2016 and those proposed for 2017 reflect a sustained emphasis on accelerating the transition from basic R&D to applications that support national priorities, while also maintaining a strong foundation of broad, fundamental research in nanoscience to provide a continuing pipeline of new discoveries that will enable future revolutionary applications. Because of this accelerating transition to applications, it is becoming increasingly challenging to specifically identify nanotechnology-related R&D programs at some mission agencies, where the nanoscale materials, components, or devices may enable key capabilities but are not the focus of the overall advanced development program. Therefore, it is likely that some significant nanotechnology-enabled R&D investments at Federal agencies are not fully captured within the \$1.4 billion documented in this report.

Agencies continue to prioritize investments in nanotechnology to meet their mission needs, including national, cross-agency needs for clean energy; advanced manufacturing; innovation in life sciences, biology, and neuroscience; national and homeland security; and information technology and high-performance computing as highlighted in the 2017 Office of Management and Budget (OMB)/Office of Science and Technology Policy (OSTP) R&D Priorities Memo.⁴⁸ Nanotechnology has such a broad impact because, as noted in the Administration's updated Strategy for American Innovation,⁴⁹ it is one of the emerging "general-purpose technologies"—a technology that, like the steam engine, electricity, and the Internet, will have a pervasive impact on our economy and our society, with the ability to create entirely new industries, generate good jobs, and increase productivity. The NNI also supports significant investments in research infrastructure and in STEM (science, technology, engineering, and mathematics) education—both of which also are called out in the 2017 OMB/OSTP R&D Priorities Memo.

The President's 2017 Budget supports nanoscale science, engineering, and technology R&D at 11 agencies. The five Federal organizations with the largest investments (representing 95% of the total) are:

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

⁴⁷ See www.nano.gov/2014StrategicPlan and www.nano.gov/2011EHSSStrategy

⁴⁸ www.whitehouse.gov/sites/default/files/microsites/ostp/m-15-16.pdf

⁴⁹ www.whitehouse.gov/sites/default/files/strategy_for_american_innovation_october_2015.pdf

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- 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 EPA, USDA/NIFA, DHHS/FDA, DHHS/NIOSH, NASA, CPSC, USDA/FS, USDA/ARS, DHS, and DOT/FHWA.⁵⁰

Table 2 presents NNI investments for 2015 through 2017 for Federal agencies with budgets and investments for nanotechnology R&D, including funding for the Nanotechnology Signature Initiatives (NSIs). Tables 3–5 list the investments by agency and by NNI Program Component Area (PCAs) for 2015 through 2017. Table 6 shows the NNI investments within Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs for 2011 through 2014. Figure 1 shows NNI annual funding by agency since the inception of the NNI in 2001. Figure 2 shows the breakdown of funding by PCA in the 2017 Budget.

Agency	2015 Actual	2016 Estimated*	2017 Proposed
CPSC	2.0	2.0	4.0
DHS	28.4	21.0	1.5
DOC/NIST	83.6	79.5	81.8
DOD	143.0	133.8	131.3
DOE**	312.5	330.4	361.7
DOT/FHWA	0.8	1.5	1.5
EPA	15.1	13.9	15.3
DHHS (total)	385.8	405.0	404.4
FDA	10.8	12.0	11.4
NIH	364.0	382.0	382.0
NIOSH	11.0	11.0	11.0
NASA	14.3	11.0	6.1
NSF	489.8	415.1	414.9
USDA (total)	21.1	21.5	21.0
ARS	3.0	3.0	3.0
FS	4.6	4.5	4.0
NIFA	13.5	14.0	14.0
TOTAL ***	1496.3	1434.7	1443.4

* 2016 numbers are based on 2016 enacted levels and may shift as operating plans are finalized.

** Funding levels for DOE include the combined budgets of the Office of Science, the Office of Energy Efficiency and Renewable Energy (DOE-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.

⁵⁰ See Table 1 (p. 8) or Appendix A for explanations of the agency abbreviations used on this page and throughout the remainder of this report.

2. NNI Investments

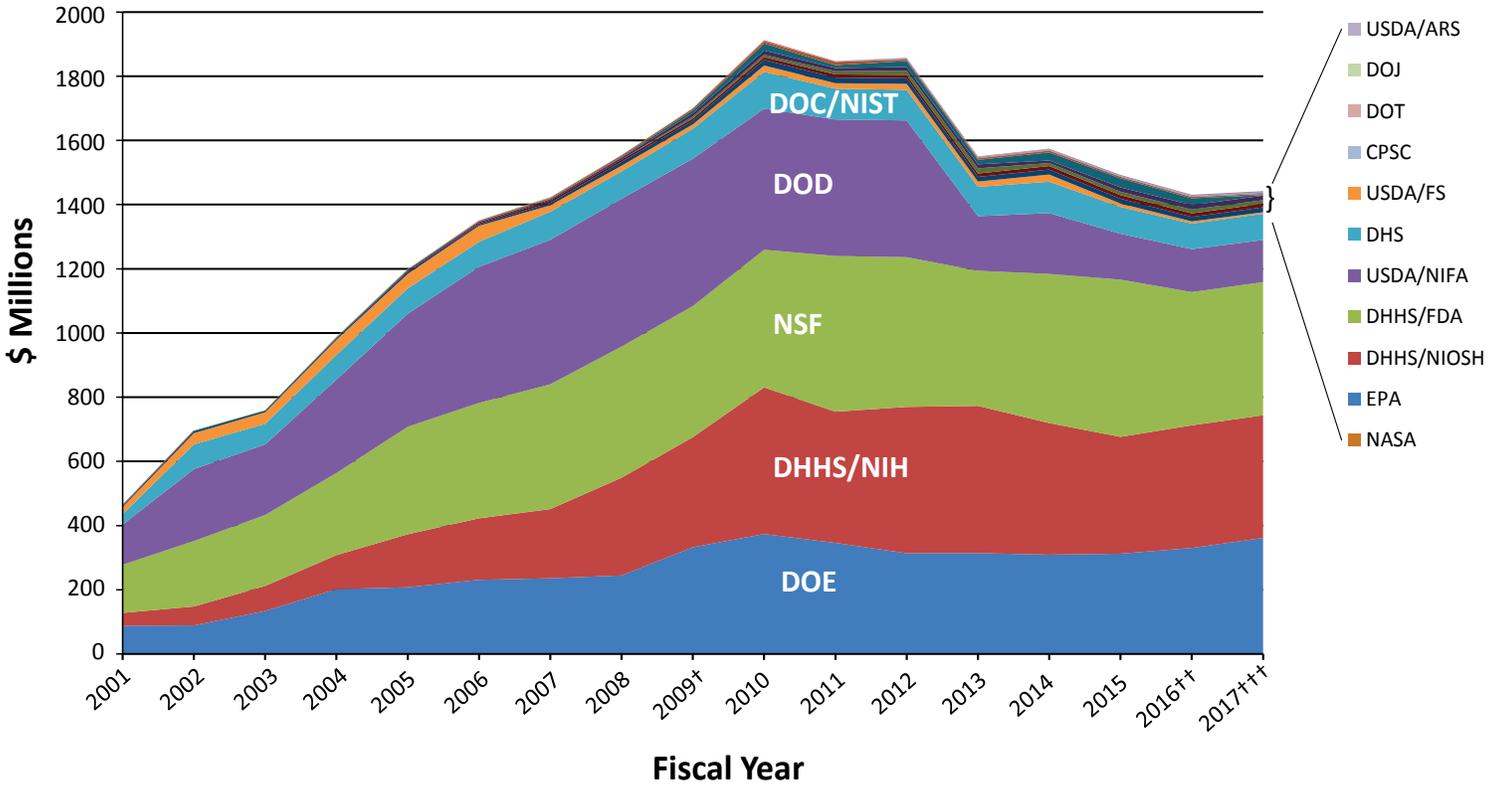


Figure 1. NNI Funding by Agency, 2001–2017.

- † 2009 figures do not include American Recovery and Reinvestment Act funds for DOE (\$293 million), NSF (\$101 million), NIH (\$73 million), and NIST (\$43 million)
- †† 2016 estimated funding is based on 2016 enacted levels and may shift as operating plans are finalized.
- ††† 2017 Budget.

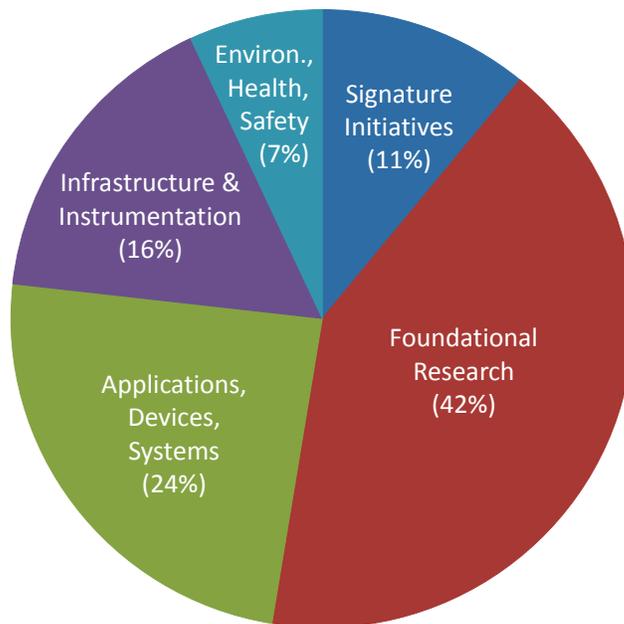


Figure 2. Breakout of NNI Funding by Program Component Area in the 2017 Budget.

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Table 3: Actual 2015 Agency Investments by Program Component Area
(dollars in millions)

Agency	1. Nanotechnology Signature Initiatives (NSIs)*	1a. Solar Energy	1b. Nanomanufacturing	1c. Nanoelectronics	1d. NNI	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	39.0	2.7	0.9	22.6	1.8	11.0	74.9	24.1	2.0	3.1	143.0
DOE	37.9	35.4	0.0	0.0	0.0	2.5	132.8	18.8	123.0	0.0	312.5
DOT/FHWA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.8
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	82.0	232.0	15.0	41.8	385.8
FDA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.8	10.8
NIH	15.0	0.0	1.0	0.0	1.0	13.0	82.0	232.0	15.0	20.0	364.0
NIOSH	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.0	11.0
NASA	3.1	0.1	0.6	0.7	0.0	1.7	6.5	4.7	0.0	0.0	14.3
NSF	158.6	24.9	34.1	60.8	23.8	15.0	210.8	54.8	40.5	25.1	489.8
USDA (total)	5.7	0.5	2.2	0.0	0.0	3.0	3.2	6.0	3.2	3.0	21.1
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	4.5	0.5	1.0	0.0	0.0	3.0	1.0	3.0	2.0	3.0	13.5
TOTAL	283.6	66.7	44.9	95.5	27.9	48.6	521.6	374.5	219.9	96.7	1496.3

* 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 2015–2017 NNI Investments

- Sustained and significant NNI investments in PCA 2, Foundational Research (\$600 million in the 2017 Budget, or 42% of the total NNI request), are consistent with calls by the President’s Council on Science and Technology (PCAST) and other NNI advisory bodies to maintain a pipeline of basic research that will lead to the innovations of the future. At the same time, and in keeping with the NNI’s renewed emphasis on translation and more advanced development, the Nanotechnology Signature Initiatives (PCA 1), which are targeted at a number of national priorities, remain a key investment category for the NNI in 2017, as are the investments in PCA 3, Nanotechnology-Enabled Applications, Devices, and Systems. PCAs 1 and 3 combined constitute 35% of the NNI investments in the 2017 Budget.
- Total NSI funding for 2017 (\$158 million) is reduced from the actual NSI funding reported for 2015 (\$284 million), much of this reduction is due to the retirement of the Solar NSI at the end of 2015.⁵¹

⁵¹ The solar NSI has achieved the objectives set out at its inception in 2010, and the NSI spotlight will transition to a new topic in 2016. See Chapter 1 of this report and www.nano.gov/NSIPROGRESSREVIEW for additional details.

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Table 4: Estimated 2016 Agency Investments by Program Component Area
(dollars in millions)

Agency	1. Nanotechnology Signature Initiatives (NSIs)*	1a. Solar Energy	1b. Nanomanufacturing	1c. Nanoelectronics	1d. NNI	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	2.0	2.0
DHS	0.0	-	0.0	0.0	0.0	0.0	0.0	21.0	0.0	0.0	21.0
DOC/NIST	22.1	-	5.4	14.5	1.3	0.9	9.5	6.3	35.7	5.9	79.5
DOD	28.8	-	0.5	23.8	1.8	2.7	74.4	25.9	0.0	4.7	133.8
DOE	6.1	-	0.0	5.0	0.0	1.1	180.2	12.7	131.4	0.0	330.4
DOT/FHWA	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	13.9	13.9
DHHS (total)	16.0	-	1.0	0.0	1.0	14.0	86.0	243.0	16.0	44.0	405.0
FDA	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0	12.0
NIH	16.0	-	1.0	0.0	1.0	14.0	86.0	243.0	16.0	21.0	382.0
NIOSH	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.0	11.0
NASA	2.0	-	0.9	0.5	0.0	0.6	5.9	3.1	0.0	0.0	11.0
NSF	90.5	-	26.4	37.5	19.1	7.5	212.7	44.6	45.7	21.6	415.1
USDA (total)	6.0	-	2.5	0.5	0.0	3.0	4.0	7.0	2.5	2.0	21.5
ARS	0.0	-	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	3.0
FS	2.0	-	1.5	0.5	0.0	0.0	2.0	0.0	0.5	0.0	4.5
NIFA	4.0	-	1.0	0.0	0.0	3.0	2.0	4.0	2.0	2.0	14.0
TOTAL	171.6	-	36.7	81.8	23.2	29.8	572.8	365.0	231.2	94.1	1434.7

- In October 2015, the NNI initiated a new Nanotechnology-Inspired Grand Challenge for Future Computing. Additional grand challenge topics remain under consideration.⁵² However, Grand Challenges are not a budget category currently; R&D aimed at achieving Grand Challenge objectives is reported under existing PCAs, most likely under PCAs 2 and 3.
- Reductions in overall NNI investments for 2015–2017 compared to previous years (e.g., 2013 and 2014) reflect the expiration of several large multi-year centers awards previously funded by NSF (e.g., the Nanoscale Science and Engineering Centers) and NIH (e.g., the National Heart, Lung, and Blood Institute and NIH-wide Nanomedicine Roadmap Initiative centers), according to normal agency funding cycles and policies. However, NSF is establishing new Nanosystems Engineering Research Centers, and NIH has renewed its Alliance for Nanotechnology in Cancer in 2015; both of these programs include several large new (or renewed) interdisciplinary research centers, but at a lower total investment than for the previous centers.

⁵² www.nano.gov/grandchallenges

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Table 5: Proposed 2017 Agency Investments by Program Component Area
(dollars in millions)

Agency	1. Nanotechnology Signature Initiatives (NSIs)*	1a. Solar Energy	1b. Nanomanufacturing	1c. Nanoelectronics	1d. NNI	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	4.0	4.0
DHS	0.0	-	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	1.5
DOC/NIST	22.3	-	4.9	15.2	1.3	0.9	10.9	6.9	35.7	6.0	81.8
DOD	18.6	-	0.0	16.2	0.7	1.7	76.9	28.1	0.0	7.7	131.3
DOE	1.9	-	0.0	0.0	0.0	1.9	208.3	16.2	135.3	0.0	361.7
DOT/FHWA	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	15.3	15.3
DHHS (total)	16.0	-	1.0	0.0	1.0	14.0	86.0	243.0	16.0	43.4	404.4
FDA	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.4	11.4
NIH	16.0	-	1.0	0.0	1.0	14.0	86.0	243.0	16.0	21.0	382.0
NIOSH	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.0	11.0
NASA	1.0	-	0.6	0.4	0.0	0.0	4.4	0.7	0.0	0.0	6.1
NSF	92.5	-	28.4	37.5	19.1	7.5	210.5	44.6	45.7	21.6	414.9
USDA (total)	6.0	-	2.5	0.5	0.0	3.0	4.0	7.0	2.0	2.0	21.0
ARS	0.0	-	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	3.0
FS	2.0	-	1.5	0.5	0.0	0.0	2.0	0.0	0.0	0.0	4.0
NIFA	4.0	-	1.0	0.0	0.0	3.0	2.0	4.0	2.0	2.0	14.0
TOTAL	158.3	-	37.4	69.8	22.1	29.0	601.0	349.5	234.6	100.1	1443.4

- NNI agencies are sustaining strong funding for PCA 4 (Research Infrastructure and Instrumentation) for 2015–2017 (\$235 million in the 2017 Budget—16% of the total NNI request and a 7% increase over actual 2015 levels). Beginning in 2015, NSF is funding a new, multi-year National Nanotechnology Coordinated Infrastructure (NNCI) network of university-based nanotechnology user facilities, a network that builds on the previous National Nanotechnology Infrastructure Network (NNIN).⁵³ Complementary user facilities established by DOE (five Nanotechnology Science Research Centers) and NIST (the Center for Nanoscale Science and Technology) are also being sustained, with ongoing investments to maintain and upgrade facilities and instrumentation. PCA 4 also includes research to develop novel or improved instrumentation, which is critical to continued progress in nanotechnology and to maintain U.S. competitiveness internationally.
- PCA 5 (Environment, Health, and Safety—EHS) investments for 2015–2017 are sustained at between \$94 and \$100 million per year; the 2017 Budget includes \$100 million for PCA 5, representing nearly 7% of the NNI total, up from 4.8% in 2011. In addition to the PCA 5 EHS direct

⁵³ www.nsf.gov/pubs/2015/nsf15519/nsf15519.htm. See also the complete list of NNI user facilities at www.nano.gov/userfacilities.

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investments, several of the Nanotechnology Signature Initiatives also involve significant EHS-related research. Including this NSI funding, combined NNI EHS research is estimated at approximately 10% of the total NNI investments for 2015–2017. Cumulative EHS investments from 2006 through 2015 have now reached over \$1 billion.⁵⁴

- The Consumer Product Safety Commission is proposing to double its nanotechnology investments for 2017 compared to previous years. CPSC’s plans for this increased investment reflect its commitment to fostering safe use of nanotechnology in consumer products, as well as its extensive engagement with other agencies participating in the NNI. The CPSC Budget for 2017 also includes funding for a new EHS research center led by NIH’s National Institute of Environmental Health Sciences.
- The Department of Energy’s nanotechnology investments also are increasing for 2017 (\$362 million, a 16% increase over 2015 actual levels), due in part to significant increases in PCA 2 (Foundational Research) at the Office of Science.
- The National Science Foundation is maintaining its nanotechnology investments at well over \$400 million per year for 2015–2017; its \$415 million request for 2017 is the largest of the NNI agencies.
- Nanotechnology investments at other mission agencies (e.g., DOD, DHS, USDA, and NASA) fluctuate from year to year as specific programs are initiated, reach fruition, and then sunset.
- Nanotechnology investments at NIH increase slightly from 2015 to 2016 in all PCAs with the bulk of the increase in PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems).
- 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 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 2011 through 2014 (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 2014 indicate that the NNI agencies have funded over \$1 billion of nanotechnology-related SBIR and STTR awards, in addition to the funding reported under the NNI PCAs. A complete listing by year (including data from 2004 through 2010) can be found at a download link in the Overview section of nanodashboard.nano.gov.

⁵⁴ nanodashboard.nano.gov

2. NNI Investments

Table 6: 2011–2014 Agency SBIR and STTR Awards (dollars in millions)												
	2011			2012			2013			2014		
Agency	SBIR	STTR	Total									
DOD	16.2	5.6	21.8	25.4	7.6	33.0	22.6	5.5	28.1	11.1	6.5	17.6
NSF	13.2	1.3	14.5	18.0	2.5	20.5	17.9	0.9	18.9	22.1	3.6	25.8
DHHS/NIH	22.6	1.5	24.1	21.7	3.9	25.6	22.9	1.9	24.8	26.9	3.2	30.1
DHHS/NIOSH	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DOE*	4.7	1.1	5.8	7.8	1.7	9.5	3.9	2.3	6.2	15.1	2.5	17.5
NASA	12.1	3.7	15.8	17.0	3.9	20.8	5.7	1.3	7.1	2.1	1.9	4.0
EPA	0.9	0.0	0.9	0.7	0.0	0.7	0.5	0.0	0.5	0.9	0.0	0.9
USDA*	1.0	0.0	1.0	0.5	0.0	0.5	0.1	0.0	0.1	0.1	0.0	0.1
DOC/NIST	0.3	0.0	0.3	0.4	0.0	0.4	0.6	0.0	0.6	0.7	0.0	0.7
TOTAL	71.2	13.2	84.4	91.4	19.6	111.0	74.2	11.9	86.1	79.0	17.7	96.6

* 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: The Consumer Product Safety Commission is reporting nanotechnology investments for 2015 through 2017 in PCA 5 (Environment, Health, and Safety [EHS]). The 2017 request incorporates an increase first introduced in 2016 for increased research efforts (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 2015, CPSC established six interagency agreements with several agencies, including DOD, NIST, NIOSH, and NSF.⁵⁵ In 2016, 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 2015 through 2017 in PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems). DHS's Science and Technology Directorate is reporting zero dollars in 2017 for the NNI; its projects on Point of Care Diagnostics and High Resolution Explosives Trace Detectors have ended. A small amount of funding for 2017 is being reported by the DHS Domestic Nuclear Detection Office.

DOD: The Department of Defense does not establish funding targets for nanotechnology, which has proven to be effectively competitive based on its contributions to meeting needs and providing opportunities for future capability. New projects are awarded on a competitive basis, and therefore the balance of investments may change from historical levels and predictions. In 2017, DOD anticipates about \$131 million in nanotechnology research and development, very similar to 2016 (\$134 million) and about 8% less than 2015 actuals. Actuals tend to be larger than estimates because of success in competitive solicitations. The traditional 50:50 breakdown between Foundational Research (PCA 2) and more application-directed research, represented by the other PCAs, is approximately retained, but the resources are now more definitively characterized by the PCAs. In 2017 about 59% of the investment is projected to be in Foundational Research (PCA 2), with about 21% in Nanotechnology-Enabled Applications, Devices, and Systems (PCA 3), which captures more applied or applications-directed research. About 14% of the investment is currently projected in the areas of the Nanotechnology Signature Initiatives (NSIs, PCA 1) and clearly shows the topical emphasis on nanoelectronics (12%). Investments in sensors and nanomanufacturing are lower as projects have matured and completed, but both remain areas of competitive opportunity for 2016 and 2017. The DOD investment in Environment, Health, and Safety (PCA 5)

⁵⁵ See Table 1 (p. 8) or Appendix A for agency abbreviations used throughout this report.

3. Changes in Balance of Investments by Program Component Area

is projected to grow from \$3 million in 2015 to \$7.7 million in 2017, making it 6% of the projected 2017 DOD NNI investment. The DOD Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) investment in nanotechnology remains very strong, with an overall investment of about \$18 million in 2014; these projects therefore constitute about 10% in additional DOD nanotechnology research investments beyond the PCA categories for 2014. The SBIR/STTR investment declined between 2013 and 2014 with the completion of certain focused NNI initiatives. Discussion follows of some significant changes and plans among the military departments and DOD agencies.

- DOD/Navy: No major redistribution of funding is planned for the 2017 budget year. However, there has been an increase in foundational research funding due to the forward funding of some activities through a 2015 Congressional add.
- DOD/Air Force: Changes to the materials and manufacturing nanotechnology investments are representative of continuous maintenance of technical strategy. The research programs continue at the same overall level of investment, with an increase in activity in the Nanomanufacturing and Nanoelectronics NSIs to explore applications in additive manufacturing and flexible electronics.
- DOD/DARPA: The Defense Advanced Research Projects Agency 2017 Budget request will continue to support research in nanotechnology across PCAs 1 and 2 (the Nanotechnology Signature Initiatives and Foundational Research). Compared with 2015 levels, the funding in 2016 decreased the total budget for PCA 1 by 91%, which reflects a decrease of \$7.9 million in the DARPA contribution to the Sensors NSI associated with planned program funding adjustments in the Basic Photon Science and Enabling Quantum Technologies programs. This includes a decrease of \$0.1 million primarily due to the completion of the Quantum-Assisted Sensing and Readout (QuASAR) program in 2015. Funding remains balanced at \$2.0 million from 2015 to 2017 for PCA 2 for the DOD–industry–university Semiconductor Technology Advanced Research Network (STARnet).
- DOD/DTRA: The Defense Threat Reduction Agency (DTRA) Basic and Applied Sciences program continues to support the NNI through targeted research programs geared toward the exploration of novel materials and processes relevant to the counter-weapons of mass destruction (C-WMD) mission space. Classification of 2015 and 2016 investments highlights a focus on PCA 2. Minimal changes to the overall anticipated investment for 2017 are related to shifts in programmatic priorities for the C-WMD mission. Time will be needed for initial basic research efforts to mature in order to identify potential transitions, so these changes are not indicative of planned decreases in other nanotechnology investments.

DOE: The balance of Department of Energy investments by PCA are changing from 2015 to 2016 and 2017. Investments in PCA 1 (Nanotechnology Signature Initiatives) are going from 12% of the total DOE investment for 2015 to 1.8% in 2016 and less than 1% in 2017, due to the retirement of the Solar NSI, which has been DOE’s largest NSI investment. DOE maintains a sustained investment in nanotechnology R&D at universities, DOE National Laboratories, and in industry. Much of this is through the Office of Science’s (DOE-SC) ongoing, long-term support for fundamental research. Additional DOE investments are made by the Office of Energy Efficiency and Renewable Energy (DOE-EERE), the Office of Fossil Energy (DOE-FE), and the Advanced Research Projects Agency for Energy (ARPA-E). A significant fraction of these investments, 58% for 2017, is in PCA 2, Foundational Research, up from 43% in 2015. Part of this increase is due to the retirement of the Solar NSI, where continuing DOE-SC investments in nanotechnology for solar energy are now reported under PCA 2 for 2016 and 2017. In addition, DOE-SC operates five Nanoscale Science Research Centers (NSRCs) with an annual operating budget of approximately \$127 million in 2017, which accounts for the majority of DOE’s \$135 million investment in PCA 4, Research Infrastructure and Instrumentation; PCA 4 accounts for 37% of the 2017 DOE NNI funding request.

3. Changes in Balance of Investments by Program Component Area

DOT/FHWA: The Federal Highway Administration's current and planned investment continues to address PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems) to leverage developments in nanotechnology by focusing them on structural and multifunctional materials for transportation infrastructure applications.

EPA: The Environmental Protection Agency's 2017 Budget request continues EPA's strong support for research in nanotechnology. The EPA investment balance is unchanged from last year and remains aligned with PCA 5 (Environment, Health, and Safety). This research focuses on understanding implications of the unique and novel properties of nanomaterials as these are exhibited under real-world conditions. In 2017, EPA will continue to apply computational and knowledge-driven approaches to amplify the impact of its research on engineered nanomaterials (ENMs). Results of this research will provide guidelines for evaluating potential impacts of emerging materials from the molecular design phase throughout the life cycle in applications to goods and products in commerce. EPA's agenda is to develop approaches to characterize the properties of nanomaterials that best represent potential human and ecological impacts and to do this in a way that can be efficiently applied across a large array of nanomaterials, minimizing the need to look at each molecule or material separately. Although EPA research aligns primarily within PCA 5, the agency maintains collaborative relationships with other Federal partners in other program areas.

FDA: The U.S. Food and Drug Administration 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 2016 and 2017.

NASA: Support by the National Aeronautics and Space Administration 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 slightly lower in 2016 compared to 2015 levels.

NIH: Currently, the National Institutes of Health invests over \$360 million annually in nanotechnology initiatives that consist of a number of projects and programs funded through several intramural and extramural laboratory activities across the Nation. In 2017, NIH anticipates investing about \$382 million in nanotechnology R&D, which is similar to 2016 investments and is 5% more than 2015 actuals. The majority of 2015 and 2016 NIH investments in nanotechnology supports both new and existing investigator-initiated projects aimed at novel R&D in PCA 1 (the Sensors and Nanotechnology Knowledge Infrastructure NSIs, 4%), PCA 2 (Foundational Research, 23%), PCA 3 (Nanotechnology-Enabled Applications, Devices, and Systems, 64%), PCA 4 (Research Infrastructure and Instrumentation, 4%), and PCA 5 (Environment, Health and Safety, 5%). A significant change will occur in 2016 due to the conclusion of four major NIH-funded nanotechnology programs: the NIH Common Fund Nanomedicine Initiative; the NIH National Heart, Lung, and Blood Institute's (NIH/NHLBI) Program of Excellence in Nanotechnology; the NIH National Institute of Environmental Health Sciences (NIH/NIEHS) Centers for Nanotechnology Health Implications Research (NCNHIR); and Phase 2 of the NIH National Cancer Institute's (NIH/NCI) Alliance for Nanotechnology in Cancer program (NCI Alliance Program). Although the impact of these changes on 2017 investments remains to be seen, NIH is not expecting a substantial reduction in nanotechnology investments from historical levels at this time due to the launch of Phase 3 of the NCI Alliance Program, release of two new Nanomaterials Health Implications Research opportunity announcements, and the successful integration of nanotechnology-driven R&D into broad areas of biomedical applications now being supported by individual NIH institutes. For instance, NIH/NCI awarded \$79.5 million in extramural research support across all program component

3. Changes in Balance of Investments by Program Component Area

areas of nanotechnology research in 2015, while investing \$17.6 million in Phase 3 of the Alliance Program and maintaining its \$3 million investment in the Nanotechnology Characterization Laboratory (NCL) at the Frederick National Laboratory for Cancer Research. The continuation of the cancer nanotechnology program signifies a substantial commitment by NIH/NCI to maintain centers of excellence, networks, and training activities in all the various PCAs for the next 5 years. These programmatic adjustments of research support within the development pipeline are not expected to significantly change the balance of investments by PCA (i.e., largely in PCA 3) for NIH activities in 2016 or 2017.

NIOSH: All support by the National Institute for Occupational Safety and Health 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 2017 as a mechanism for accelerating key areas of nanotechnology investigation along the natural technology development pathway into advanced manufacturing, to provide direct support to the EHS needs of the emerging National Network for Manufacturing Innovation. A critical focus area increasing in 2017 will be the development and implementation of engineering control strategies and workplace design 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 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. Key areas of research that will increase in 2017 will be to conduct hazard assessments employing *in vitro* and *in vivo* models of exposure–response relationships, applying predictive risk assessment models to classes of nanomaterials, and refining methods to relate actual manufacturing exposure experience to toxicology testing protocols.

For 2017, the NIOSH investment will continue to focus in the five strategic areas described in the NIOSH Nanotechnology Research and Guidance Strategic Plan.⁵⁶

- 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: The National Institute of Standards and Technology’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. The 2017 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.

⁵⁶ www.cdc.gov/niosh/docs/2014-106/pdfs/2014-106.pdf

3. Changes in Balance of Investments by Program Component Area

NSF: The National Science Foundation supports nanoscale science and engineering (NSE) throughout all of its research and education directorates as a means to advance discovery, inventions, and innovation, and to integrate various fields of research and education. The NNI enables increased interdisciplinarity through research at atomic and molecular levels for about 5,500 active awards with full or partial content related to NSE. NSF will conduct research in support of the Nanotechnology-Inspired Grand Challenge for Future Computing. An increased focus is on support of convergence research and education activities in confluence with other priority areas in programs such as the National Strategic Computing Initiative (NCSI); 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), the Materials Genome Initiative, Understanding the Brain, Quantum Information Science and Engineering, and synthetic biology. 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. NSF will give research priority in support of the NNI Grand Challenge on Future (brain-like) Computing, as well as for emerging priorities in nanobiomanufacturing and water desalination, water treatment, and water purification.

Two additional Nanosystems Engineering Research Centers (NERCs) were awarded in the 2016 competition—Nanotechnology Enabled Water Treatment Systems (NEWT) at Rice University and Power Optimization for Electro-Thermal Systems (POETS) at the University of Illinois at Urbana-Champaign. A new competition for 2017 awards will be announced in 2016. A Center for Sustainable Nanotechnology was awarded in 2015 by MPS and will be in operation in 2016. In 2017, 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. Two new Emerging Frontiers in Research and Innovation (EFRI) topics announced in 2015 will be competed in 2016 in the areas of "Quantum Information Systems" and "New Law."

The National Nanotechnology Coordinated Infrastructure (NNCI) is a newly established NSF program, funded at about \$15 million annually from 2015–2019, consisting of 16 independent awards to universities around the Nation as user facility sites in nanotechnology. It is the successor program to the National Nanotechnology Infrastructure Network (NNIN). In addition, NSF plans to support a coordination office for the NNCI, which will be selected in 2016 from among the awarded sites to enhance their combined impact as a national infrastructure network of user facilities.

NSF has mainstreamed nanotechnology-related research, education, and infrastructure in core programs in several directorates. Strong support will continue for the Nanoelectronics for 2020 and Beyond NSI through core programs and for the Nanomanufacturing NSI through the Scalable Nanomanufacturing solicitation. Other NNI-affiliated awards include NSECs, NNCI, the NERCs (in ENG), and MPS centers investments (MRSECs and the Centers for Chemical Innovation).

USDA/ARS: The U.S. Department of Agriculture's Agricultural Research Service has a relatively small nanotechnology research program distributed among various projects within PCA 3 (Nanotechnology-

3. Changes in Balance of Investments by Program Component Area

Enabled Applications, Devices, and Systems). ARS research projects address issues relevant to bioproducts from agricultural feedstocks, technologies to rapidly and accurately identify pathogens and toxins, countermeasures to prevent and control agricultural pathogens, food alloys with improved functional properties, food packaging, and applications in non-food bioproducts. The budget request in nanotechnology for 2017 will be approximately \$3 million.

USDA/FS: Forest Service nanotechnology research supports the agency priorities of sustaining forest health, stimulating rural development, and creating value as an incentive for forest restoration operations. In 2017, Forest Service nanotechnology investments are in PCA 1 (NSIs; in particular, the Nanomanufacturing NSI) as well as PCA 2 (Foundational Research). 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. The Forest Service will continue to move towards commercialization of cellulose nanomaterials–based technologies. The commercialization strategy includes continued investment in the Public–Private Partnership for Nanotechnology “P³Nano”⁵⁷ with the U.S. Endowment for Forestry and Communities and in support for a cellulose nanomaterials–focused national manufacturing innovation institute as part of the National Network for Manufacturing Innovation.

USDA/NIFA: The National Institute of Food and Agriculture continues to support research, education, and extension activities in nanotechnology for agriculture and food systems. About 460 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 2017 will essentially remain the same as the 2015 investment.

⁵⁷ www.usendowment.org/p3nano.html

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 National Nanotechnology Initiative. The NNI’s activities for 2015 and 2016 and plans for 2017 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.

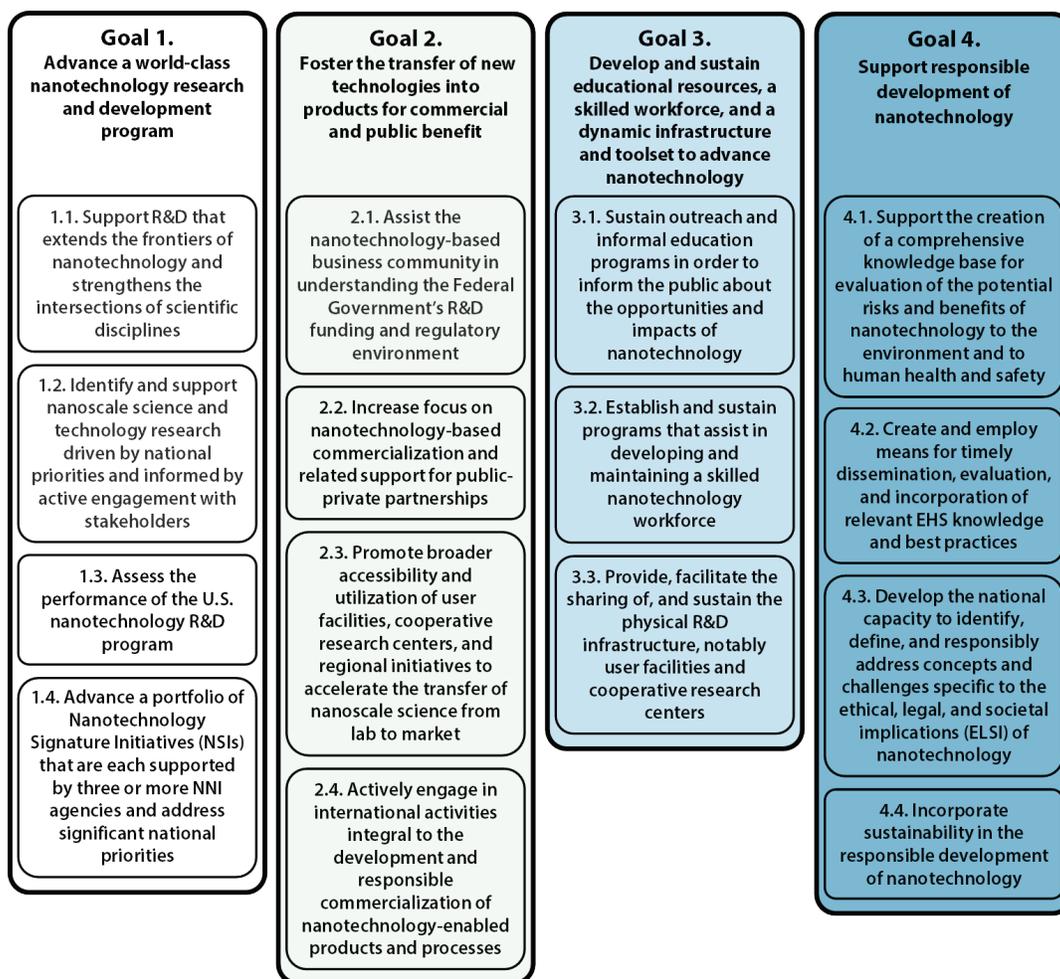


Figure 3. A summary of NNI goals and objectives from the 2014 NNI Strategic Plan.⁵⁸

⁵⁸ 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, not a comprehensive description of all 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 fifteen 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

DOD/Army:⁵⁹ The Army Research Laboratory (ARL) is investing in the underpinning science and technology of nanomaterials to enable long-term capability for the Army through systematic integrated computational materials engineering (ICME) of materials and agile manufacturing research to realize the full potential of materials and processing.

Researchers at the Massachusetts Institute of Technology Institute for Soldier Nanotechnologies (MIT-ISN) have demonstrated next-generation fiber functionality for multifunctional active fabrics by harnessing newly discovered multimaterial in-fiber fluid instabilities. These scientists are harnessing nonlinear effects to produce “fiber capillary breakup” localized domains in an otherwise continuous fiber and to demonstrate the ability to generate millions of discrete devices in a fiber. Specifically, this research has designed and successfully drawn a fiber structure at various scales that contains a semiconductor core (amorphous chalcogenide glass) flanked by two electrodes (conductive polyethylene) in polycarbonate cladding. The work has demonstrated the ability to use these self-assembled fiber structures as photodetectors that have a unique resonant characteristic in the electro-optical response of the fiber due to the presence of spherical semiconductors in the structure.

Researchers at the Aviation and Missile Research, Development and Engineering Command (AMRDEC) have developed comprehensive theoretical models of the plasmonic behavior of electrons in nanometer-scale metal structures and have explored associated quantum mechanical tunneling and nonlinear optical effects that could be exploited for novel sensing methodologies and optical protection from laser threats.

⁵⁹ See Table 1 (p. 8) or Appendix A for agency abbreviations used throughout this report.

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

The U.S. Army Medical Research and Materiel Command (USAMRMC) Clinical and Rehabilitative Medicine Research Program has invested in several research projects to foster nanomaterial applications in injury restoration, including the following:

- Investigators at the University of Pittsburgh worked to develop a novel nanofibrous biomaterial sheath, enhanced with native meniscal extracellular matrix in combination with stem cell-based therapy that should improve restoration of meniscus integrity after surgery and promote meniscal tissue regeneration.
- Researchers investigated methods to repair the internal endothelial cell layer of the cornea utilizing magnetic nanoparticles to guide endothelial cells to the inner surface of the cornea.
- Researchers at Virginia Tech investigated a keratin nanomaterial coating for interfacing advanced, musculoskeletal anchored prosthetics to epithelial tissues; keratin proteins can be used to coat implant surfaces and trick the body into thinking it is interacting with a fingernail-like interface.

DOD/DTRA: Areas of DTRA research include tamper-evident nanostructures to help with securing and monitoring weapons of mass destruction (WMD), 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 engineered nanomaterials for unattended sensing of WMD; nanomaterials as fast-responding diagnostics to measure temperature, pressure, or mechanical strain within reacting energetic materials; 2D nanomaterials for development of microelectronic components with low radiation cross section, radiation effects in nanophotonic resonators and waveguides, and nanoparticle scintillators for radiation detection. *[Sensor efforts are also applicable to the Sensors NSI.]*

DTRA basic research is invested in efforts to use nanotailored structures as laser targets to improve x-ray emissions from the targets for potential future counter-weapons of mass destruction (C-WMD) experiments. Successful tests of metal foam targets were conducted at the Omega Laser Facility at the University of Rochester and at the National Ignition Facility at the Lawrence Livermore National Laboratory in 2014–2015. These experiments showed agreement between modeling prediction and observed performance. As a result, targets can be designed with copper metal that efficiently produce warm x-rays, and there is expectation that other metal targets can also be created. The work resulted in three patent applications for the target fabrication, as well as publications on the analysis of the basic research target tests.

DOD/CBDP: The Chemical and Biological Defense Program (CBDP), working with the University of Rochester, is developing slow-light-enhanced spectrometers for molecular detection for sensors that are much smaller than those currently available and for on-chip spectrometers with resolutions comparable to those of conventional 0.1-meter grating spectrometers. Such spectrometers would be extremely useful for the detection and recognition of molecular species, such as those that could pose a security threat. CBDP-sponsored research at Columbia University has explored the fundamental knowledge of interfacial properties using nonlinear spectroscopies to detect, identify, and quantify chemical and biological agents, and protective agents at aqueous interfaces to defend against WMD agents. Through collaboration between the University of California, San Diego, and Sandia National Laboratory in nanocatalytic machines, CBDP has developed a 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 the Army's Edgewood Chemical Biological Center. CBDP thrusts in the coming fiscal year also include nanocatalytic machines that target the multistep degradation of nerve agents *in vivo* for medical countermeasures.

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

A new thrust of enabling platform technology will have a large portion of nanomaterial-based medicine. The Nanostructured Active Therapeutic Vehicles program was designed to develop nanomaterial carriers capable of targeted drug delivery and active detection of insult- and microbioenvironment-triggered payload release for improved performance of medical countermeasures from the standpoint of cost, military logistics, improved therapeutic index, and drugability. Non-ionic surfactant vesicles are being investigated as nanotechnology-based platforms for targeted delivery of antibiotics and antivirals so that some FDA-approved drugs that are as of yet ineffective for chemical and biological defense purposes will be revitalized against multiple-drug-resistant bacteria or tough alphaviruses. *[Sensor efforts are also applicable to the Sensors NSI.]*

DOD/Navy: The nanoscience program at the Naval Research Laboratory (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 bio/inorganic 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. NRL's Foundational Research (PCA 2) projects include utilizing direct electrical access to study and develop the technological applications of topological insulators, understanding and addressing the degradation of electrical energy storage in nanomaterials, understanding and enhancing enzyme/nanoparticle acceleration, confining and manipulating infrared radiation using surface phonon polaritons, creating biosupported living heterogeneous nanocatalysts, developing "protonics" to enhance the communication between electronic and biological systems, and creating new nanomaterials via surface-controlled phase transitions.

The Office of Naval Research's Biomaterials and Bionanotechnology Program is funding research to develop new processes for the construction of DNA nanostructures, and to advance DNA nanostructures for the creation of nanodevices. A process whereby a synthetic molecular structure grows isothermally in a kinetically controlled fashion, called developmental self-assembly, was engineered using DNA hairpin monomers and a single-strand DNA initiator strand. Additionally, a method was developed for the reproducible high-fidelity placement of single DNA origami molecules on silicon dioxide or related substrates. Finally, DNA nanostructures were successfully demonstrated to serve as a template for patterning inorganic materials (e.g., insulators, semiconductors, and metals) for sub-16-nanometer nanofabrication, and to serve as molds for the manufacture of metallic nanoparticles with prescribed 3D shapes and positional surface modifications.

DOE: In support of the DOE mission, the Office of Science provides a diverse investment in nanoscience R&D, 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 EFRCs and Hubs are multi-investigator, multidisciplinary research centers that are designed to address challenging problems in energy science and technology by strengthening the intersections of scientific disciplines. 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. Examples of such research include the following: nanostructured materials for electron and ion transport in next-generation batteries and fuel cells; nanoscale quantum materials for future energy technologies; fundamental understanding of nanoscale defects that will enable predictive design of materials with superior mechanical properties and radiation resistance; elucidation of

the elementary steps of light absorption, charge separation, and charge transport in nanostructured materials and chemical systems for improved solar energy conversion; atomically precise materials for molecular electrocatalysts that efficiently convert electrical energy into chemical bonds in fuels; enhanced computational capabilities for the simulation of chemical and geochemical processes at the molecular and nanoscales; and structural and dynamical studies of atoms, molecules, and predictive understanding at the nanoscale of the basic chemical and physical principles involved in chemical separations systems.

FDA: In 2015, FDA centers continued to provide research funding for regulatory science projects related to the products under their purview such as medical products, foods, and feeds. The FDA Office of the Chief Scientist funded several cutting-edge projects focused on cross-agency nanotechnology-related issues through the Collaborative Opportunities for Research Excellence (CORES) grants program. With funding beginning in 2006, these projects have led to the development of vital regulatory science tools such as biological and toxicological assays, assessment methodologies, and test protocols that FDA staff use when reviewing the safety and efficacy of nanotechnology in FDA-regulated products. FDA will continue to support agency-wide collaborative nanotechnology research in 2016 and 2017. FDA has two main core facilities to support nanotechnology-related research, at the White Oak campus in Maryland and at the National Center for Toxicological Research at the Jefferson campus in Arkansas (also the location of the FDA Office of Regulatory Affairs Arkansas Regional Laboratory). Both FDA facilities have state-of-the-art equipment, tools, and personnel for nanomaterial measurement and support and conduct research relevant to the FDA mission in collaboration with other FDA centers and other NNI agencies.

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 work NASA has done on advancing the technology maturation of structural carbon nanotubes (CNTs) by working across disciplines to advance molecular modeling of CNT composites, with the goal of eventually enabling predictive modeling and design of structural nanocomposites. Further, by engaging system analysts, NASA work on the maturation of CNT composite processing and fabrication was driven by material property targets that yielded substantial systems-level benefits and permitted the rapid advancement of CNT materials development. The processing method used to produce these nanocomposites has been scaled up for implementation on a commercial filament winder. A CNT composite–overwrapped pressure vessel will be flight-tested in the fall of 2016. Internal research and development (IRAD) funds are currently being used to support activities to develop additive manufacturing methods for multifunctional components employing high-strength CNT materials and alternative methods for producing boron nitride nanotubes (BNNTs), and to explore the use of “holey” nanocarbons for energy storage. Hybrid CNT/carbon fiber (CF)–reinforced polymer composites are being explored under Aeronautics programs, with the work spanning foundational research as well as Small Business Innovation Research (SBIR) activities.

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, nanotechnology-based therapeutics, tissue engineering, regenerative medicine, biomedical imaging, and biomaterials. Research funded through grants is the primary method utilized by the majority of NIH institutes and centers. In 2016 and 2017, scientists funded through that mechanism will continue to develop nanoscale multifunctional materials that capitalize on progress in genomics, proteomics, radiogenomics, and other fields to allow targeted delivery of molecular therapies to

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enhance efficacy, with an emphasis on the Precision Medicine Initiative⁶⁰; a White House–NIH initiative.⁶¹ Other NIH-funded researchers 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 disease states, but also allow the identification of unique biological molecules, chemicals, and structures not addressable by current assays.

NIH is also pushing the frontiers of science and strengthening the intersection of scientific disciplines through a series of funding opportunity announcements (FOAs) in response to the White House Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative, where advances in nanotechnologies in nanophotonic probes, biomimetic chips, and sensors, for instance, play a key role in R&D aimed at achieving a better understanding of human brain function. Such endeavors will enable new ways of thinking on the subject, with potential impact on new therapeutic targets, predictability in identifying early signatures of neurological diseases or disorders, and the development of precision medicine–based drugs and interventions. Advances in nanoscience and engineering are also inspiring new discoveries and tackling therapeutic challenges associated with blindness, diabetes, autoimmunity, and other diseases leading to kidney failure, degenerating nerves, and organs.

Due to the comprehensive nature and diversity of research supported by NIH in this field, its contributions to the individual NNI goals are described below in terms of a few key investment programs and opportunities that illustrate NIH’s world-class, basic, and translational nanotechnology research program:

- The NIH National Institute of Allergy and Infectious Diseases (NIH/NIAID) has funded innovative nanotechnology research to improve drug delivery, vaccines, and diagnostics for infectious diseases. This research includes the development of a "universal" influenza vaccine providing proof-of-concept that a vaccine targeting the hemagglutinin stem can offer broad protection against diverse influenza subtypes (see the left image on the front cover of this document and corresponding description on the inside front cover), and the delivery of drugs and vaccines using biodegradable nanoparticles. Other examples include: lipid-based nanoparticles as a delivery platform for HIV vaccination and immune targeting; sustained release nanoformulations of HIV drugs to provide monthly therapeutic options; a novel nanoparticle vaccine delivery platform targeting influenza and dengue viruses to induce enhanced immunity and facilitate dose-sparing; nanoemulsion adjuvant technology for an intranasal anthrax vaccine; and ferritin, gold, and P22 bacteriophage-derived nanoparticle vaccine platforms to improve potency and breadth of influenza virus immunity and to provide a foundation for broader vaccine protection against emerging influenza viruses and other pathogens. A recent highlight was the development by NIAID intramural researchers of a nanoparticle vaccine targeting Epstein-Barr virus (EBV), one of the most common human viruses in the world and the major cause of mononucleosis. The nanoparticle EBV vaccine uses structure-based design to target the part of the virus required for attachment to host cells, and represents a marked improvement over previous vaccine designs in a mouse model.⁶²

⁶⁰ www.whitehouse.gov/the-press-office/2015/01/30/fact-sheet-president-obama-s-precision-medicine-initiative

⁶¹ www.nih.gov/precision-medicine-initiative-cohort-program and www.cancer.gov/research/key-initiatives/precision-medicine

⁶² www.sciencedirect.com/science/article/pii/S0092867415009599

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- The NIH National Heart, Lung, and Blood Institute (NIH/NHLBI) supported the Programs of Excellence in Nanotechnology (PENs) for 10 years to develop and apply nanotechnology solutions to the diagnosis and treatment of heart, lung, blood, and sleep disorders. During this time, the PENs have demonstrated the ability to sustain highly productive collaborations among multiple institutions to address significant clinical needs. The Washington University–contracted PEN, for example, recently completed a first-in-human clinical trial (NCT02498379) designed to assess the safety, biodistribution, and dosimetry of a novel atherosclerotic imaging positron emission tomography (PET) radiotracer, (64)Cu-labeled C-type atrial natriuretic peptide. This nanoprobe detects the upregulation of natriuretic peptide clearance receptor on atherosclerosis-like lesions. Interestingly, this PEN collaboration with scientists at the University of California, Davis, and Georgia Institute of Technology also led to the development of a multifunctional nanoparticle capable of delivering anti-microRNA therapeutics that can inhibit the progression of atherosclerosis without adverse, off-target effects.⁶³ Other researchers, such as the team at the Johns Hopkins University PEN have developed highly compacted biodegradable DNA nanoparticles capable of overcoming the mucus barrier for inhaled lung gene therapy, providing new therapeutic opportunities for respiratory diseases including cystic fibrosis.⁶⁴
- The NIH National Cancer Institute (NIH/NCI) Alliance Program has addressed multiple challenges aimed at treating cancer across the spectrum of cancer patient management. Researchers at the Nanomaterials for Cancer Diagnostics and Therapeutics Center for Cancer Nanotechnology Excellence at Northwestern University have been developing gold nanoparticles surrounded by densely packed, highly organized nucleic acids known as spherical nucleic acids (SNAs) for use as a treatment for glioblastoma. SNAs were designed to deliver glioma-suppressive miRNA-182 and siRNAs targeted to silence Bcl2L12, an overexpressed protein that plays an important role in driving the pathogenesis of glioblastoma and in mediating therapeutic resistance.^{65, 66} This work is among the first to report stable and robust RNA interference delivery to intracranial tumors. Because SNAs have the capacity to cross both an intact and a tumor-compromised blood–brain barrier, this represents a promising new approach for treating a highly lethal malignancy.

Efforts undertaken in 2015 with continuation into 2016 and/or 2017:

- Phase 3 of the NIH/NCI Alliance Program was launched in 2015 with awards given to six Centers of Cancer Nanotechnology (RFA CA-14-013, U54) across the United States. Each center is expected to address an overarching problem in cancer biology or oncology using a nanotechnology-based, multidisciplinary approach to establish the translational potential of the supported nanotechnology. At the same time, awards were granted for seven projects for Innovative Research in Cancer Nanotechnology (IRCN) (PAR-14-285, U01) and five Cancer Nanotechnology Training Centers (CNTCs) (PA-14-015, T32). The goal of the IRCN research is to emphasize fundamental understanding of nanomaterials and nanodevice interactions with biological systems and/or mechanisms of their *in vivo* delivery. The centers will support research in the use of nanotechnology in a number of emerging areas of importance in oncology, including cancer

⁶³ pubs.acs.org/doi/10.1021/acs.nano.5b02611

⁶⁴ www.pnas.org/content/112/28/8720.long

⁶⁵ Jensen, S.A., *et al.* Spherical nucleic acid nanoparticle conjugates as an RNAi-based therapy for glioblastoma. *Science Translational Medicine* **5**, 209ra152 (2013).

⁶⁶ Kouri, F.M., *et al.* miR-182 integrates apoptosis, growth, and differentiation programs in glioblastoma. *Genes & Development* **29**, 732-745 (2015).

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immunotherapy and interventional imaging, in addition to areas of historical importance in cancer nanotechnology like drug and gene delivery and diagnostic device development. NCI plans to continue to make IRCN and CNTC awards in 2016 and 2017. Other NCI programs supporting nanotechnology research in specific component areas, such as the Innovative Molecular Analysis Technology program and the Image-Guided Drug Delivery program announcement (PAR-16-044), are expected to continue to make awards into 2017.

- The NIH National Institute of Dental and Craniofacial Research (NIH/NIDCR) launched a multidisciplinary Dental Oral and Craniofacial Tissue Regeneration Consortium (DOCTRC) to develop safe, predictive, and effective clinical strategies for regeneration of functional tissues of the human dental, oral, and craniofacial complex. The goal of this consortium is to conduct preclinical studies leading to the submission of Investigational New Drug/Investigational Device Exemption applications to FDA. DOCTRC will bring together professionals working in different disciplines, including clinicians, biologists, materials scientists with expertise in nanotechnology, bioengineers, and regulatory experts to work on the common goal of advancing the most promising tools and approaches of tissue engineering and regenerative medicine toward clinical trials. Nanomaterials are expected to be widely utilized in developing such tools and approaches. DOCTRC is a three-stage effort. Stage 1 Planning Grants awards were released in 2015; Stage 2 Resource Center Development awards will be released in 2017.
- NIH/NIDCR funded several U01 (multicenter) research projects via a special solicitation (RFA-DE-13-001) that promotes the development of novel composite polymers as part of a complete dental composite restorative system capable of exceeding current commercial product performance by two years. These projects include the development of nanometer-sized polymers used to design novel restorative systems with overall superior material properties. Three to five candidates will be selected from among 25 developed thus far for small-scale production as part of this effort. Funding will continue through 2017.
- The NIH National Institute of Neurological Disorders and Stroke (NIH/NINDS) and National Institute of Mental Health (NIH/NIMH) are continuing to solicit requests for applications (RFAs), as part of the BRAIN Initiative, focused on developing a range of tools and devices directed at recording or modulating the nervous system and analyzing cell-specific and circuit-specific processes in the brain. Nanotechnology-specific projects funded thus far are focused on single-cell-resolution monitoring of neurons using functional optical reporters (RFA-NS-14-007). Others employ nanoparticles for drug or cell delivery.

New NIH opportunities and plans for 2017:

- NIH/NIDCR plans to release two new initiatives entitled (1) Biosensors in the Oral Cavity and (2) Dental, Oral and Craniofacial 3D Tissue/Organ Models to Mimic Health and Disease, utilizing 2017 funds. The goal of the first FOA is to develop new prototype biosensors for noninvasive, dynamic, real-time monitoring of physiological processes in the oral cavity. The second will support proposals to develop tools and technologies that allow robust, precise, and predictable *in vitro* assembly and functional morphogenesis of 3D human dental, oral, and craniofacial tissues/organs. The biosensor chips will take advantage of the latest advances in bioengineering, materials science, and nanotechnology that can provide answers to key mechanistic questions regarding healthy and disease states while generating new exploratory insights into novel therapeutic targets and toxicity studies.
- NIH plans to 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

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advanced medical diagnostics, therapeutics, and approaches to disease management. Examples include clinical laboratory 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. It is pioneering semiconductor nanosystems, chip-scale optoelectromechanical devices, and nanoplasmonics for long- and short-range quantum communication as well as for precision metrology applications. NIST is enabling devices for classical and quantum information handling at the ultimate limits of today's silicon-based (Si-based) electronics by developing atomically precise manufacturing methods for single-atom-based electronic structures and by creating ultrapure, highly enriched nanomaterials for applications in Si quantum electronics and ultrapure material standards. Furthermore, NIST is developing Si-based nanodevices for single-electron metrology; practical, chip-scale, deployable devices for high-precision electrical current metrology; and standards to meet industry needs. In 2016 and 2017, NIST will make available nanomechanical property Reference Materials and Standard Reference Materials—RM 8191 for measuring strain and SRM 3461 for calibrating cantilever stiffness in atomic force microscopes—that will enable accurate determinations of mechanical performance and reliability of nanodevices. NIST is developing measurement tools to quantify interface durability and accelerate the commercial use of nanotechnology-reinforced polymeric composites, including a database of stability and reliability values, measurements of stress transfer at the fiber–matrix interface in pristine and degraded nanocomposites, and models for the damage tolerance of these materials in a range of temperature and humidity conditions.

The NIST Innovations in Measurement Science (IMS) Program competitively awards internal funds to support high-risk, leading-edge research that anticipates future measurement and standards needs. Several IMS teams are working on measurement methods to advance nanoscale science; for example, atomically precise fabrication of devices, nanoelectronic device technologies based on graphene and related 2D materials, and cold-atom focused ion beams to create breakthrough battery measurements. In 2016 a new IMS project will begin development of nanoscale superconducting devices (Josephson junctions) to extend quantum voltage standards into the microwave communications frequency range and to lay the foundation for more energy-efficient computing.

NSF: The agency 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 2015 supported about 5,500 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 SBIR and Small Business Technology Transfer (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. In 2015 NSF sponsored the workshops "Rebooting the IT Revolution" and "Energy-Efficient Computing from Devices to Architectures" in partnership with the Semiconductor Research Corporation (SRC) and the Semiconductor Industry Association. Other topical workshops will be supported in 2016 and 2017, including one on fundamental aspects of a "brain-like computer."

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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 nanophotonics. *[See also the section below on Coordinated Activities Contributing to Objective 1.1.]*

USDA/NIFA: The National Institute for Food and Agriculture continues to advance the frontiers of interdisciplinary nanoscale science, engineering, and technology for solving significant societal challenges facing agriculture and food systems. NIFA investments in nanotechnology research, education, and extension are reflected in multiple portfolios including sustainable agricultural production systems, the bio-based economy, food safety and quality, human nutrition, environmental systems, natural resources, water quality, and climate changes. 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 and other NNI agencies: All DOD nanoscience and engineering materials, processing, and manufacturing research is coordinated through the DOD Advanced Materials and Manufacturing Processes Community of Interest, the Defense Basic Research Advisory Group, and the interagency Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council. Additionally, less formal interagency collaborations are well established at the program officer level. *[This applies to all objectives in which the DOD has active research or coordinated planning with other organizations.]*

DOD/Army and academia: In partnership with Rice and Duke Universities, the U.S. Army Aviation and Missile Research, Development, and Engineering Center pioneered a new concept for photocatalysis involving metal nanoparticles whose plasmon resonances are in the ultraviolet. The strong field concentration and hot electron generation in this spectral region, where bonds are easily broken in most organic molecules, will rapidly accelerate photodecomposition of toxins and selective photochemistry of challenging industrial reactions.

DOD/Army, DOE, academia, and industry: ARL is working with industry (MicroLink Devices, Emcore), academia (University of Texas, UCLA, and University College 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.

DOD/Army, academia, and industry: The MIT-ISON brings together researchers from the university, the Army, and industry to discover and field technologies that dramatically advance soldier protection and survivability capabilities. 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

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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-crosslinked 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/Army, NSF, and academia: Army efforts are highly embedded within universities, including collaborations with George Mason University, MIT, Pennsylvania State University, University of Alabama, Arizona State University, University of North Carolina, University of North Texas, Mississippi State University, Lehigh University, Johns Hopkins University, Rutgers University, 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 (a joint effort of Penn State and Georgia Tech), an NSF-supported Industry/University Cooperative Research Centers (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 some 65% in alloys with ultrahigh toughness.

DOD/DARPA, DOD/AFOSR, NSF, and industry: The Semiconductor Technology Advanced Research Network (STARnet) Program has built a large multiuniversity research community to explore beyond current evolutionary directions and make discoveries that drive technology innovation beyond what can be imagined for electronics today. The program is 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. STARnet is jointly funded by U.S. member companies (Applied Materials, GLOBALFOUNDRIES, IBM, Intel, Micron, Raytheon, Texas Instruments, and United Technologies), DARPA, and the Air Force Office of Scientific Research (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 and the other DOD component organizations. *[Also applicable to the Nanoelectronics NSI.]*

FDA and NIST: Most FDA research activities are coordinated with other agencies through the National Nanotechnology Coordination Office (NNCO). Specific research projects in standards development have come about through discussions with NIST for reference material and documentary standards development.

NASA and DOD/Air Force: NASA achievements in structural CNTs (see NASA entry in Individual Agency Contributions to Objective 1.1) were possible through leveraged efforts with the Air Force Office of Scientific Research where mutual interest in advancing structural CNT properties have yielded collaborations with and among universities funded by AFOSR. AFOSR has also co-funded an Early Stage Innovation topic around the development of computational materials tools to understand how load transfer occurs in structural CNT composites.

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

NIH and NIST: 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. The NIH National Institute of Dental and Craniofacial Research (NIH/NIDCR) participated in an interagency agreement with NIST to provide funding support and clinical advice towards the development of clinical standards for resin composite-based dental restorative materials and a biologically relevant calcium phosphate (CaP) Standard Reference Material. This work resulted in the development of a new device, a tensometer, to evaluate the tensile properties of newly developed nanomaterials as functions of polymerization shrinkage, stress, temperature, and substrate hardness. This dual-agency program will continue into 2017 with the purpose of developing new standard reference materials, methods to characterize the properties of restorative materials at the nanometer length scale, and new analytical instrumentation for their characterization. Examples include the development of surface-enhanced Raman spectroscopy substrates for biofilm quantification using controlled nanotopography, and new approaches to quantify demineralization with nanometer resolution using innovative data analysis procedures.

NIST, DOE, and industry: NIST and DOE are working with SBIR-supported companies to complete the infrastructure required to make two novel synchrotron imaging capabilities operational at the new DOE synchrotron facility, National Synchrotron Light Source II (NSLS-II), which is designed specifically for nanoscale measurements. In 2016, NIST will commission a large-area, near-edge x-ray absorption fine structure (NEXAFS) imaging microscope that will provide high-efficiency parallel measurements of thousands of compositional samples, and an x-ray photoelectron spectroscopy (XPS) microscope that will provide full 3D mappings of nanomaterials and nanodevices, combining nanometer-scale spatial resolution with chemical and electronic state specificity. NIST is also designing and developing an x-ray scattering capability on the NEXAFS instrument for simultaneous determination of average size, shape, and local molecular structure of carbon-based nanomaterials.

NSF and DOD/AFOSR: Both agencies collaborate in the Two-Dimensional Atomic-layer Research and Engineering (2-DARE) program that had two competitions in 2014 and 2015 for four-year group awards. This program addresses fundamental challenges in the creation of 2D nanoscale materials beyond graphene and their hybrids, scalable manufacturing strategies, characterization tools and methods, and novel devices. These awards 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/Army: AMRDEC has demonstrated integration of nanomaterials in weaponry components, to include formulations to enhance the physical and mechanical properties of solid and gel propellants, environmentally friendly missile structures and housings, smart seekers with nano-optic characteristics, and cost-reduction methods for fabrication of filament-wound composite missile structures.

ARL is producing thermally stable nanocrystalline feedstock to be used as part of its research endeavors to develop superior additive manufacturing technologies for agile manufacturing capabilities. The Army has advanced the ability to obtain nanostructured powders to achieve novel properties through balancing the strength/ductility tradeoff associated with nanocrystalline materials. Using an ICME approach, ARL produces

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stable nanocrystalline powders that resist microstructural changes during the high-temperature processing needed for full-density consolidation. Researchers and engineers are exploiting 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 microstructures. These include aluminum alloys for lightweighting ballistic applications, nanostructured steels for ultrahigh strength at high temperatures, and nanostructured materials for penetrators.

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 industrial stakeholders. The STARnet Program funds research directly at U.S. universities. *[Also applies to Objective 1.1 and the Nanoelectronics NSI.]*

The 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 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 and weight as well as power requirements. 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, 3D 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. *[Also applies to the Sensors NSI.]*

DOD/SERDP: The DOD's Strategic Environmental Research and Development Program (SERDP) completed a project investigating nanotechnology processing methods to develop alternatives for copper-beryllium (CuBe) alloys that pose an inhalation hazard during manufacturing. This method utilized grain refinement to the nanoscale (instead of age-hardening with CuBe or work-hardening with current CuBe alternatives) to produce suitable alternative materials to CuBe for insertion into applications within the defense sector. These materials could be produced with low surface roughness, low stress, no porosity, and moderate-to-high build rates—attributes important for the near-net generation of bulk forms. These nanostructured materials have a number of significant benefits over CuBe and conform to property requirements for current and future CuBe alloy needs within DOD, including sheet/foil and high-strength wire replacements. *[Also contributes to Objective 4.4.]*

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DOE: DOE Office of Science (DOE-SC) continues to support two Energy Innovation Hubs: the Joint Center for Artificial Photosynthesis⁶⁷ and the Joint Center for Energy Storage Research.⁶⁸ A significant fraction of the effort in both hubs involves nanotechnology. By fostering unique, cross-disciplinary collaborations, these hubs 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.

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. For example, scientists funded by ARPA-E have adapted a biological strategy to create a robust and very low-friction surface.⁶⁹ They created a surface that was porous on the nanoscale and then filled the pores with a low-friction fluid over which other fluids flow readily. The approach is flexible, allowing differently structured coatings with different liquid fillers. These surfaces repair themselves when scratched or damaged, resulting in highly robust coatings with the potential to outperform conventional technologies in friction and drag reduction while repelling a broad range of contaminants. The ARPA-E funded research team spun out a company after securing venture capital financing to commercialize this technology for a range of applications, including refrigeration, marine shipping, wastewater treatment, industrial cooling, and liquid transport through pipelines.

The Solar Energy Technologies Office 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's \$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 Advanced Manufacturing Office (AMO) in DOE-EERE supports promising clean energy R&D on ultraconductive nanomaterials for improved efficiency in thermal processes, a more efficient electric grid infrastructure, and next-generation electric machines. In addition, AMO funds atomically precise manufacturing of high-performance membranes for chemical separations, and atomically precise catalysts for high-efficiency chemical reactions.

The Fuel Cell Technologies Office (FCTO) 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. Ongoing nanomaterials efforts focus on conventional and alternative cementitious materials. Nanoscale interrogation and characterization techniques are expanding the fundamental understanding of cement hydration kinetics and the ability to model them. Applied coatings and material interface behavior are being exploited to enable improved performance, structural health monitoring, and self-repair capability.

NIH: Early in 2016, NIH/NCI released an updated version of the Cancer Nanotechnology Plan referred to as caNanoPlan 2015,⁷⁰ a vision for the future of cancer nanotechnology R&D that is coordinated by the NIH/NCI

⁶⁷ solarfuelshub.org

⁶⁸ www.jcesr.org

⁶⁹ arpa-e.energy.gov/?q=slick-sheet-project/slippery-coatings-reduce-friction-and-energy-loss

⁷⁰ nano.cancer.gov/about/plan

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Office of Nanotechnology Research. Researchers from academia, small business, government labs, and pharmaceutical companies participated in drafting this vision, which includes milestones and strategic insights for cancer nanotechnology development. The 2015 caNanoPlan also informs the cancer nanotechnology and oncology communities on the state of the field and potential near-term developments. In addition, NIH/NCI maintains active engagement with key stakeholders in the Translation of Nanotechnology in Cancer consortium, a public–private partnership initiated in 2012 consisting of members from large pharmaceutical companies, small biotechnology firms, and patient advocacy organizations (see Objective 2.1) to facilitate clinical translation of nanotechnologies in 2016 and 2017.

NIH/NINDS plays a leading role in the coordination, representation, and implementation of NIH activities contributing to the BRAIN Initiative, driven by community stakeholders and the White House (see the BRAIN 2025 report⁷¹). As a result, NIH/NINDS has released several requests for applications that open the door to utilizing current advances in nanotechnology-related tools, devices, and systems as well as their developments to better understand the functioning of the human brain. These collaborations will continue well into 2017.

USDA/ARS: Agricultural Research Service nanotechnology investments include research in the following areas:

- Use of biopolymers to develop sustainable technologies and bioproducts: utilize conventional and novel processing technologies to produce and characterize nanofibers from biopolymers and investigate potential applications; utilize biopolymers to encapsulate and/or deliver beneficial soil microbes that improve crop production; and enable new commercial materials based on biopolymers and biobased fillers.
- Development of commercially targeted technologies for producing value-added bioproducts such as specialty/commodity chemicals and biopolymers made from renewable agriculture feedstocks or biomass: fungus-based processes for the commercial production of carboxylic acids and microbial oils, and chemical and enzymatic processes for the commercial production of sugar-based biopolymers/oligosaccharides and ethers derived from sugars or polyols.
- Imaging technologies for the detection and characterization of food safety pathogens, toxins, and bacterial threat agents, including hyperspectral microscopic imaging systems, Raman scattering with silver nanorods, and applications of nanoscale peptides and DNA aptamers.
- Development of countermeasures to prevent and control agricultural pathogens such as Rift Valley Fever, which is the most significant arthropod-borne animal disease threat to the U.S. livestock industry.
- Use of a wide range of technological approaches in the utilization of agricultural by-products and feedstocks to improve functionalities of protein/carbohydrate particles for elastomer, coating, agricultural, medical, and cosmetic applications, including new products based on functionalized particles for use in elastomeric composites and latex coatings; production of marketable biochar particles for rubber composite filler applications; new products based on nano- or microparticles for controlled release of chemicals; new products based on biodegradable nanoparticles from starch, and expansion of their end-use applications; and new products based on micro and nanosized particles of lignin and cellulose.
- Development of nanoscale coatings to make cotton flame-resistant, and deposition of enzymes and/or peptides on cotton nanocrystals for applications in biosensors, antimicrobials, and bioremediation.

⁷¹ www.braininitiative.nih.gov/pdf/BRAIN2025_508C.pdf

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- Development of new bioactive and biobased 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.
- Study of bioactive food ingredients that influence the gut microbiome and inhibit the growth of bacterial pathogens.
- Processing technologies to produce healthy, value-added foods from specialty crops, including applications of methylcellulose and chitosan nanoparticles in edible films.
- Environmentally friendly processes and new applications for animal hides and leather, including collagen-based nanofibers for high-efficiency, biodegradable air filters.

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

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 1.2

DOD/Air Force, industry, and academia: The Air Force Research Laboratory (AFRL) Materials and Manufacturing and Aerospace Systems Directorates work in coordination with other DOD and Government agencies through both the Reliance 21 Communities of Interest (Advanced Materials and Energy & Power) and through the Interagency Advanced Power Group. AFRL collaborates with many industrial partners and educational institutions such as Clemson University, MIT, the Georgia Institute of Technology, Northwestern University, and the University of Chicago.

DOE and NSF: NSF and DOE cosponsor the Quantum Energy and Sustainable Solar Technologies (QESST) Engineering Research Center (ERC), which conducts photovoltaic (PV) research.

FDA and standards developing organizations: FDA protects public health by ensuring that products regulated by FDA are safe and effective for their intended uses. Standards are vital for the FDA mission, playing a key role in reviewing product performance for efficacy and safety evaluation, and enabling industry to have benchmarks for translating novel technologies into products. FDA is actively engaged in standards development in the committees on nanotechnology at the International Organization for Standardization (ISO) and ASTM International, and it continues to participate in this activity with stakeholders through interagency working groups, industry, and academia. A Global Summit on Regulatory Science workshop in nanotechnology was held by FDA in 2015 in Parma, Italy, in collaboration with European Union regulatory and standards agencies, to discuss the standards needed for expedient regulatory review.

NASA and industry: Flight testing of nanoengineered surfaces has been conducted with a commercial partner. Measureable reduction in insect residue adhesion was observed and shown by analysis to support the benefits of laminar flow wing designs for energy efficiency under the Environmentally Responsible Aviation Project.

NIOSH, industry, and academia: The National Institute for Occupational Safety and Health continues to give broad support to advancing nanotechnology research through active partnerships with the private sector and with public research institutes. Research collaboration agreements with organizations such as the Center for High-Rate Nanomanufacturing at Northeastern University, the Colleges of Nanoscale Science and

Engineering at the State University of New York Polytechnic Institute, and Purdue University give NIOSH unique insights into the materials and processes that are being explored for commercialization. Direct partnership with private-sector nanomanufacturers gives NIOSH an opportunity to make significant contributions to safe and responsible development early in the material and/or product life cycle. In addition to protecting the nanotechnology workforce from R&D through production, this activity has potential to enhance speed to market and create competitive advantage by developing effective risk management practices.

NIST, NSF, industry, and academia: The SRC Nanoelectronics Research Initiative (NRI) has worked with NIST and NSF in a public-private partnership to address key national priorities that are also associated with U.S. Government interagency research initiatives such as the NNI and the National Strategic Computing Initiative. Through research investments in centers across the United States, NRI seeks the next device that will propel computing beyond the limitations of current technology. *[Also relevant to Objectives 2.2 and 2.3.]*

NIST, NIOSH, FDA, NIH, industry, and academia: 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 an NSF-led study and 2013 report created in collaboration with NIH, EPA, DOD, NASA, and USDA/NIFA, entitled *Convergence of Knowledge, Technology, and Society*.⁷² 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. For example, about 800 of the new nanoscale science and engineering awards at NSF in 2015 (or about 6 percent of all new NSF awards in that year) include research and education on biological aspects, information technology, and cognitive sciences.

NSF, USDA/NIFA, DOE, and DOD: Engineering biology incorporates many advances of nanotechnology to develop advanced manufacturing technologies. NSF is working with USDA/NIFA, DOE, and DOD to develop formal joint activities starting in 2017, and has participated in a number of studies and workshops to develop a strategic focus since 2015.

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.—depending on the program structure and governance. For instance, as noted in the 2016 NNI Budget

⁷² 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).

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Supplement, the NIH/NCI Alliance for Nanotechnology in Cancer completed a performance assessment as part of planning exercises in 2013 to prepare a strategy for NIH/NCI's nanotechnology investment for 2015 onwards. The results of this assessment led to Phase 3 of the Alliance Program, maintaining both research and training centers and individual research grant awards. Key scientific and translational accomplishments from the NCI Alliance Program are described in several publications listed on NIH/NCI's website.⁷³ The Alliance office plans to continue evaluation efforts throughout the third round of Alliance funding. In addition to the Alliance review, the NCI Office of Cancer Nanotechnology Research engages the research community to increase understanding of the trajectory and success of nanomedicine research at large. Efforts included participation in the Science of Team Science annual meeting in June 2015.

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.

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

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 the President's Council of Advisors on Science and Technology.

USDA/NIFA and NSF: NIFA and NSF provided funding and leadership to the inaugural Gordon Research Conference on Nanoscale Science and Engineering for Agriculture and Food Systems, which was held at Bentley University in Waltham, MA, June 7–12, 2015. The conference covered a broad range of topics, including nanotechnology and its relevance to future agriculture and food systems, public perception and acceptance of nanotechnology applications in food, advances in nanoscale materials and their applications in sensors for rapid detection, nanoscale delivery systems for food and feeds, risk assessment, policy and regulation, intervention strategies for improving food safety and agricultural biosecurity, nanotechnology

⁷³ nano.cancer.gov/action/recent

applications and implications in plant production and the environment, discovery and applications of novel nanobiomaterials, and nanotechnology-based approaches for improved livestock systems. The cutting-edge research findings presented at this conference drew 139 participants from 15 countries. The NNCO Deputy Director delivered a keynote presentation.

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.⁷⁴

Nanotechnology for Solar Energy Collection and Conversion⁷⁵

Individual agency contributions to this NSI

DOD/Air Force: The AFRL Materials and Manufacturing Directorate continued to contribute to this NSI through the end of 2015. Activities were focused in three areas: (1) developing approaches to fabricate nanotechnology-based solar collection and conversion 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 density, such as unmanned air vehicles and persistent high-altitude airships. The AFRL Aerospace Systems Directorate, in collaboration with university researchers, is continuing solar energy research by exploring carbon nanodots as a fuel adjunct and possible solar hydrogen generation technology.

DOD/Army: Under the Solar NSI, AMRDEC researchers patented a tiny photovoltaic solar cell for the conversion of light energy into electrical energy. The active region was composed of nanometer-thick layers of metals like silver or gold between similarly thin semiconductor layers, dramatically reducing the size of the photovoltaic cell by a factor of almost a thousand.

DOD/Navy: The Office of Naval Research (ONR) Biomaterials and Bionanotechnology Program contributed to this NSI by supporting academic researchers to investigate the influence of biomolecules, specifically peptides, during the growth process of platinum (Pt) nanocrystals (i.e., from nucleation to the final crystal) in order to achieve rational materials synthesis and functionalization; and explore the use of silk-based materials as the foundation of a new generation of eco- or bioresorbable energy-harvesting devices (photoactive devices).

DOE: The DOE Office of Science has supported a wide array of basic research related to solar energy collection and conversion in areas such as photovoltaics, solar photochemistry, and solar fuels. Funded Solar NSI projects in the Office of Basic Energy Sciences included 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). This research has been aimed at gaining a fundamental understanding of light capture and conversion, charge separation and transport, and catalytic processes in a wide variety of materials and chemical systems.

⁷⁴ For additional information on the Nanotechnology Signature Initiatives, see the 2014 NNI Strategic Plan www.nano.gov/2014StrategicPlan and www.nano.gov/signatureinitiatives.

⁷⁵ The Solar NSI was sunset in 2015.

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The DOE-EERE Solar Energy Technologies Office supported 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.

NSF: NSF has supported 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 was on the education, at all levels, of a highly trained scientific and technical workforce. NSF activities that addressed research topics related to this NSI included Engineering Research Centers such as the QESST ERC and the Emerging Frontiers in Research and Innovation 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 addressed the goals of the Solar NSI is the Development of Economically Viable, Highly Efficient Organic Photovoltaic Solar Cells program, 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 were responsible for over 80% of the NSF investment in the Solar NSI. Examples of investments relating to this NSI included 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 Agriculture and Food Research Initiative (AFRI) nanotechnology program supported research on interfacing plant-based photosystem I (PS I) proteins for biohybrid solar energy conversion. PS I is a protein that converts almost 100% of the light it absorbs into chemical energy to drive photosynthesis in green plants. The research team established the highest reported light-driven current (~ 1 mA/cm²) for PSI-coated electrodes by depositing films of extracted PSI onto p-doped silicon to enable unidirectional transfer of electrons from the electrode into the protein film. The project has made continued technical breakthroughs leading to the production of commercially viable biohybrid solar cells.

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

NIST and academia: Working with the University of Nebraska and the University of Toledo, NIST developed a suite of optical and electron-beam-based spectroscopic techniques for nanoscale mapping of local efficiency correlated with maps of material composition and defects in polycrystalline inorganic thin-film PV materials (e.g., cadmium telluride, CdTe) and emerging thin-film PV materials (perovskites).

NSF and DOE: In addition to continued participation by NSF and DOE in the Solar NSI through September 2015, the two agencies are cosponsoring the Engineering Research Center for Quantum Energy and Sustainable Solar Technologies, another research center that involves industry collaboration. This center has been jointly funded by NSF and DOE's Solar Energy Technologies Program 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,” cosponsored by DOE, NSF, and NIST, continued to be held in each of the years following the articulation of this NSI (2010 through 2015). This conference also included a workshop titled PV Velocity Forum: Accelerating the PV Economy, which was jointly planned and implemented by DOE and NIST.

NSF, industry, and academia: 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/Air Force: The AFRL Materials and Manufacturing Directorate is conducting research efforts in nanomanufacturing technologies; 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 electronics. Nanomaterials are being developed for monitoring the spatial and temporal cure of composites to improve process efficiency and throughput. Large-area fabrication of optical nanostructures for spectral imaging and photonics is a focus of research leveraging existing manufacturing techniques. The Aerospace Systems Directorate, in collaboration with industry and academia, is developing nanocarbon-based membrane technology for catalysis, filtration, and refinement of fuels to improve system performance as well as logistics, resource accessibility, and sustainability.

NASA: NASA continues to work with industry, universities, and other Federal agencies in the development of ultralightweight cores for efficient load-bearing structures and their application in aerospace components. This project, supported by the Space Technology Mission Directorate’s Game Changing Development Program, is focused on the maturation and development of scalable methods to manufacture ultralightweight core materials as lower-mass alternatives to honeycomb or foam cores in composite sandwich structures. NASA will integrate the vendor-provided ultralightweight cores with both standard carbon fiber/epoxy- and carbon nanotube–reinforced face sheets. The resulting sandwich structures promise more than 40% mass reduction relative to conventional composite/honeycomb sandwich structures. Ultimately, NASA plans to construct large-scale (nominally 3 m x 3.4 m) sandwich panel dry structures for launch vehicle applications such as upper-stage skirt segments for the Space Launch System.

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 for the electrical conductivity of carbon nanotube–based wires. Part of this work has continued in 2015 with support

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from the Game Changing Development Program for the development and maturation of polyimide aerogels as wire insulators.

NIOSH: NIOSH is expanding its research activities that have direct connections to the NSIs. Many activities begun in 2014 and carried into 2017 are focused directly on safe and responsible development of nanomaterials, nanomanufacturing processes, and nanotechnology-enabled products throughout the life cycle. In 2015, NIOSH began to develop and disseminate case studies that demonstrate the utility of applying Prevention through Design (PtD) principles to nanomanufacturing. In 2017, NIOSH will continue 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 TiO₂ nanowires was published. NIOSH will use strategic partnerships with business and academia to develop and deploy effective Environmental, Health, and Safety (EHS) practices that can be incorporated into business and research plans. Partnerships with private nanomanufacturing companies will be expanded in 2016–2017 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. 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 is developing quantitative, high-resolution tomography methods that can provide input data for nanocomposite models. These models accurately predict the electromagnetic properties of carbon nanotubes and graphene nanoparticles. NIST continues to develop new methods to aid in understanding the long-term reliability of carbon nanocomposites, including new approaches to performing accelerated aging and damage tolerance studies and fluorescence methods for *in situ* diagnosis of mechanical damage and aging effects.

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 five competitions from 2011 to 2015, with another planned for 2016. Activities are being organized for 2016 and 2017 in the Directorate for Biological Sciences and the Directorate for Engineering aimed at researching biology at the nanoscale for advanced manufacturing.

USDA/FS: The two Forest Service-funded cellulose nanomaterial pilot production facilities, one at the Forest Service Forest Products Laboratory in Madison, Wisconsin, and a second located at the University of Maine in Orono, Maine, continue to be the two major suppliers of cellulose nanomaterials for research in the United States and internationally.

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 energy and fuels.

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

DOD/Army and international organizations: ARL participated in the International Materials Research Congress 2015 to establish a pathway for more formalized international R&D alliances on various topics related to nanomaterials and nanomanufacturing. The conference highlighted groundbreaking nanotechnology-related materials science R&D from the Americas, including 2D materials for electronics, enhanced light–matter interactions for photonics, materials for structural polymers, advances in drug delivery, and CNT fibers and ropes.

DOD/OSD and industry: A project of the Office of the Secretary of Defense (OSD) with Nanocomp Technologies under the Defense Production Act Title III Program for Advanced Carbon Nanotube Volume Production is providing infrastructure for the world’s first industrial-scale CNT materials manufacturing facility, and is producing ultralightweight functional products from CNTs in yarn, sheet, tape, and slurry formats. CNTs are some of the strongest, stiffest, and most robust materials yet discovered. Advanced CNT products play a major role in maintaining our military’s technological edge, providing warfighters with improved protection and survivability, enhanced mission effectiveness, and reduced operating costs. The project successfully stood up an operational pilot facility to produce CNT materials, using sustainable raw materials, for program test and evaluation purposes. Results from the past year’s program activities have increased CNT product output by one order of magnitude with costs being reduced more than twelve-fold. Annual production now approaches one metric ton, translating to millions of meters of CNT yarns and hundreds of thousands of square feet of CNT sheets and tapes. Demonstrations have included electrostatic discharge/electromagnetic interference shielding for spacecraft; the flight of lightweight CNT sheet–based structural honeycomb on a cube satellite; the flight of CNT data cables on several technology demonstration satellites and military aircraft; testing of CNT-enhanced thin soft ballistic vests and pressed composite armor for lightweighting helmets; and space flight of 3D printed brackets made from CNT-based slurry. Products have been or are being evaluated by more than 250 companies and organizations; of those products, approximately 80% are government-related, with the rest being engineered for commercial applications.

NIST, NNI agencies, academia, and industry: In October 2015, NIST held a workshop, Advancing Nanoparticle Manufacturing, bringing together researchers from industry, academia, and government to identify challenges and opportunities for fast, accurate, low-cost methods to characterize nanoparticle properties in a manufacturing environment and thereby enable more efficient nanoparticle manufacturing.⁷⁶ The organizers of this NIST workshop are currently preparing a report for publication.

NIST, academia, 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. Resulting from these interactions, commercial microwave measurement systems are now available. NIST has partnered with universities to advance the understanding of carbon nanocomposite mechanical properties and lifetime performance.

Nanoelectronics for 2020 and Beyond

Individual agency contributions to this NSI

DOD/Air Force: The AFRL Materials and Manufacturing Directorate 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-

⁷⁶ www.nist.gov/cnst/anm.cfm

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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 0D (e.g., quantum dots), 1D (e.g., nanotubes and nanowires), and 2D (e.g., monolayer) approaches. These materials and processes are of strategic importance both for 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 research advancements and applications development via the Flexible Hybrid Electronics Manufacturing Innovation (“Flex-Hybrid”) Institute and the Integrated Photonics Institute for Manufacturing Innovation. Current research focuses on high-performance carbon, 2D and structured oxide nanomaterials for advanced radio-frequency electronics, robust nanoparticle quantum light sources, and cathode materials that have dramatically advanced the state of the art by leveraging nanostructure. The AFRL Information Directorate has invested in nanoelectronic memristor systems for 3D integrated, dynamic, neuromorphic, and low-power electronic systems.

DOD/Army: In partnership with researchers at Duke University and the University of Virginia, AMRDEC researchers have explained how nanostructures of the environmentally friendly wide-bandgap semiconductor zinc oxide efficiently emit visible light. Showing that the emission efficiency depends on the density of certain defects and the dynamics of certain carriers, the researchers were able to demonstrate quantum efficiencies approaching that of commercially available white light phosphors used in commercial fluorescent and solid state lighting.

ARL researchers are leading a program entitled Understanding and Exploiting the Electronic Interface in Stacked 2D Atomic Layered Materials, the goal of which is to explore and exploit the layer interaction phenomena observed between 2D atomic layers in a heterogeneous stack. Emerging 2D 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. The interface and surface properties of 2D materials are intertwined, allowing the engineering of new material systems that behave quite differently from their bulk counterparts. The program utilizes theoretical and computational modeling as well as research in materials growth, materials characterization, device fabrication, and testing.

DOD/DTRA: Foundational research has matured to the point where DTRA is beginning to transition to nanotechnology-enabled applications, devices, and systems (PCA 3) to support development in topics supporting the Nanoelectronics for 2020 and Beyond NSI.

DOD/Navy: The Nanoelectronics NSI project at the Naval Research Laboratory is focused in the area of quantum information science and has as its goal to create a new paradigm for manipulating quantum systems by trapping ultracold atoms in the evanescent field of silicon nitride (SiN) waveguides. This advancement will enable chip-scale quantum information systems.

NIST: NIST is making significant advances in developing measurements and fabrication approaches for high-performance nanoelectronic materials and devices. Programmatic efforts span a wide range of topics such as graphene and related atomically two-dimensional materials (including detailed insights into the ways that these materials interact with metals to form high-performing device contacts), semiconductor nanowires, carbon nanotubes, and thin-film device platforms for electronic applications. Further, NIST is developing novel ways to measure and manipulate photons for a range of nanophotonic applications including nanoelectromechanical resonators for advanced radio-frequency communications. NIST is helping fill knowledge gaps for electronic devices, including improved measurement of device structure and

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performance as well as energy barriers at materials interfaces for future ultralow-powered electronics. NIST is advancing quantum information and communication technologies through activities such as fabrication of nanoscale superconducting devices and development of epitaxial semiconductor quantum dots, and it is developing the expertise to enable the transition of quantum information–based technologies to platforms compatible with current silicon electronics technology. The NIST NanoFab, a shared resource in NIST’s Center for Nanoscale Science and Technology (CNST) user facility, and the MicroFabrication Facility located at NIST’s Boulder campus are supporting this NSI by providing researchers access to state-of-the-art tools 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 on 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 for Quantum and Spin Phenomena in Nanomagnetic Structures at the University of Nebraska, Lincoln. NSF has also supported the National Nanotechnology Infrastructure Network (or NNIN, the foundation for the new National Nanotechnology Coordinated Infrastructure program,⁷⁷ NNCI), whose 14 universities have provided capabilities that include nanoelectronics. NSF’s newly established NNCI program consists of 16 university user facility sites across the Nation, with a coordinating office to be awarded in 2016, with a diverse user facility portfolio for nanobiotechnology, nanoelectronics, nanomanufacturing, and other areas.

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

DOD/Air Force and other NNI agencies: The AFRL’s Materials and Manufacturing and Sensors Directorates work in coordination with other DOD and Federal agencies to direct the Integrated Photonics and Flex-Hybrid Manufacturing Innovation Institutes’ technical development strategies.

DOD/DARPA, academia, and industry: 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/SRC 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-off 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.

NIST, DARPA, NSF, industry, and academia: Via the NRI and STARnet public–private partnerships, NIST, DARPA, NSF, and U.S. member companies support nine major interdisciplinary research teams at academic

⁷⁷ www.nsf.gov/news/news_summ.jsp?cntn_id=136211

institutions across the Nation. Benchmarking of new devices in order to optimize the selection of future technology is a component of these programs. *[Also applicable to Objective 2.2.]*

NIST, ODNI, 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.⁷⁸ Raytheon BBN Technologies, Hypres, Northrop Grumman, and IBM are part of this program. NIST is developing state-of-the-art measurement tools and benchmark data and devices for IARPA.

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

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

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 deficiency of understanding has had significant industrial impact where carbon nanotube synthesis is not well-controlled, which impedes our ability to scale production and decrease cost. Highly parallel and automated experimentation has the ability to map the huge, multiparameter processing space to explore growth behavior and examine alternative processing conditions. The newly developed Advanced Rheometric Expansion System (ARES) has been used to perform thousands of experiments in months, dramatically expanding the understanding of growth and leading to conclusive information on catalyst forms and growth processes. The system is being transitioned to explore other nanomaterial processing spaces.

DOD/Navy: The ONR Biomaterials and Bionanotechnology Program is funding three efforts addressing computational materials by design: (1) developing a general-purpose, physics-based computational modeling platform that accurately predicts the 3D structure, mechanical properties (including flexibility), thermodynamic stability, and defect rate of nucleic acid-based nanostructures; (2) developing and applying atomistic-based, multiscale simulation models for three classes of proteins in order to predict the properties of protein materials throughout disparate ranges of time and length scales, i.e., creating a hierarchical theory of protein materials and designing materials with advanced functions; and (3) establishing a predictive modeling approach for the design of entropic forces in alpha helix/polymer conjugates to achieve hierarchical self-assembling polymer conjugated peptide systems with predictable order. Each of these efforts involves collaborations with experimentalists for validation of the models.

NIH: NIH/NCI, the NIH National Institute of Biomedical Imaging and Bioengineering (NIH/NIBIB), and the NIH National Institute of Environmental Health Sciences (NIH/NIEHS) have been and will continue to be active

⁷⁸ www.nano.gov/futurecomputing

participants in the NKI Signature Initiative as it seeks to support the development and adoption of consistent standards for reporting nanomaterial properties, databases to store nanomaterial characterization data, and protocols and best practices for publication and sharing of data. For example, the NKI objectives align well with NIH/NCI's efforts to continue support for caNanoLab, a web portal and data repository for annotating and sharing information on the physicochemical, *in vitro*, and *in vivo* characterization of nanomaterials relevant to cancer prevention, diagnosis, treatment, and control. This knowledge base also provides insight into regulatory filings, long-term use of nanomaterials, and computational modeling of nanoparticle behavior for diagnostic and therapeutic applications. Materials will be updated in 2016 and 2017 as the NCI data-sharing coordinators from the Phase 3 Alliance for Nanotechnology in Cancer and researchers within the Innovative Research in Cancer Nanotechnology program carry out their research projects. To ensure timely release of research publications, the data coordinators receive hands-on training in the use of the caNanoLab.

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 execution 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 advancing the availability of tools for predicting the physicochemical properties of nanomaterials. NIST efforts include the development of 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 NIST nanoparticle database was completed in 2015, and deployment of the database will occur in 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 (nanoHUB),⁷⁹ 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.

⁷⁹ www.nanohub.org

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

CPSC, DOD/Army, and NIST: A cooperative agreement established by CPSC and other agencies will conduct testing and develop models to identify the impacts that various matrices may have on the biological activity of nanomaterials. The models will incorporate information from a variety of sources on the potential impacts of nanomaterials on humans and organisms in the environment.

NIH, NIOSH, NSF, academia, and industry: NIH/NCI and NIH/NIEHS are actively engaged in this NSI and have jointly supported the Nanomaterial Registry with NIH/NIBIB since 2012. This registry is designed 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 given particles. This homogenized vocabulary enables searches and comparisons based on MIAN similarity. The registry team is also working on integrating modeling and simulation tools through a portal between the Nanomaterial Registry and nanoHUB, an online simulation resource for nanotechnology supported by NSF.

The NIH/NCI National Cancer Informatics Program (NCIP)⁸⁰ continues to support the Nanotechnology Working Group, an NCIP interest group comprised primarily of external and academic researchers who develop and promote adherence to best practices in nanoinformatics. In 2015, working group members published a series of consensus papers focused on nanocuration as part of a Nanomaterial Data Curation Initiative and issued a call for nanotechnology data reporting guidelines.⁸¹ The working group also worked with publishers to improve access to and increase acceptance of nanomaterial data repositories. caNanoLab is now a recommended data repository for papers submitted to the Nature Publishing Group⁸² and the Public Library of Science (PLOS).⁸³ In July 2015, Elsevier and NIH/NCI announced the implementation of two-way linking between articles published on Elsevier's ScienceDaily⁸⁴ full-text scientific research database and datasets stored in caNanoLab. Two-way linking provides simple and fast access to primary data underlying research results, improving communication between scientists, and hopefully enabling greater reproducibility of research results. Elsevier journals will also allow deposition of data into caNanoLab by authors during the publication process.

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.

NIOSH, NNI agencies, industry, and academia: 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, and DOD, and many public- and private-sector partners: UCLA, the National

⁸⁰ cbiit.nci.nih.gov/ncip

⁸¹ www.beilstein-journals.org/bjnano/single/articleFullText.htm?publicId=2190-4286-6-179

⁸² www.nature.com/sdata/data-policies/repositories

⁸³ journals.plos.org/plosone/s/data-availability#loc-recommended-repositories

⁸⁴ www.elsevier.com/solutions/sciencedirect

Nanomanufacturing Network, nanoHUB, RTI International, MIT, and the NanoBusiness Commercialization Association. [Also relates to Goal 4.]

NIST, industry, and academia: 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 an array of projects including many with a focus on nanotechnology, such as directed self-assembly for nanomanufacturing, 2D nanoscale materials, and organic electronics. [This is also relevant to Objective 1.1.]

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

Individual agency contributions to this NSI

DOD/Air Force: The AFRL Materials and Manufacturing Directorate is continuing the development of nontraditional sensors to detect biomarkers that indicate fatigue, cognition, and other indicators of human performance. Work is also 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 and reliable, repeatable performance.

DOD/Naval: The ONR Biomaterials and Bionanotechnology Program funded a university researcher to develop a versatile, rapid (<1 minute) sensing module for the detection of explosives (picric acid, trinitrotoluene [TNT], and hexahydro-1,3,5-trinitro-1,3,5-triazine [RDX]) that uses luminescent silver nanoclusters as transducers. The sensing module consists of a nucleic acid scaffold modified with silver nanoclusters and electron-donor units. Formation of donor-acceptor complexes between the electron-donor unit associated with the sensing unit and the analyte explosives exhibiting electron-acceptor properties concentrates the explosives in close proximity to the silver nanoclusters, leading to the luminescence quenching (decreased luminescence) of the silver nanoclusters, which provides a readout signal for the quantitative detection of the explosives.

FDA: FDA plans to continue participating in the Sensors NSI in 2016 and 2017, especially because many nanotechnology-based sensors are being developed for purposes that will require FDA review and approval.

NASA: NASA continues to support 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. Work on the development of autonomous chemical-biological sensor platforms based on carbon nanotube and nanofiber sensing elements was initiated at the NASA Ames Research Center in 2014 with funding from the Space Technology Mission Directorate's Game Changing Development Program. The work has demonstrated the ability of carbon nanofiber sensors to detect at low concentrations biomarkers for cardiac disease in devices that exceed medical requirements. A high school intern working on this project presented the results of her research to President Obama at the 2015 White House Science Fair.⁸⁵

NIH: Several NIH institutes fund research in the area of nanosensors. NIH/NCI has a wide grant support portfolio in *in vitro* diagnostics 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

⁸⁵ www.youtube.com/watch?v=ZLOsvjtD7hw

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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 the EHS-focused Thrust 2 of the Nanosensors NSI.⁸⁶ 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 recently developed a nanoparticle-based sensor for detection of urinary markers for point-of-care diagnosis of acute kidney injuries or chronic kidney conditions. This highly sensitive system uses an automated on-chip assay followed by detection with a hand-held device that conveys the results.⁸⁷

In 2017, significant advances in the dental field will be pursued as a result of the proposed initiatives from NIH/NIDCR on biosensors in the oral cavity (see NIST contributions to Objective 1.1). Recent progress in wireless technologies, dissolvable nanotechnology-based electronics, microfabrication technologies, and improved sensing and drug delivery instrumentation will enable new capabilities for oral cavity biosensing. These advances will significantly contribute to improving and protecting health, because the biosensors developed as a result of this initiative will enable interactive and integrative communication between patients and healthcare providers, and for certain applications, will allow monitoring and treatment remotely. A complete list of funded grants can be found using the NIH RePORTER research project online reporting tool.⁸⁸

NIOSH: In 2017, 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, and a prototype was created 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 designing and fabricating nanomaterials for chemical and biochemical sensors and is developing chemical, spectroscopic, electrical, and optical measurement methods for environmental, biomedical, and defense applications. NIST is developing chip-scale technologies combining microfluidics, ultrafast lasers, and biochemistry to rapidly characterize the performance of fluorescent proteins in living cells, and to select those cells with the most useful performance characteristics. NIST has also developed and deployed cryogenic x-ray spectrometer systems based on nanoscale superconducting sensors for use at national synchrotron facilities to enable new measurements on nanoscale materials such as biological molecules. NIST is developing methods for fabricating and measuring small-footprint, wearable, and flexible sensors based on semiconductor nanowires that detect environmental pollutants and explosives, as well as carbon-based nanostructures that detect and deactivate chemical threat agents. An ongoing effort to develop periodic arrays of metallic nanodomes for photonic signal-based detection of drugs and DNA will be expanded in 2016 to include nanoantennae for detection of disease biomarkers in noninvasive breath analysis testing.

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

⁸⁶ More information on the Nanosensors NSI and its thrust areas can be found at www.nano.gov/NSISensors within the Sensors Portal Menu section, "About the NSI."

⁸⁷ journals.plos.org/plosone/article?id=10.1371/journal.pone.0133417

⁸⁸ projectreporter.nih.gov/reporter.cfm

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development of novel biorecognition strategies; multifunctional nanomaterials and interfaces with predefined physical, chemical, or biological characteristics for biosensing applications; and fundamental studies 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: NIFA continues to utilize 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. For example, the AFRL nanotechnology program funded a project to develop a multiplex biosensor system with biomolecular probes for rapid detection of common foodborne bacterial pathogens. 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 (NC1194⁸⁹: Nanotechnology and Biosensors). The committee has been effective in advancing nanoscale science and engineering for nanosensor development and commercialization.

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

DOD/Air Force, industry, and academia: The AFRL 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 (NBMC). Numerous universities, including Northeastern University and the University of Cincinnati, contribute to the work, as do several companies, including MC10, General Electric, and Brewer Science. (See below under Coordinated Activities for Objective 2.2 for more information about NBMC.)

DOD/Army and academia: In partnership with Duke University and the Universidad de Santander (Columbia), AMRDEC pioneered a demonstration of ultraviolet surface-enhanced Raman spectroscopy using novel metal nanostructures, detecting analytes up to 10 million times more sensitively than without the nanostructures.

NIH and NNI agencies: NIH/NCI has actively participated in the redesign of the Sensors NSI web portal on the NNI website⁹⁰ based on feedback from participants in the 2014 NNI Sensor Fabrication, Integration, and Commercialization Workshop.⁹¹ The new sensors portal has one section devoted to sensor development and one section devoted to sensing nanomaterials. Each section includes information about and links to programs within agencies participating in this NSI, funding opportunity announcements, fabrication and testing facilities, standards organizations, regulatory guidance and information, databases, and professional and industrial organizations. The portal is intended to act as a consolidated source of information on Federal support for sensor development and private resources open to outside users. NIH/NCI also participated in the July 2015 information webinar that accompanied the launch of the new web portal.

NIOSH, NIH, FDA, NIST, DOD, NASA, NSF, and EPA: NIOSH participates with other agencies in 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

⁸⁹ www.nimss.org/projects/13116

⁹⁰ www.nano.gov/SensorsNSIPortal

⁹¹ www.nano.gov/2014SensorsWorkshop

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detection and measurement capability will support the efforts of private-sector companies to demonstrate responsible development. In 2017, NIOSH plans to continue 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 and continuing into 2017, 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.]*

NIST and DOD/Navy: NIST is working with NRL to develop nanometer-scale, magnetic tunnel junction sensors to detect magnetic fields for use in military, space, and civilian applications.

NIST and industry: NIST is working with a small company to develop nanoparticle-containing, inkjet-printed sensor substrates for ultrasensitive detection of illicit narcotics and explosives. This work includes the establishment of optimal protocols for sensor production as well as nanometer-scale surface chemical characterization of the as-prepared sensor surfaces.

NIST is collaborating with a small company to scale up a NIST-developed, top-down process of dry and wet etching to fabricate gallium nitride (GaN) nanowire arrays for low-power, high-selectivity chemical and biochemical sensors.

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 focuses its resources and broadens 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 from lab to market, 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 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

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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 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, conferences, and workshops. For example, FDA has issued four final guidance documents 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 submitting documentation to FDA or 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 to address questions related to safety, efficacy, public health impact, and/or regulatory status of the product. FDA plans to issue at least one draft guidance in 2016 for public comment. FDA has a webpage that provides nanotechnology-based businesses and consumers with relevant documentation to understand FDA's position on nanotechnology, to communicate information about research that FDA is conducting, and to notify businesses and the public regarding public meetings held by FDA.⁹²

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, now publicly available,⁹³ 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.

NSF: The agency supports programs to promote university–industry interaction (Grant Opportunities for Academic Liaison with Industry or GOALI, I/UCRCs, and Partnerships for Innovation or PFIs); translational research (ERCs and the Innovation Corps or I-Corps™); and small business innovation (SBIR/STTR) in nanotechnology. It has supported the National Nanomanufacturing Network since 2005 for university–industry–government collaboration and databases in nanomanufacturing.

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. It 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.

⁹² www.fda.gov/scienceresearch/specialtopics/nanotechnology

⁹³ techport.nasa.gov/home

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 2.1

NSF and NNI agencies: NSF will continue to cosponsor 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.

NNCO and NNI agencies: The National Nanotechnology Coordination Office conducts a number of activities in support of this objective, in conjunction with and in support of NNI participating agencies:

- NNCO staff includes a full-time industry and state liaison (ISL) staff member who maintains contacts with industry organizations and many individual companies, serving as a resource to help the nanotechnology business community understand the Federal Government's R&D funding and regulatory environments. The NNCO ISL had nearly 400 in-person or telephone meetings with companies in 2015. The ISL staff member also attends various industry conferences and participates in the monthly conference calls of the NanoBusiness Commercialization Association.
- The NNCO Director and Deputy Director perform a significant amount of outreach to both the business and academic communities, including visits to individual companies and presentations at various conferences. Together, NNCO staff members attended over 50 meetings and conferences in 2015 that also included industry attendees, or where commercialization issues of interest to industry were discussed.
- In cooperation with NNI participating agencies, NNCO maintains an industry "frequently asked questions" (FAQ) page on the NNI website that includes information about both funding opportunities and regulatory issues.⁹⁴ The website also includes a "business development" section with additional information relevant to this objective.⁹⁵
- In 2015 and continuing into 2016 and 2017, NNCO has been working with NNI agencies to implement a new series of webinars to increase the NNI's outreach to the research and business communities. These include a specific series of webinars on issues of interest to small and medium-sized enterprises and another series in support of the Nanotechnology Signature Initiatives.⁹⁶ An NSI webinar held in November 2015, "A Regulatory Case Study for the Development of Nanosensors," directly addressed this objective and featured a presentation from FDA intended to help the business community understand better how it reviews nanotechnology-enabled products.

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

Individual Agency Contributions to Objective 2.2

DOE: In order to transfer new technologies into the market, the DOE Office of Energy Efficiency and Renewable Energy supports incubator programs in key program offices, which provide early-stage assistance to help startup companies cross technological barriers to commercialization while encouraging private sector investment. A new High Performance Computing for Manufacturing program, funded through the DOE Advanced Manufacturing Office, provides national laboratory supercomputing resources and modeling expertise to U.S. industry. Additionally, DOE-EERE funds three manufacturing development centers through

⁹⁴ www.nano.gov/bizfaqs

⁹⁵ www.nano.gov/businessdevelopment

⁹⁶ See www.nano.gov/PublicWebinars for a complete list.

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the Photovoltaic Manufacturing Initiative and the National Renewable Energy Laboratory's Process Development Integration Laboratory.

ARPA-E's Technology-to-Market program provides awardees seeking to develop novel energy technologies with practical training and critical business information to equip projects with a clear understanding of market needs to guide technical development and identify follow-on funding. Awardees are required to provide a technology-to-market plan prior to receiving an award and must work closely with ARPA-E's technology-to-market advisors throughout the project, developing custom strategies to move projects toward the marketplace. In addition, ARPA-E facilitates the relationships with investors, government agencies, small and large companies, and other organizations that are necessary to move awardees to the next stages of technology development.

NASA: NASA continues to support the development and commercialization of nanotechnology-related products through its SBIR and STTR programs. In 2015, this support 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 laboratory 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.

In October 2015, NCI partnered with the Center for Advancing Innovation (CAI)⁹⁷ to launch the Nanotechnology Startup in Cancer Challenge (NSC²).⁹⁸ The challenge features nanotechnology inventions from scientists at NIH but also is open to teams that wish to bring their own technologies into the challenge. The goal of the challenge is to accelerate the commercialization of cancer nanotechnology by launching and mentoring new start-up companies around nanotechnology inventions. Teams enter the NSC² by submitting the business plans they have built around their chosen inventions, including details on the expertise and backgrounds of team members and the suitability for the challenge of any external inventions. Promising teams and inventions will be invited to join the NSC² and to prepare a two-minute elevator speech and business summary in order to determine their progression to the business plan stage of the NSC². In that stage, participants will develop ten-page business plans and 20-minute "pitches" to be delivered to NSC² judges; CAI will coach participants, who are expected to be young entrepreneurs and students. The winners (a maximum of three per NIH invention and no more than four companies built on external inventions) will receive \$2000 and advance to the final stage of the challenge, start-up. At start-up, teams will launch their companies, apply for licenses for the inventions, and seek funding to advance development of their technologies. NIH/NCI management hopes that this model will increase market access to promising inventions that currently lack a commercialization path.

Phase 3 of the NIH/NCI Alliance for Nanotechnology in Cancer maintains NCI's commitment to clinical translation of promising nanotechnologies for the prevention, diagnosis, treatment, and control of cancer,

⁹⁷ www.thecenterforadvancinginnovation.org

⁹⁸ www.nscsquared.org

with each of the six centers in the Alliance expected to bring one technology to the point of clinical testing by the end of the five-year program. This phase is a continuation of the Alliance's previous successes, in which eight Alliance-affiliated therapeutics and five devices and instruments were brought to clinical trials or Institutional Review Board–approved studies in humans.

NSF: NSF sponsors public–private partnerships (e.g., NRI 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 and consists of a 30-question online survey supplemented by interviews.⁹⁹

USDA/FS: To foster the commercialization of cellulose nanomaterials, the Forest Service will continue to co-invest in the P³Nano public–private partnership with the U.S. Endowment for Forestry and Communities. In 2015, P³Nano held a meeting to review the progress of the first eight projects funded for a total of \$3 million. Several of the project leads presented laboratory-prepared prototypes seeking industry support. Examples of these prototypes include cellulose nanomaterials to improve concrete strength, cellulose nanomaterials coatings to preserve fruit freshness, and reduced-noise snack bags. The Forest Service continues to participate in the International Organization for Standardization Technical Committee 229 (ISO TC 229) Nanotechnologies technical committee and leads the ISO TC 229 cellulose nanomaterials terminology project.

USDA/NIFA: The USDA SBIR program housed in NIFA has supported nanotechnology R&D aiming at commercialization. Topics of the NIFA SBIR projects included 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 NIH: In 2017, CPSC, in collaboration with NIH/NIEHS, proposes the development of a new nanotechnology center at NIH/NIEHS to assist stakeholders, including manufacturers, in 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. The center will serve as a resource for manufacturers and distributors of nanotechnology-enabled products for approaches to ensuring the safe use of nanotechnologies in products, as well as for consumer groups and others in the general public having a desire to learn more about nanomaterial use and implications. *[Also relevant to Objectives 2.3, 4.1, and 4.3.]*

DOD/Air Force, other DOD agencies, industry, and academia: The Nano-Bio Manufacturing Consortium and the National Network for Manufacturing Innovation (NNMI) programs are two examples of where DOD is utilizing public-private partnerships to support fundamental and applied research and foster commercialization.

The AFRL Materials and Manufacturing and Sensors Directorates work in coordination with other DOD and Government agencies to direct the America Makes, Integrated Photonics, and Flex-Hybrid Manufacturing Institutes to promote the industrialization of nanomaterials and nanotechnology. AFRL's nanotechnology investments will substantially contribute to the development of manufacturing technologies via these and

⁹⁹ www.ncms.org/index.php/2014/01/ncms-launches-2014-u-s-nanomanufacturing-survey

other NNMI institutes, and those investments will be leveraged to synergistically transition advances in nanotechnology.

NBMC, sponsored by several AFRL directorates, aims to explore new partnering, business, and collaboration models between suppliers, integrators, innovators, and government researchers. This three-year effort 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. This consortium is based on government-industry-university cost-sharing, with technical efforts selected by a team representing the 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. Nanomaterial-based sensors operating on nature-inspired principles will produce unprecedented levels of sensitivity and performance for a range of applications in aerospace, medicine, and human performance monitoring. *[Also applies to the Nanosensors NSI and Nanomanufacturing NSI.]*

DOD/DARPA, industry, and academia: The private companies and universities participating in DARPA's STARnet Program 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.

DOE and NSF: NSF (Directorate for Engineering) and DOE (EERE Solar Training and Education for Professionals) cosponsor the Quantum Energy and Sustainable Solar Technologies ERC, which works with companies to advance technologies toward commercialization.

NIST, NSF, industry, and academia: NSF and NIST continue their support of the NRI, which in 2015 performed a benchmarking of the new proposed devices and is planning for a more systems-oriented research strategy. Annual funding for three multiuniversity research centers and 18 university awards continued in 2015. *[Also relevant to Objective 2.3.]*

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), which are national user facilities for interdisciplinary R&D at the nanoscale that serve as the basis for a national program that encompasses new science, new tools, and new computing capabilities. These are the 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, CFN conducts energy-related research on electronic nanomaterials and soft and nanobiomaterials, with emphasis on block co-polymer and DNA-mediated self-assembly of nanostructures; and MF emphasizes combinatorial synthesis of nanomaterials, multimodal *in situ* imaging and spectroscopy, interfaces in nanomaterials, "single-digit" nanofabrication, and

high-resolution electron scattering. Information about capabilities at all five centers can be found at the newly launched NSRC Portal, <https://nsrcportal.sandia.gov>.

DOE-EERE supports solar energy activities at the National Renewable Energy Laboratory (NREL) through 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.

DOE SBIR-STTR programs help small businesses to develop and commercialize advances in ultraconductive nanomaterials, nanoscale and atomically precise catalysts, nanotechnology-enabled sensors and nanomaterials for nuclear applications, and atomically precise materials and nanomaterials for membranes for energy-efficient chemical separations.

NIST: The CNST user facility continues to provide users from industry, academia, and government access to the NanoFab, a state-of-the-art commercial tool set available at economical hourly rates and supported by a dedicated technical support staff. CNST continues to expand the range and depth of its nanofabrication processes, making it easier to maintain and distribute the latest processes within the nanotechnology R&D community of researchers in academia and industry. The NanoFab hosts 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 academia: The Nanotechnology Characterization Laboratory (NCL) is a formal interagency collaboration between NIH/NCI, FDA, and NIST. This collaboration initially started in 2004. In 2015, FDA and NIH/NCI signed a memorandum of understanding to continue ongoing collaborations in 2016 and beyond. NCL continues to regularly engage with the nanotechnology R&D community by conducting preclinical assessments of nanomaterials for submission to FDA for regulatory approval. Over the past ten years, NCL has characterized over 100 different nanoparticle-based projects originating from academic, government, and industrial laboratories. The results contributed to the nine nanotechnology-enabled technologies that have gone on to receive Investigational New Drug (IND) approval from FDA. FDA has recognized an increase in nanotechnology-based products containing more complex technologies.

NCL makes its assays freely available to the public¹⁰⁰ 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. NCL's routine physicochemical characterization of nanomaterials goes beyond basic measurements of size and surface charge; it 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 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.

NIST, DOD/Army, industry, and academia: NIST is working with the Center for Research on Extreme Batteries (CREB) with participants from Government laboratories (ARL), academia (University of Maryland), and industry promoting access to nanoscale fabrication and characterization facilities for collaborative research in advanced battery materials, technologies, and characterization techniques.

¹⁰⁰ ncl.cancer.gov/working_assay-cascade.asp

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.¹⁰¹ Specifically, BIS has published “Compliance Guidelines: How to Develop an Effective Export Management and Compliance Program and Manual”¹⁰² and “EMCP Audit Module: Self-Assessment Tool.”¹⁰³ 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 and characterization against metrics that indicate technology potential. In areas such as graphene nanodevices, nanomagnetic materials, and bio-inspired nanosensors, the AFRL Materials and Manufacturing Directorate has used both domestic and international input to establish 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.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 2.4

DOD/Air Force, Army, Navy, and international organizations: AFRL actively maintains close coordination with ARL and ONR to maintain a DOD-level awareness of international investment and research activities in electromagnetic, acoustic, and optical metamaterials as well as functional and structural nanomaterials technologies via informal and formal coordination bodies such as The Technical Cooperation Program with Australia, Canada, New Zealand, and the United Kingdom.

DOD/Army, EPA, NIST, OECD, standards developing organizations, and academia: To support environmental evaluations of technologies containing nanomaterials, the Army Engineer Research and Development Center (ERDC) is leading the development of standardized methods and technical guidance through ASTM International and Organisation for Economic Co-operation and Development (OECD). These guidance documents focus on the environmental risk framework and on measuring nanoparticle dispersion, dissolution, aggregation and agglomeration, and bioaccumulation. These guidance documents are being developed through numerous partnerships with Federal agencies (EPA, NIST), universities, and international partners.

¹⁰¹ www.bis.doc.gov/index.php/compliance-a-training/export-management-a-compliance

¹⁰² www.bis.doc.gov/index.php/forms-documents/doc_download/1256-emcp-guidelines-november-2013

¹⁰³ www.bis.doc.gov/index.php/forms-documents/doc_view/10-emcp-audit-module-self-assessment-tool

FDA, NNCO, other NNI agencies, and international organizations: FDA scientists co-chair the US–EU Communities of Research (CoRs) for characterization of nanomaterials. This activity is part of the NNI/NNCO effort to coordinate and engage through international collaborations. FDA has participated in these collaborative research activities and engages other research, funding, and regulatory agencies. FDA scientists participated in a 2015 US–EU CoR workshop in Italy designed to bring together and coordinate these research and funding activities. This activity will be continued through 2016 and beyond, coordinated through NNCO.

NIH and international organizations: NCL is a partner with the European Union Nanotechnology Characterization Laboratory (EU-NCL). The EU-NCL brings together nine partners from eight countries to facilitate harmonization of analytical protocols for characterization of nanomaterials intended for use in medicine and to standardize regulatory requirements for these materials.

NIOSH and international organizations: In 2017, NIOSH will continue research partnerships that started in 2015 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 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 new 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 that is representative of an emerging high-value nanomaterial 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, other NNI agencies, and international organizations: 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 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 ISO 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 2017. 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, international organizations, and industry: NIST and the National Physical Laboratory (NPL), the national metrology institutes for the United States and the United Kingdom, respectively, are co-leading a large international team of more than ten countries that has undertaken an effort to measure, validate, and make traceable Raman microscopy. Raman instrument manufacturers are also active participants. This technique, which is extensively used in nanotechnology, especially for carbon nanostructures such as nanotubes and graphene, provides detailed structural, mechanical, and electronic information. The results from this effort will enable all systems to provide reproducible and comparable data around the world.

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 expertise relating to a broad range of nanomaterials. NIST engagement for developing nanotechnology standards in ASTM International, the International Electrotechnical Commission, and ISO has led to standards for physicochemical and biological characterization, EHS-related topics, terminology, and device characterization. NIST participation has also ensured that international standards support the competitiveness of U.S. industry and do not adversely impact U.S. global trade and commerce. NIST contributes expertise informed by its 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 Working Party on Manufactured Nanomaterials of the OECD. NIST raises awareness of standards development activities with other Federal agencies and helps in articulating U.S. nanotechnology-related standards positions through standards leadership and engagement in interagency groups such as the NSET Subcommittee, the Nanotechnology Environmental and Health Implications (NEHI) Working Group, and the nanotechnology subgroup of the White House Emerging Technologies Interagency Policy Committee.

NNI agencies and international organizations: NSF, NIST, EPA, the U.S. Department of State, and other NNI member agencies continue to participate in OECD and other international forum activities.

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. This new classification system is based on an internationally used patent classification system (IPC) that contains most of the world's patent documents. As USPTO completes its initial transition to this new classification system, 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).

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

This goal encompasses three objectives¹⁰⁴ 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 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.¹⁰⁵

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: Through the DARPA 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 conduct outreach to companies and government labs, and present their work in public meetings.

NIH: Community and public outreach about cancer nanotechnology is 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 continue to participate in the NSF–initiated Nanoscale Informal Science Education Network (NISE Net) “NanoDays,” either by developing their own outreach activities or by participating in other activities organized in their areas. Alliance members also have developed courses and symposia on nanotechnology that are eligible for continuing medical education credits. In addition, the NIH/NCI Office of Cancer Nanotechnology maintains an informational website, nano.cancer.gov, that serves to educate the public in understanding nanotechnology and its impact on cancer as well as where it stands now. It also houses perspectives in the field for researchers engaged in cancer nanotechnology R&D.

Training and education at the middle and high school levels is also an integral component of the grants funded by NIH/NHLBI through the *Washington University Community Outreach* program. In January 2015, Washington University investigators worked with the St. Louis Science Center Teen Café to organize a program on nanotechnology for primary school children. The students were introduced through presentations and experiments to the use of nanotechnology for ultraviolet light protection and stain-resistant fabrics. On April 14, 2015, the Washington University PEN in conjunction with the Washington University Institute for School Partnership, organized a nanotechnology in-reach event for middle school students to raise awareness of the latest innovations in nanotechnology. In addition, NIH/NIBIB supported two research conferences that addressed research dissemination and education in nanotechnology: The June 2015 Telluride Science Research Meeting on Frontiers in Biomagnetic Particles IV and the ASME Conference on NanoEngineering for Medicine and Biology.

NSF: Two Centers for Nanotechnology in Society with significant educational components are funded at Arizona State University (CNS-ASU) and the University of California, Santa Barbara (CNS-UCSB). CNS-UCSB

¹⁰⁴ 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.

¹⁰⁵ For more information on NNI-supported research infrastructure see www.nano.gov/centers-networks.

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

supports interdisciplinary education across its research activities in various ways. For example, 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 have 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 nanoscale science and technology. A program to increase diversity in science, technology, and political studies has been established. Public engagement efforts include media interviews, speaker series, NanoDays, web-based materials, and public presentations. CNS-UCSB has established programs on integration of nanotechnology studies with societal sciences, nanotechnology undergraduate students and postdoctoral scholars' participation in societal implications studies of the center, and a Research Experience for Undergraduate (REU) internship program with the Center for Nanotechnology Science Infrastructure (CNSI), initiating over 100 new courses with over 50 new books and manuals. 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 also established an annual, two-week "Winter School" for doctoral students and postdoctoral scholars; the fourth annual Winter School took place in January 2016. 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 recruiting events with the Hearing Research Center, the ASU American Indian Studies Program, and the American Indian Policy Institute, among others. It contributes to the international Society for the Study of Nanoscience and Emerging Technologies (S-NET). Both CNS centers have recently expanded their definition of nanotechnology to include synthetic biology and have applied some of the same practices in public engagement and public policy to issues related to synthetic biology and engineering biology at the nanoscale.

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 community and the informal science education community in 2015. NSF has supported the Nanotechnology Undergraduate Education program since 2003, with the last competition in 2015, and it plans to have another proposal solicitation in 2016. NSF also supported an in-depth workshop on education needs and approaches for nanotechnology in December 2014.¹⁰⁶ A dedicated portal of resources for the nanotechnology education community has been established based on the need identified at the NSEE workshop.¹⁰⁷

NSF has sponsored a series of videos in collaboration with NBC for mass distribution via TV: "Nanotechnology: Very Small Science," and it is sponsoring a high school student competition "Generation Nano" in 2016, the results of which will be disseminated in 2017.

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.

¹⁰⁶ www.nsf.gov/crssprgm/nano/reports/educ09_murdyworkshop.pdf

¹⁰⁷ nseeducation.org/2014

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 academia: Community and public outreach about cancer nanotechnology is a systemic function 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. As noted above, Alliance members will continue to participate in the NSF NISE Net NanoDays. Other efforts include Nanotechnology Town Hall meetings 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 and open to the public; and annual The Art of Systems Biology and Nanoscience 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: Through its 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 nanodevices allows for greater exposure of students to topics in both nanoscience and nanosafety. This initial student 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 nano-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 is also relevant to Objective 4.4.]*

DOD/Army: In partnership with the University of Arizona, AMRDEC laboratories were used for pioneering explorations of the relaxation dynamics of photo-excited electrons in graphene. The research was performed by a graduate student in the DOD Science, Mathematics and Research for Transformation (SMART) program who was subsequently hired by AMRDEC to develop nanoparticle-enhanced local welding of composite materials.

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 SBIR/STTR and the SunShot Incubator help create a skilled nanotechnology workforce. DOE-SC manages the Office of Science Graduate Student Research Program, which provides supplemental awards to outstanding U.S. graduate students to pursue part of their graduate thesis research at a DOE National Laboratory in areas that address scientific challenges central to the Office of Science mission.¹⁰⁸

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

¹⁰⁸ science.energy.gov/wdts/scgsr

properties of engineered nanomaterials relevant to FDA-regulated products. In 2016, FDA will expand its training capacity to include focused lectures for regulatory reviewers, product-specific review training, and hands-on training on novel instrumentation. 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 2016 and 2017.

NASA: NASA funds student fellowships in the area of nanotechnology. These fellowships train students in technical disciplines related to nanotechnology and familiarize the students with capabilities in Government labs that constitute some of the infrastructure that supports the advancement of nanotechnology. NASA is also funding foundational research specifically targeted to NASA mission needs in areas where there are gaps in the understanding of 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.

NIH/NCI has awarded five Ruth L. Kirschstein National Research Service Award Institutional Research Training Grants (T32) focused on cancer nanotechnology. These Cancer Nanotechnology Training Center grants are part of NCI's Alliance Program, including participation in annual Alliance principal investigator meetings and data sharing activities. NIH/NCI will continue to make awards to meritorious applicants to the T32 program announcement, PA-14-015, that are organized around training centers in cancer nanotechnology, and to bring these training centers into the Alliance. These T32 awards are successors to the successful R25 Cancer Nanotechnology Training Center components of the second phase of Alliance funding and are being supported by a \$2 million set-aside from NIH/NCI for cancer nanotechnology training. NIH/NINDS has also utilized the T32 mechanism to support predoctoral and postdoctoral researchers in the neurology field. In addition, the NIH National Institute of Child Health and Human Development (NIH/NICHHD) has established a summer educational program on pediatrics and nanotechnology, and NIH/NIDCR is requiring U01 grantees involved in the novel dental restorative program to train postdoctoral fellows, graduate students, undergraduate students, and high school students in order 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. Going forward in 2017, NIOSH hopes to have specific examples of nanomaterial safety and Prevention through Design 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 continue collaborations between the NIOSH 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.

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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. NSF will continue to support two networks for formal and informal nanotechnology education with national outreach, led by The Pennsylvania State University (Penn State) and the Museum of Science, Boston, respectively.

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.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 3.2

DOE and NSF: DOE and NSF cosponsor 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.

NIST and NIH: NIST, in addition to providing training for any interested participants from the NIH/NIDCR 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 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. In 2015, seven students "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 NIST/NSF jointly funded Summer Undergraduate Research Fellowship (SURF) program provides nanotechnology research opportunities throughout NIST laboratories and user facilities at both the Gaithersburg, MD, and Boulder, CO, campuses. In 2015, NIST hosted over 180 students for a variety of research activities, including nanotechnology-related projects.

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

DOD/Navy: Through a Defense University Research Instrumentation Program (DURIP) grant, a university researcher is able to manipulate bacterial populations and measure their growth dynamics and gene expression, which he is utilizing while programming bacteria for functional materials fabrication. Another portion of the DURIP investment can be devoted to the researcher's online worldwide DNA nanotechnology utility, "Computer-aided engineering for DNA origami (CanDo)," which automates the modeling and design of nucleic acid-based nanostructures.

DOE: The Office of Science's five Nanoscale Science Research Centers 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

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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 communities 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's National Center for Toxicological Research and Office of Regulatory Affairs/Arkansas Regional Laboratory (NCTR-ORA) Nanotechnology Core Facility at the FDA Jefferson, Arkansas, Campus actively engage and collaborate with academic groups on research projects related to nanotechnology. A consortium of local universities in Arkansas is conducting research on graphene for the detection, quantitation, and application of this novel material. This research is funded by FDA through a Broad Agency Announcement.

NIH: NIH supports cooperative or program-based laboratory resources and centers through a series of grant mechanisms (U01, U10, U24, P30, P41, P50, etc.) that service network and center awards. NIH/NIBIB has funded, for example, a Biotechnology Resource Center (P41 grant) on Biomodular Multi-scale Systems for Precision Molecular Diagnostics. The goal of this resource center is to design, build, and utilize a set of modular components that will be assembled into functional units in a plug-and-play format, resulting in a universal molecular processing system that can be deployed into a wide range of specific analysis formats. These platforms would be tested for the isolation, separation, characterization, and quantification of disease-specific circulating biomarkers.

NIST: NIST continues to sustain and update the capabilities and capacity in its nanotechnology user facility, the Center for Nanoscale Science and Technology, 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 state-of-the-art commercial 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 for industry-compatible 200 mm wafer processing, with notable additions, including an ion-beam-assisted cluster metal deposition system capable of processing wafers using twelve different materials in a single run; a high-rate deep silicon etching tool for microelectromechanical system (MEMS) applications; a fast-scan atomic force microscope for nanoscale topography characterization; a resist spray coater that enables processing of wafers with extreme topography; a soft lithography laboratory with state-of-the-art equipment, including a fully integrated microfluidic test station for bio researchers in a class-10,000 cleanroom environment; and a cryogenic sample preparation system to enable biomaterial transmission electron microscopy. New capabilities in the NanoLab include nitrogen vacancy magnetometry, providing fast, nanoscale measurements of extremely small local magnetic fields, enabling diagnosis of inhomogeneities and defects in next-generation nonvolatile magnetic memory and spintronic devices; novel cold-atom-based focused ion beam imaging of optical microresonator modes, enabling development of new nanophotonic devices and architectures; and single-nanoparticle magnetometry with high throughput using nanoscale indicator films, enabling better process control in nanoparticle manufacturing applications.

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

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semiconductor nanowire LEDs (light-emitting diodes), to complex aerospace coatings and conducting oxides. PIF promotes collaborative research with local universities and DOE National Laboratories.

A primary mission of NIST's Center for Neutron Research (NCNR) is to provide state-of-the-art neutron measurement capabilities to the U.S. research and industrial communities. Installation of two new instruments (VSANS and CANDOR) will finish in 2017. VSANS will allow researchers to measure the characteristic size of material structures across five orders of magnitude, down to the nanoscale. This capability is critical to a broad range of real-world problems: for example, it can be used to measure the size distribution of voids that determine the shock resistance of explosives or the integrity of concrete used in nuclear waste storage. VSANS is a very small angle neutron scattering diffractometer that will collect data at rates 100 times faster than comparable instruments, making possible the study of nanoscale feature evolution in real time. Similarly, CANDOR is a reflectometer/diffractometer that will provide at least a ten-fold gain over existing instruments used to study nanostructured materials such as proteins, magnetic storage devices, and solar cells; it will enable kinetic studies as a function of temperature or magnetic field.

Coordinated Activities with Other Agencies and Institutions Contributing to Objective 3.3

FDA, academia, and other NNI agencies: FDA's Core Facilities at NCTR-ORA and its White Oak campus contain state-of-the-art equipment for the characterization, detection, and quantification of nanomaterials. These facilities are maintained through FDA-allocated funding for the purpose of providing FDA scientists the appropriate equipment and methods for conducting research. These facilities are used for collaboration and cooperation with several agencies, including NIST, NIH/NIEHS, and NIH/NCI, and with universities.

NIST, industry, academia, and other NNI agencies: 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, using the CNST NanoFab user facility, scientists from NIST, the University of Maryland, Rutgers University, and DOE's Argonne National Laboratory collaborated to build a compact, low-loss, scalable nanomechanical plasmonic phase modulator. This device is small enough to support on-chip dynamic routing of optical communication signals. In the past year, researchers from a biotechnology startup, working with NanoFab staff, have developed a diagnostic device capable of identifying infection-causing bacteria in less than one hour. In an ongoing project, NIH scientists are working with NanoFab staff to develop a process for fabricating substrates with precisely controlled nanoscale curvature to measure the ability of proteins to bind to lipid bilayer membranes with negative curvature. These results will be used to help design more effective drug delivery vehicles.

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—both 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.

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In 2011, the NNI developed, with input from stakeholders, a nanotechnology-related environmental, health, and safety (nanoEHS) research strategy with a broad, multiagency perspective.¹⁰⁹ 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 interactions 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, 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. Although the Air Force is working to minimize issues 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 sensitivity of the systems to accidental initiation during storage and delivery, but in generating more energetic propulsions/explosions and in 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.

DOD/Army: ERDC is focusing on the development of predictive tools (NanoExPERT Tool Suite) to support the safe development of Army and DOD technologies containing engineered nanomaterials.¹¹⁰ To support these tools ERDC has developed nanoparticle databases, including tools, such as Value of Information (VOI) and Multi-Criteria Decision Analysis (MCDA) tools, that can be used to inform investments in nanoEHS research. These studies have been applied to a wide range of engineered nanoparticles and will support future environmental assessments within DOD as well as other Federal agencies and industry. The research was published in 2015 in *Nature Nanotechnology*.¹¹¹

¹⁰⁹ www.nano.gov/you/environmental-health-safety

¹¹⁰ el.erd.c.usace.army.mil/nano

¹¹¹ www.nature.com/nnano/journal/vaop/ncurrent/full/nnano.2015.249.html

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EPA: EPA research on ENMs is conducted within the agency's Chemical Safety for Sustainability (CSS) research program. In 2015, EPA published the Chemical Safety for Sustainability Strategic Research Action Plan 2016–2019¹¹² describing new objectives and outputs for EPA research on implications of ENMs. A key scientific issue for EPA nanomaterial research 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. Accurately predicting impacts of ENMs used in real-world conditions will depend on properties of both the ENMs and the matrices. 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 also has funded the creation of the EPA STAR Center for Organotypic Culture Models at the University of Washington, a Predictive Toxicology Center for Organotypic Cultures 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 adverse outcome pathways (AOP) model. The funding period for this center is December 2014–November 2018.¹¹³

NIH: NIH/NIEHS research efforts are designed to gain a fundamental understanding of the molecular and pathological pathways involved in mediating responses to ENMs. Towards this goal, comprehensive profiles are needed to gain detailed molecular understanding of the interactions between ENMs and biological systems. The recently concluded NIH/NIEHS Centers for Nanotechnology Health Implications Research (NCNHIR) consortium investigated the correlation between chemical and physical properties with biological endpoints to define hazard characteristics for a small library of ENMs. To gain a clear relationship between physicochemical properties and molecular, cellular, and organismal toxicological endpoints, two new funding opportunities (RFA-ES-15-013 and RFA-ES-15-012) were issued for which applications are currently being accepted. The research supported by these new funding opportunities is built on the foundation of the earlier effort and aims to expand our understanding of the interactions between ENMs and biological systems using a wider and more representative set of ENMs with a high likelihood of human exposure. The redesigned structure and focus of the goals of the new Nanotechnology Health Implications Research (NHIR) consortium are twofold. The first is to enrich our knowledge base on ENM–biological interactions by expanding the library of ENMs and physicochemical properties to be investigated. This expansion will be achieved by focusing on specific ENMs with high production and use in consumer products as well as recently emerging 2D and 3D materials. The second is for NHIR to develop a comprehensive biological response profile for selected ENMs by surveying a wide range of test systems reflecting physiologically relevant models.

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 2017, NIOSH will continue its 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

¹¹² www2.epa.gov/research/chemical-safety-sustainability-strategic-research-action-plan-2016-2019

¹¹³ cfpub.epa.gov/ncer/abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/10443/report/0

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focused effort on developing risk management practices that support responsible development of nanotechnology. In 2017, that particular element of the NIOSH field research effort will focus on outputs that support the Nanomanufacturing NSI along the life cycle of the nanomaterial. In 2016, NIOSH published a summary of the principles outlined in the 2012 NIOSH-sponsored Safe Nano Design Workshop.¹¹⁴ In 2017, NIOSH will continue with development and dissemination of key areas identified by workshop attendees and stakeholders, which include demonstrating change in nanomaterial toxicology through material design changes and 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.

NIST: NIST continues to lead and make critical contributions to the Nanomaterial Measurement Infrastructure core research area as described in the 2011 NNI EHS Research Strategy. A hallmark of NIST's nanoEHS research is the development of validated methods for physicochemical and biological measurements in complex environmental and biological media. For example, the first single-particle inductively coupled plasma mass spectrometer (sp-ICP-MS) traceable to the international system of units (*Le Système International d'Unités*) will be completed in 2016. This instrument will be used to determine bioaccumulation and particle size distribution of gold nanoparticles ingested by whole organism *Caenorhabditis elegans* roundworms. The robustness of an *in vitro* nanocytotoxicology assay defined by nine quality metrics was demonstrated via an interlaboratory study in 2015, and the assay is being finalized as an ISO standard. In 2016 and 2017, additional nanotoxicity assays will be validated using similar strategies.

NIST is developing validated hyphenated instruments and methods capable of simultaneously measuring size, size distribution, and elemental composition of nanoparticles in complex environmental media, as well as advanced spectroscopy methods such as XPS to quantitatively measure the composition and coverage of surface-bound molecular coatings and conjugates. Such methods, along with NIST silver nanoparticle Reference Material 8017 issued in 2015, are being used to develop additional advanced methods for quantifying transformations of silver nanoparticles in environmental media, including bulk transformation products such as silver sulfide and surface transformation products. Another growing area of EHS research at NIST concerns the development of methods to detect and characterize nanomaterials incorporated in consumer products, both dispersed in matrices and as surface coatings, and methods to detect and quantify releases of nanomaterials from consumer products. For example, in 2016, NIST will complete a multiyear project on the determination and comparison of the detection limits of carbon nanotubes in CNT-polymer composites for four different orthogonal methods. NIST is developing and evaluating novel nanoparticle-based (nanoclay and nanosilica) fire-retardants and self-assembled coatings applied to many home furnishings and appliances, and it is developing capabilities to characterize fire behavior and combustion properties, including release of nanoparticles from such coatings. These nanoparticle-based fire retardant layer-by-layer coatings have been demonstrated to reduce the fire hazards associated with polyurethane foam by 30%. Decreasing the flammability of polyurethane foam, which is used in many home furnishings, will in turn lead to significant reduction in residential fire losses. This research will provide U.S. manufacturers with a novel and EHS-compliant fire-resistant coating technology. In 2017, NIST will develop methods to evaluate release of silver nanoparticles during common consumer activities, such as washing from cotton fibers intentionally loaded with varying concentrations of nanoparticles, and from commercial textiles.

¹¹⁴ www.cdc.gov/niosh/topics/PtD/nanoworkshop/default.html

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NRC: The Nuclear Regulatory Commission is an independent agency created by Congress. Its 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 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 behaviors of nanobiomaterials in the gastrointestinal (GI) tract and their risk assessment. Another project will attempt to elucidate absorption, accumulation, and toxicity mechanisms of titanium dioxide nanoparticles present in foods in the human GI tract. These studies will fill voids in the current knowledge matrix.

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 CPSC 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 and NIH: CPSC, in coordination with NIH/NIEHS, is proposing for 2017 a new nanotechnology center at NIH/NIEHS 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 nanotechnology and develop innovative methods for the responsible use of nanomaterials in products. The center will also serve as a resource for manufacturers and distributors 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 with a desire to learn more about nanomaterial use and implications. *[Also relevant to Objectives 2.2, 2.3., and 4.3.]*

CPSC, NIOSH, and NIST: CPSC, in coordination with NIOSH and NIST, has developed a research program to characterize, quantify, and identify exposure limits for airborne nanomaterials released from products. Robust methods to quantify exposure will be developed in addition to testing of materials to identify thresholds for biological effects of materials released from manufactured products.

DOD/Air Force and Army: AFRL coordinates with the 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 their development. The organizations will use predictive and computational modeling approaches to identify potential releases of nanoscale particles from nanostructured materials and technologies. *[Also applies to Objective 4.2.]*

DOD/Army, DTRA, NIOSH, NIH, and academia: DTRA and the U.S. Army Center for Environmental Health Research (USACEHR) collaborated with the NIOSH Nanotechnology Research Center, the NIH/NCI NCL, and

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Oregon State University to develop *in silico* models to predict the human toxicity of engineered nanomaterials. The physiochemical properties of ENMs, combined with rapid biology-based data and systematic literature datasets, will be used to improve predictive models of toxicity, provide a tiered approach to toxicological testing, and develop a strategy for grouping nanomaterials into subcategories based on their likely modes of toxic action (biological impact).

DOD/Army, industry, and academia: USAMRMC's investments with the University of Michigan and NanoBio Corp. focus on the development of a novel, safe, and rapidly effective antimicrobial oil-in-water nanoemulsion for use as a DOD/Army topical treatment for multidrug-resistant wound infections. Work has included identifying the optimal concentration of the nanoemulsion to use in an infected trauma wound animal model. The nanoemulsion, with and without drugs, will be manufactured in 2016 in accordance with good manufacturing practices, and required stability testing will be completed.

DOD/Army, other NNI agencies, industry, and academia: 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 MIT-ISN, academic partners, and industry. For example, the Armament Research, Development and Engineering Center (ARDEC) has partnered with the 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 benefits and impacts 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/Army, other NNI agencies, industry, and academia: ERDC is partnering within the DOD (U.S. Army Center for Environmental Health Research) and with other Federal agencies including NIST, EPA, CPSC, NIOSH, and NIH/NIEHS to develop the NanoGRID framework and ensure consistency in approaches within the Federal Government. The NanoGRID framework is being evaluated for use in supporting the development and transition of commercial products, including coatings, composites, sensors, and electronics, through multiple public-private partnerships with industry. This approach is also leveraging the expertise at several NIH/NIEHS, NSF, and EPA research centers—located at Oregon State University, Arizona State University, and Duke University, respectively—that are focusing on the development of life cycle- and risk-based approaches for evaluating the risks of nanotechnologies.

EPA and CPSC: EPA and CPSC are nearing completion of a collaborative research project evaluating potential release of copper from pressurized copper-treated commercial wood products. The composition, particle size distribution, leaching, bioavailability, and exposure to micronized copper have been evaluated. Reports are now available to the public.¹¹⁵ EPA has entered into a new collaboration with CPSC on Evaluation of CPSC Wipe Method and Exposure Estimate to Nanomaterials in Surface Applications. The research under this agreement will focus on: application and utilization of the CPSC wipe method for comparison across (product) matrices and with different emerging nanomaterials; characterization of the nanomaterial

¹¹⁵ nepis.epa.gov/Exe/ZyPDF.cgi?Dockkey=P100LJWI.txt

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products either in development or currently available in the marketplace; evaluation of the potential for exposure from the use of the products identified through oral and inhalation exposure routes using *in vitro* assays; characterization of the aerosol formation from application of emerging nanomaterials to surfaces; and determining the pulmonary, cardiovascular, and neurological responses to inhalation of the emerging nanomaterials during applications and throughout the life cycle.

EPA, NSF, and academia: EPA and NSF have co-funded a 2014–2018 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.¹¹⁶

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 nanomaterial migration from solid and semisolid materials used in consumer products that contact food. This work is planned to continue through 2016.

FDA, NIST, and NIH: Apart from its research activities described under Goal 1, FDA actively engages in toxicological research in collaboration with the NIH/NIEHS National Toxicology Program (NTP) to understand the health hazards of nanomaterials (hazard assessment) and to develop novel methods for detection of nanomaterials in FDA-regulated products. FDA continues to conduct physicochemical characterization and standards development processes to enable responsible development of nanotechnology. Standards are also critical for the responsible development of nanotechnology-derived products from the standpoints of safety and efficacy. FDA continues to participate in standards development so that industry and other stakeholders can validate methods relevant to nanotechnology through reference materials produced by NIST. FDA publishes its research in peer-reviewed journals and communicates through guidance documents to industry. FDA collaborated with NCL to develop a panel of *in vitro* assays, which appear in the *Handbook of Immunological Properties of Engineered Nanomaterials*,¹¹⁷ to evaluate the effects of nanomaterials on blood platelets and endothelial cells. Findings from these projects also serve in drafting guidances to industry and in helping to provide sound and scientifically based responses to inquiries from stakeholders. In 2016 and 2017, FDA will continue to fund projects on an as-needed basis in areas where knowledge gaps exist.

NIH, EPA, CPSC, and NSF: NIH/NIEHS has had a wide range of discussions within the NEHI Working Group of the NSET Subcommittee and independently with NSF, EPA, and CPSC on the selection of nanomaterials to be investigated in Phase 2 of the Nanotechnology Health Implications Research Consortium, so that the research output will fill the gaps in the data needed for regulatory agency needs. EPA and CPSC may potentially participate once the new program is established.

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 nanoEHS. In 2016, NTP, an interagency program headquartered at 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. The nanomaterial characterization, standards, and safety assessment projects in collaboration with NTP will continue through 2016.

NIH and NIOSH: The NIH/NIEHS National Toxicology Program will be initiating a chronic toxicity evaluation of multiwalled carbon nanotubes in rodent models to better understand the potential health effects from

¹¹⁶ cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/10212/report/0

¹¹⁷ www.worldscientific.com/worldscibooks/10.1142/9677

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low-dose “lifetime” exposures. This research will complement exposure assessment of nanomaterial manufacturing facilities being conducted in collaboration with NIOSH.

NSF, CPSC, the European Union, and academia: In 2015, NSF and CPSC participated in a joint solicitation for international collaborative efforts to support nanoEHS research with European Union countries.¹¹⁸ This program will support participation of investigators at U.S. universities in 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 and CPSC: NIOSH continues formal collaborations with CPSC to deliver research results that provide basic knowledge in two fronts: (1) characterization of the exposure potential and biological responses to inhalation of select nanomaterials from consumer products in support of human exposure risk assessments, and (2) investigations of actual worker exposure potential during manufacture and use of engineered nanomaterials along the life cycle. *[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 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 2017, 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 ERDC and 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 2017, NIOSH will continue to 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, EPA, NIOSH, CPSC, OSHA, NRC-Canada, industry, and nongovernmental organizations: U.S. and Canadian federal agencies are working with industry on two interlaboratory pilot studies under the auspices of the NanoRelease Project, an effort to address the potential release of CNTs from CNT-polymer-based composites by sanding and by weathering. The protocols to produce released material were generated by small teams of researchers, and agreed-on methods are being used to detect and quantify discrete CNTs released by the two processes. Data and metadata from the two interlaboratory studies are being deposited into the private NanoRelease Data Repository hosted by NIST.

NIST and FDA: NIST is working with FDA to develop reproducible methods to release silver nanoparticles from food containers by wear processes and to examine the container surfaces for the presence of free silver nanoparticles. The use of nanosilver in food applications is an area of growing consumer concern; this joint research will enable evaluation of potential risks.

¹¹⁸ www.siinn.eu/en/joint-calls/50.html

NSF, EPA, and academia: 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 focusing on the environmental implications of nanotechnology at UCLA and Duke University; the awards are approximately \$5 million per year for each center. 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.

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 ENMs and identifying appropriate exposure limits, contributing to timely dissemination, evaluation, and incorporation of relevant EHS knowledge and best practices.

DOD: The DOD Nanomaterials Environment, Safety, and Occupational Health (ESOH) Working Group works in coordination with the DOD Emerging Contaminants Governance Board to provide technical, policy, and legal information and guidances relating to safety and health issues associated with ENMs as well as their impact on DOD acquisitions policies. *[This program is also relevant to Objective 4.4.]*

DOD/OSD: The DOD Emerging Contaminants Program, part of DOD's Chemical and Material Risk Management Program¹¹⁹ and its "strategic sustainability" goals,¹²⁰ looks "over-the-horizon" to identify and assess chemicals and materials of emerging potential risk. Evaluation includes assessment of nanomaterials and involves proactive risk management actions to reduce risks to human health, the environment, and business functions, often in advance of regulatory requirements. The 2015 program continued screening of emerging nanomaterials and evaluation of their significance to DOD applications; the potential for incorporation into DOD weapons systems; and the associated business function, environmental, safety, and occupational health risks. The program also made progress in developing a framework for characterizing toxicity of engineered nanomaterials during DOD research and development phases to ensure better-informed decision making with regard to selection of lower-risk, more sustainable nanomaterials.

EPA: In 2015, results of EPA intramural research on engineered nanomaterials were published on its website¹²¹ and in approximately 35 peer-reviewed manuscripts or book chapters, and were 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. FDA staff members who review the safety and efficacy of FDA-regulated products meet regularly to discuss products using nanotechnology and consult with FDA experts on nanotechnology.

¹¹⁹ denix.osd.mil/cmrm/ECMR/ECProgramBasics.cfm

¹²⁰ denix.osd.mil/sustainability/upload/DoD-SSPP-FY15-Final.pdf

¹²¹ www.epa.gov/nanoscience

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External to FDA, the projects funded by FDA result in peer-reviewed journal articles as well as scientific contributions to standards development. FDA provides nanotechnology reports and guidance documents on its website. In 2015, it issued a final guidance providing greater regulatory clarity for industry on the use of nanotechnology in FDA-regulated animal food products.¹²²

NIH: To impact the timeliness of important EHS knowledge and practices, the research output from the earlier extramural efforts supported through the NIH/NIEHS NCNHIR and the newly formed NHIR consortia, and all research conducted by the National Toxicology Program, will be available publicly in the Chemical Effects in Biological Systems (CEBS) database, hosted by the National Toxicology Program at NIEHS. This data will be made available for meta-analysis on an as-needed basis. NIH/NIEHS is also participating in the international ProSafe data analysis efforts for dissemination and support for the widespread adoption of principles and methodology of Europe's NANOREG¹²³ related to testing, regulation, and safety of manufactured nanomaterials.

NIOSH: NIOSH will continue to disseminate the results of research from its nanotechnology research program in the form of publication of progress reports from all NIOSH Nanotechnology Research Center projects, updates to the NIOSH nanotechnology topic webpage, the NIOSH Science Blog, technical meeting and symposia presentations, formal peer-reviewed journal publications, and NIOSH publications (also available online). The NIOSH Workplace Safety and Health Nanotechnology Topic webpage¹²⁴ is one of the top pages visited on the agency website. In 2017, NIOSH will continue with 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 has refined the content and delivery of a higher-level exposure measurements and assessment strategy training course for EHS professionals and will continue to deliver the course in 2017. Plans for 2017 include publishing nanotechnology health and safety strategies for small to mid-sized nanomaterial producers and users of nanomaterials. In 2017, NIOSH will disseminate to companies information on individual process-based control strategies (Workplace Design Solutions) that draw from the broader 2013 NIOSH guidance document, *Current Strategies for Engineering Controls in Nanomaterial Production and Downstream Handling Processes*.¹²⁵

NIST: In 2015, NIST released a publicly accessible website, www.nist.gov/mml/nanoehs-protocols.cfm, which now contains 20 laboratory protocols concerning sample preparation, physicochemical measurements, and biological measurements of relevance to nanoEHS. These protocols for as-produced nanomaterials and nanomaterials in typical product matrices will enable researchers to perform step-by-step, reproducible, and validated procedures, an essential step in the harmonization of property measurements to enable direct comparisons between laboratories and greater consistency in reporting. NIST is continuing to populate the website with new and updated protocols.

NSF: Research on the safety of manufacturing nanoparticles is performed and also provided to researchers and the public by four Nanoscale Science and Engineering Centers and the NNIN (now transitioning to the NNCI¹²⁶). Environmental implications of nanotechnology, including development of new measurement methods for nanoparticle characterization and toxicity of nanomaterials, will continue to be investigated in

¹²² www.fda.gov/ScienceResearch/SpecialTopics/Nanotechnology/ucm301093.htm

¹²³ www.nanoreg.eu

¹²⁴ www.cdc.gov/niosh/topics/nanotech

¹²⁵ www.cdc.gov/niosh/docs/2014-102/pdfs/2014-102.pdf

¹²⁶ www.nsf.gov/news/news_summ.jsp?cntn_id=136211

and promulgated by 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, EPA, and NIST: CPSC, in collaboration with EPA and NIST, has begun to develop mathematical models that will be used to characterize the behavior of selected nanomaterials in the indoor environment and to estimate occupant exposure to nanomaterials. These models will address the unique properties of nanomaterials and use data derived from other interagency collaborations for development.

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.

CPSC, DOD/Army, EPA, NIOSH, and NIST: CPSC partnered with the U.S. Army ERDC, NIOSH, EPA, and NIST to lead a national workshop, held in the summer of 2015 in Washington, DC, focusing on quantifying exposure to engineered nanomaterials.¹²⁷ The Quantifying Exposure to Engineered Nanomaterials (QEEN) workshop addressed the needs of industry and government partners in determining “real world” exposures to nanoparticles from products and technologies. Information from the workshop report will be used in development of the proposed CPSC–NIH/NIEHS nanotechnology center mentioned above in the section on Coordinated Activities Contributing to Objective 4.1.

DOD/Army, other NNI agencies, and NNCO: ERDC is partnering with NEHI and NNCO to develop a webinar series to communicate solutions to industry concerns regarding workforce development in safe handling of nanomaterials, regulatory challenges, and quantitative methods to address uncertainty in liability assessments by insurance companies.

DOD/OSD, NNI agencies, and national organizations: The DOD Emerging Contaminants Program maintains a Nano Materials Working Group that serves as the coordinating body for nanomaterials-related environmental, safety, and health technical, policy, and legal information. The working group and its leadership provide a means to coordinate and connect with all military departments and DOD agencies and with other agencies and stakeholders broadly, including the Sustainable Chemicals and Materials for Defense Forum, a partnership between DOD and the American Institute of Chemical Engineers. The 2015 focus of the working group included supporting an update to DOD policy 6055.05 on occupational and medical surveillance that ensures conservative, risk-based measures in protection of workers, recognizing that traditional control measures may be ineffective and that there is a need for tailored exposure controls and medical surveillance. In addition, the group continued its systematic evaluation of emerging nanomaterials, identifying and screening nanomaterials of particular interest to DOD including a detailed evaluation of nanoscale cobalt phosphorous for potential DOD use as a hard-chromium coating substitute and its associated toxicological and exposure risks.

NSF, EPA, and academia: The Centers for the Environmental Implications of Nanotechnology at UCLA (UC-CEIN) and at Duke University (CEINT) will increase dissemination of information to government regulators at

¹²⁷ www.nano.gov/qeenworkshop

State and Federal levels and to industry stakeholders, with a focus on decision support tools, nanosafety training, and consumer product safety. In March 2015, UC-CEIN organized a workshop focused on advancing methods for considering environmentally relevant exposures to improve design of ecotoxicology studies of ENMs.

NSF, CPSC, and the European Union: NSF, CPSC, and the EU are continuing their collaboration on a joint U.S.–EU solicitation for nanotechnology EHS. A focus is 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 ongoing efforts to leverage knowledge and resources between researchers in the United States and the EU.¹²⁸ The results will be disseminated via the participating agencies’ websites, the annual NSF nanotechnology grantees conference, peer-reviewed journal publications, and presentations at professional meetings in the United States and 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 along the product life cycle. 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, nongovernmental organizations, 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 (broadly known as “ELSI”) through the Centers for Nanotechnology in Society (CNS) at the University of California, Santa Barbara, and Arizona State University, which 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, and to be addressed by multiple stakeholder groups having multifaceted, complex, and evolving relationships. CNS-ASU focuses on the unifying framework of anticipatory governance, which 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 policy makers. They also continue to engage in various public outreach engagements via media interviews,

¹²⁸ www.us-eu.org

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. Several public workshops were funded in 2015 and others will be funded in 2016. NSF (BIO, ENG, and SBE Directorates) have been working with the Nanotechnology in Society centers at both UCSB and ASU to explore the implications of synthetic biology as an emerging technology through the same lens as was done for the general nanotechnology area.

Several of the newly awarded NSF National Nanotechnology Coordinated Infrastructure sites have defined programs in studying the ethical, legal, and societal implications of nanotechnology and will disseminate those outcomes to the broader research community.

USDA/NIFA: NIFA's Agriculture and Food Research Initiative nanotechnology program supports research on assessment and analysis of the perception and acceptance of nanotechnology and nanotechnology-based food or nonfood products by the public and agriculture stakeholders. For example, a new project funded in 2015 used advanced eye-tracking methodologies to obtain a greater understanding of consumer decision processes while facing food and agricultural products that are affected by nanotechnology.

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

Individual Agency Contributions to Objective 4.4

DOD/Army: ERDC is developing the Nano Guidance for Risk Informed Deployment (NanoGRID), which is a framework to evaluate the environmental, health, and safety risks throughout the life cycle of DOD technologies. This approach is being evaluated using Army technologies currently in development (coatings, armor, and energetics) and is currently being evaluated by OSD for use in the DOD acquisition process. Ultimately, the framework will be used to address the uncertainty in U.S. and international regulatory requirements as well as liability concerns regarding the use and end of use of technologies containing nanomaterials.

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. Continuing in 2017, 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

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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. Another area of investment in 2016 that will expand in 2017 is a focus on Innovations at the Nexus of Food, Energy, and Water Systems. In 2015, NSF funded a Workshop to Identify Opportunities and Challenges for Nanotechnology to Optimize and Unify Food, Energy, and Water Systems.

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 nanocellulose-based hybrid fuel to reduce agriculture's dependence on nonrenewable petroleum. Another example is to transform nanocellulose into an advanced biorenewable reinforcement with hyperbranched polymers to improve performance. A seed grant has been provided to explore technical feasibility of using nano-chitosan to improve fire-retardant and antifungal functions of wood products.

Coordinated Activities with other Agencies and Institutions Contributing to Objective 4.4

DOD/Army, USDA/FS, and academia: 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 and on developing improved materials and techniques for secondary processing; and with applied Army engineering laboratories and NIST to test and evaluate new materials.

NSF and USDA/NIFA: NSF and USDA/NIFA are developing a joint solicitation under an Innovations at the Nexus of Food, Energy, and Water Systems program that will include funding for research that will lead to innovative system and technological solutions to critical food, energy, and water problems. An overarching goal of this solicitation is to enhance understanding of sustainability in food, energy, and water systems.

APPENDIX A. ABBREVIATIONS AND ACRONYMS

AFOSR	Air Force Office of Scientific Research	DOS	Department of State
AFRI	Agriculture and Food Research Initiative (USDA/NIFA)	DOT	Department of Transportation
AFRL	Air Force Research Laboratory	DOTreas	Department of the Treasury
AMRDEC	Aviation and Missile Research, Development and Engineering Command (DOD/U.S. Army)	DTRA	Defense Threat Reduction Agency (DOD)
ARDEC	Armament Research, Development and Engineering Center (DOD/U.S. Army)	EERE	(Office of) Energy Efficiency and Renewable Energy (DOE)
ARL	Army Research Laboratory	EHS	environment(al), health, and safety
ARO	Army Research Office	ELSI	ethical, legal, and societal implications
ARPA-E	Advanced Research Projects Agency-Energy (DOE)	ENG	Engineering Directorate of NSF
ARS	Agricultural Research Service (USDA)	ENM	engineered nanomaterial
BIS	Bureau of Industry and Security (DOC)	EPA	Environmental Protection Agency
BRAIN	Brain Research through Advancing Innovative Neurotechnologies (White House Initiative)	ERC	Engineering Research Centers (NSF)
caNanoLab	cancer Nanotechnology Laboratory portal (NIH/NCI)	ERDC	Engineer Research and Development Center (DOD/U.S. Army)
CDC	Centers for Disease Control and Prevention (DHHS)	EU	European Union
CNS	Centers for Nanotechnology in Society at Arizona State University and University of California, Santa Barbara (CNS-ASU and CNS-UCSB) (NSF)	FDA	Food and Drug Administration (DHHS)
CNST	Center for Nanoscale Science and Technology (DOC/NIST)	FHWA	Federal Highway Administration (DOT)
CNT	carbon nanotube	FOA	Funding Opportunity Announcement
CoR	Community of Research	FS	Forest Service (USDA)
CPSC	Consumer Product Safety Commission	IC	Intelligence Community
DARPA	Defense Advanced Research Projects Agency	ISO	International Organization for Standardization
DHHS	Department of Health and Human Services	I/UCRC	Industry/University Cooperative Research Center (NSF)
DHS	Department of Homeland Security	MIT-ISN	The Massachusetts Institute of Technology Institute for Soldier Nanotechnologies
DNI	Director of National Intelligence	MPS	Mathematical and Physical Sciences Directorate of NSF
DOC	Department of Commerce	MRSEC	Materials Research Science and Engineering Centers (NSF)
DOD	Department of Defense	nanoEHS	nanotechnology environment, health, and safety (research, etc.)
DOE	Department of Energy	nanoHUB	Network for Computational Nanotechnology online user-focused resource for nanotechnology computation, simulation, and presentation (NSF)
DOEd	Department of Education	NASA	National Aeronautics and Space Administration
DOE-SC	DOE Office of Science	NBMC	Nano-Bio Manufacturing Consortium (DOD/Air Force)
DOE-EERE	DOE Office of Energy Efficiency and Renewable Energy	NCI	National Cancer Institute (DHHS/NIH)
DOJ	Department of Justice	NCL	Nanotechnology Characterization Laboratory (DHHS/NIH/NCI)
DOL	Department of Labor	NCNHIR	NIEHS Centers for Nanotechnology Health Implications Research consortium (NIH)

Appendix A. Abbreviations and Acronyms

NCTR-ORA	National Center for Toxicological Research and Office of Regulatory Affairs (FDA)	NSI	Nanotechnology Signature Initiative
NEHI	Nanotechnology Environmental and Health Implications Working Group of the NSET Subcommittee	NSRC	Nanoscale Science Research Centers (DOE)
NHIR	Nanotechnology Health Implications Research consortium (a successor to the NCNHIR)	NSTC	National Science and Technology Council
NHLBI	National Heart, Lung, and Blood Institute (DHHS/NIH)	NTP	National Toxicology Program (DHHS/NIH/multiagency)
NIBIB	National Institute of Biomedical Imaging and Bioengineering (DHHS/NIH)	OECD	Organisation for Economic Co-operation and Development
NICE	Nanotechnology Innovation and Commercialization Ecosystem Working Group of the NSET Subcommittee	OMB	Office of Management and Budget (Executive Office of the President)
NIDCR	National Institute of Dental and Craniofacial Research (DHHS/NIH)	ONR	Office of Naval Research
NIHES	National Institute of Environmental Health Sciences (DHHS/NIH)	OSD	Office of the Secretary of Defense
NIFA	National Institute of Food and Agriculture (USDA)	OSHA	Occupational Safety and Health Administration (DOL)
NIH	National Institutes of Health (DHHS)	OSTP	Office of Science and Technology Policy (Executive Office of the President)
NINDS	National Institute of Neurological Disorders and Stroke (NIH)	PCA	Program Component Area of the National Nanotechnology Initiative
NIOSH	National Institute for Occupational Safety and Health (DHHS/CDC)	PCAST	President's Council of Advisors on Science and Technology
NIST	National Institute of Standards and Technology (DOC)	PtD	prevention through design
NKI	Nanotechnology Knowledge Infrastructure (Nanotechnology Signature Initiative)	PV	photovoltaic
nm	nanometer(s)	QESST	Quantum Energy and Sustainable Solar Technologies (NSF/DOE Engineering Research Center)
NNCI	National Nanotechnology Coordinated Infrastructure (NSF)	RFA	request for applications
NNCO	National Nanotechnology Coordination Office	RFI	request for information
NNI	National Nanotechnology Initiative	SBIR	Small Business Innovation Research Program
NNIN	National Nanotechnology Infrastructure Network	SI	International System of Units
NNMI	National Network for Manufacturing Innovation	SRC	Semiconductor Research Corporation
NRC	Nuclear Regulatory Commission	STAR	Science to Achieve Results (EPA)
NRC-Canada	National Research Council of Canada	STARnet	Semiconductor Technology Advanced Research Network (DARPA, industry, universities)
NRI	Nanoelectronics Research Initiative	STEM	science, technology, engineering, and mathematics
NRL	Navy Research Laboratory	STTR	Small Business Technology Transfer Research Program
NRO	National Reconnaissance Office (IC/DNI)	TONIC	Translation of Nanotechnology in Cancer
NSE	nanoscale science and engineering	USACEHR	U.S. Army Center for Environmental Health Research
NSEC	Nanoscale Science and Engineering Centers (NSF)	USAF	U.S. Air Force
NSET	Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC	USAMRMC	U.S. Army Medical Research and Materiel Command
NSF	National Science Foundation	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
		XPS	x-ray photoelectron spectroscopy

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