United States Government Accountability Office

Testimony

Before the Subcommittee on Research and Technology, Committee on Science, Space, and Technology, House of Representatives

For Release on Delivery
Expected at 10:00 a.m. ET
Tuesday, May 20, 2014

NANOMANUFACTURING AND U.S. COMPETITIVENESS

Challenges and Opportunities

Statement of Timothy M. Persons, Chief Scientist,
U.S. Government Accountability Office

Chairman Bucshon, Ranking Member Lipinski, and Members of the Subcommittee:

Thank you for the opportunity to be here today to discuss nanomanufacturing and U.S. competitiveness,[1] including opportunities, challenges, and related issues. As you know, in July of 2013, at the request of Committee Chairman Lamar Smith and former Committee Chairman Ralph Hall, the Comptroller General of the United States convened a strategic forum on nanomanufacturing. The forum brought together experts from a wide range of relevant backgrounds[2] to discuss the status, issues, and implications of nanotechnology's ongoing movement from the laboratory to commercial markets, mass manufacturing, and the global marketplace.[3] In January 2014, we issued a synthesis report from this initiative, which includes key messages stemming from forum discussions as well as four nanomanufacturing industry profiles.[4]

Based on views expressed by forum participants as well as a broader array of expert interviews, my testimony today will *first*, present a brief background on nanomanufacturing and discuss how the United States compares with other countries in research and development (R&D) and competitiveness in nanomanufacturing; *second*, identify the key challenges facing the United States in nanomanufacturing and discuss their significance; *third*, identify some key policy issues concerning nanomanufacturing; and *fourth*, discuss a few examples of public-private partnerships and how they are designed to promote U.S. innovation in

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[1] For purposes of this testimony, we define national competitiveness as the productivity with which a nation utilizes its set of institutions, policies, and human capital and natural endowments to produce goods and services, for the prosperity of its people. See also Council on Competitiveness (2007).

[2] Addendum I lists forum participants, whom we selected with the assistance of the National Academies.

[3] Nanotechnology has been defined as the control or restructuring of matter at the atomic and molecular levels in the size range of about 1-100 nanometers (nm); 100 nm is about 1/1000th the width of a hair.

[4] See GAO 2014; that report also lists experts we consulted additional to forum participants (App. III) and provides detailed information on our Scope and Methodology (App. V).

nanomanufacturing. We conducted our work in accordance with GAO's quality assurance framework.[5]

Background and Discussion of How the United States Compares with Other Countries

According to forum participants, nanomanufacturing is an emerging megatrend that will bring diverse societal benefits and new opportunities—potentially creating jobs through disruptive innovation.[6] Further, nanomanufacturing has characteristics of a general purpose technology (GPT)—such as electricity or computers, or historically, innovations such as the smelting of ore and the internal combustion engine.[7] As one participant said: "Everything will become nano."

Figure 1, below, provides examples of nanomanufacturing products that illustrate four diverse areas being affected by nanomanufacturing. Different manufacturing activities occur at different stages of the value chain.[8]

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[5] Notably, we recognize that many forum participants are active in nanotechnology research or manufacturing—and thus could benefit from increased government funding or other supportive efforts; therefore, we developed the forum with an emphasis on achieving a balance of views, to the extent possible.

[6] "Disruptive innovation" refers to a new technology that creates a new market (and a new value chain or "value network") and that ultimately, and often unexpectedly, overtakes an existing technology. See Christensen and Raynor (2003). For example, innovations such as the Ford Model T production line have been described as creating new markets, displacing earlier technologies, and in some cases, creating jobs.

[7] Addendum II lists historical examples of GPTs.

[8] We drew these examples from four of the nine areas listed by the National Nanomanufacturing Network (NNN). Other areas listed by NNN (which the four examples in fig. 1 may overlap in some cases) include (1) information technology and telecommunications; (2) aerospace and automotive; (3) forest and paper products; (4) environment, infrastructure, and national security; and (5) clothing, textiles, and personal care.

Figure 1: Diverse Value Chains Involving Nanoscale Materials, Components, or Devices, as of 2013—Looking Forward

Stage 1: Evolving nanoscale materials, components, or devices	Stage 2: Nano-enabled products or intermediates	Stage 3: Improved, nano-enhanced or new products
Nano-transistors	further improved semiconductor chips	ever-faster computers,[a] smaller smartphones
Copper nano-wires[b]	lithium-ion batteries	more powerful battery-powered vehicles
Carbon nanotubes	concrete additives that conduct electricity	road pavement with remote sensing
Protein nanoparticles	carriers of chemo-therapeutic drugs	chemotherapy targeted to cancer cells (only)

Source: Forum presentation (Persons 2013).

Note: We defined a value chain, for purposes of reporting on the forum, as a series of key steps starting with the processing of raw materials and continuing to the production of a finished consumer product; each step adds value—and may or may not involve a different company or intermediate product. The figure uses three main stages, drawn from a conceptualization by Lux Research (see Bradley 2010 and Holman 2007), to summarize four examples of nanotechnology value chains.

[a] With respect to "ever faster computers," digital development has generally followed "Moore's law" (briefly, a doubling of processing power every 18 months) in part by utilizing chips with nano-features; however, further advances and more innovations in nanotechnology—such as the use of a new generation of nanomaterials in conjunction with 3D chip architecture and optical interconnects—or other novel approaches may be needed for continuous improvement in future decades.

[b] Copper nano-wires represent one example of how nanotechnology might be used to enhance lithium-ion (Li-ion) batteries for vehicles.

Comparison for Nanotechnology R&D: Two Indicators

According to experts, the United States likely leads in nanotechnology R&D today but faces global-scale competition—which one forum participant described as a "moon race." Two indicators of how the U.S. compares with other countries are R&D funding levels and scientific publications.

With respect to R&D funding, there is some uncertainty about international comparisons because relevant definitions may vary across nations—and some countries may not adequately or effectively track R&D investments or not share such information externally. However, forum participants viewed the United States as currently appearing to lead in terms of overall (that is, combined public and private) funding of nanotechnology R&D. When public funding alone was considered, a participant in the July 2013 forum presented projections showing the United States as likely being surpassed by some other nations.

With respect to scientific publications, the United States appears to dominate in numbers of nanotechnology publications in three highly cited journals[9]—which is an apparent indication of U.S. competitiveness in quality research. However, China overtook the United States in 2010 through 2012 (the most recent year reported) in terms of the quantity of nano-science articles published annually.

Comparison for Nanomanufacturing: Four Industry Areas

Turning to U.S. competitiveness in nanomanufacturing itself, profiles of four nano-industry areas, developed for the forum, and related forum discussions indicate the following:

- **Nanotherapeutics:** According to experts, one of the most promising medical applications for nanotechnology is nanotherapeutics, the delivery of medicine using nanoparticles (particles having one or more dimensions on the order of 100 nanometers—100 billionth of a meter—or less). The potential of nanotherapeutics is the ability to target the delivery of drugs to specific cells—e.g., cancer cells—thereby reducing negative side effects. As one expert said, nanotherapeutics have "the potential to address problems in drug delivery for cancer and other diseases that cannot be solved using contemporary technologies." Experts viewed the United States as currently leading in the commercialization and manufacturing of nanotherapeutics. However, experts also cautioned that: (1) other regions or countries (for example, Europe and South Korea) are investing in nanotherapeutics—by, for example, supporting public-private partnerships; (2) in the United States, many efforts to commercialize nanotherapeutics are being carried out by small companies, which typically cannot sustain the costs of clinical trials and regulatory review; and (3) private U.S. investors may be reluctant to invest in new drugs because of uncertainty about approval by the U.S. Food and Drug Administration (FDA).
- **Energy storage:** By contrast, experts said the United States is struggling in the area of lithium-ion batteries for hybrids, plug-in hybrids, and fully electric vehicles (EV). Battery-powered vehicles now

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[9] This is based on an analysis by Roco (2013) of three journals: *Science*, *Nature*, and *Proceedings of the National Academy of Sciences*. Note that another forum participant cautioned that these journals might have favored U.S. authors.

represent about 3 to 4 percent of the U.S. and worldwide auto markets. Factors limiting demand for these vehicles include (1) the cost of an advanced battery, which increases the price of a battery-powered vehicle above that of a comparable all-gasoline car, and (2) the long battery-recharging times required by plug-in hybrids and EVs, and the EVs' limited driving ranges. Potentially, nano-improved batteries will cost less than those currently available, have decreased recharge times, and provide the power to lengthen driving ranges. Although U.S. research developed the underlying technology, almost all lithium-ion batteries are currently manufactured in Asia. According to varied forum participants: (1) the manufacture of smaller lithium-ion batteries for consumer electronics has long been centered in Asia because, as one participant put it, the United States "gave up on [that industry] some time ago;" (2) Asian firms appear to have a competitive advantage in the manufacturing process, which is similar for small lithium-ion batteries and the larger ones manufactured for vehicles; and (3) some U.S. researchers now look to Asia for opportunities to pursue innovation in lithium-ion batteries. While some experts felt that "the jury is still out" on future U.S. success in this area—or that new versions of lithium-ion batteries requiring different manufacturing processes would present new opportunities—others were less positive.[10]

- **Semiconductors:** The diffusion of semiconductor[11] chips with nanoscale features is pervasive in this $300-billion industry, and the technology continues to evolve. For example, production of a number of the components in semiconductors currently takes place at the nanoscale—that is, at scales of less than 100 nanometers (nm). In 2012, semiconductors with features spaced 22 nm apart and with layers just a few nanometers in thickness entered high-volume production. As previously noted, further advances and more innovations in nanotechnology—such as the use of a new generation of nanomaterials in conjunction with 3D chip architecture and optical interconnects—or other novel approaches may be needed for continuous improvement in future decades. Experts told us that the United States is dominant in the design of new advances in

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[10] However, according to recent news reports, Tesla Motors Inc.—an American manufacturer of all electric vehicles—has announced plans to construct a new plant to manufacture batteries in the United States for its vehicles.

[11] A semiconductor is the generic term for the various devices and integrated circuits that regulate and provide a path for electrical signals. As such, semiconductors are the foundation of the electronics industry.

semiconductors. However, they also said that U.S. manufacturing in this area has declined (although some plants are located here) and that the United States does not have a strategy to assure U.S. leadership in the semiconductor industry.

- **Nano-based concrete:** Concrete is the most heavily used construction material in the world—with about 5-billion cubic yards annually produced worldwide—and demand for it is expected to increase to meet the infrastructure needs of a growing global population. Nanomaterials can enhance the performance of the concrete used to construct this infrastructure. These materials might potentially result in roads, bridges, buildings, and structures that are more easily built, longer-lasting, and better-functioning than those that currently exist. Experts offered differing views on U.S. global competitiveness in the commercialization and use of nanomaterials in concrete. A key forum participant said that while cement for domestic use is produced in the United States, today's dominant companies—which are spearheading development of new technologies—are headquartered elsewhere (although this industry was previously dominated by the United States). Additionally, some experts said that other countries are spending more resources than the United States to promote commercialization; for example, one expert said that China established a national technology center to improve its competitiveness and domestic production of high-value, nano-based construction products. On the positive side, chemical admixtures are one means to introduce nano-materials into concrete—and the United States has a 15% market share of chemical sales, worldwide.

Key Challenges Facing U.S. Nanomanufacturing

According to forum participants and experts interviewed, challenges to U.S. competitiveness in nanomanufacturing include U.S. funding gaps, significant global competition, and lack of a U.S. vision for nanomanufacturing, among others.

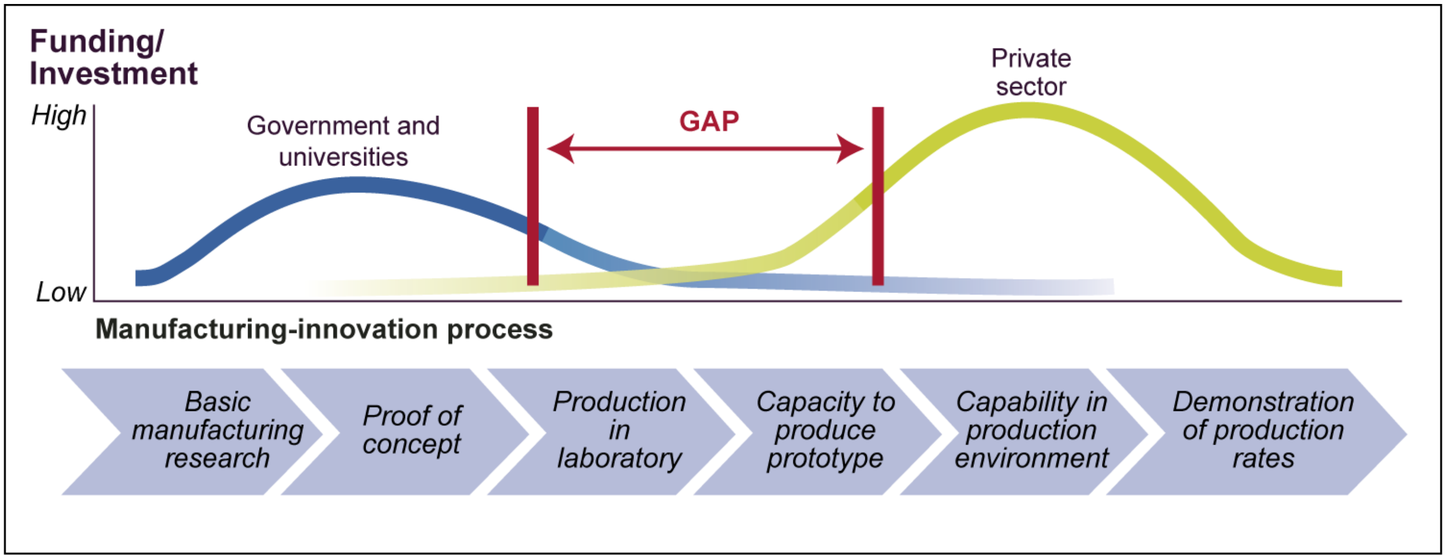
U.S. Funding Gaps and Possibly a Diversion of Venture Capital

Participants said that in the United States, government often funds research or the initial stages of development, whereas industry typically invests in the final stages. As a result, U.S. innovators may find it difficult to obtain either public funding or private investment during the middle stages of innovation. For nano-innovators, this support gap can characterize the middle stages of both (1) efforts to develop a new technology or product, and/or (2) efforts to develop a new manufacturing process. Thus, U.S. innovators may encounter two support gaps, which participants termed:

- the ***Valley of Death*** (the lack of funding or investment for the middle stages of developing a technology or product), and
- the ***Missing Middle*** (a similar lack of adequate support for the middle stages of *developing a process or an approach to manufacture the new product at scale*).

The *Valley of Death* begins after a new technology or product has been validated in a laboratory environment and continues through testing and demonstration as a prototype in a non-laboratory environment (but before industry acquires it as a commercial technology or product). The *Missing Middle* occurs during analogous stages of the manufacturing-innovation process, as illustrated below (fig.2). Participants further said that substantial amounts of funding/investment are needed to bridge the *Valley of Death* and the *Missing Middle*—and that high costs can be a barrier to commercialization, especially for small and medium-sized U.S. enterprises.

Figure 2: Missing Middle: Funding/Investment Gap in the U.S. Manufacturing-Innovation Process



Source: GAO, adapted from Executive Office of the President (2012, 21).

Additionally, some said that recently, venture capital (VC) funding has been diverted from physical science areas like nanotechnology to fund new ventures in Internet services that may provide larger and faster returns on investment.

Significant Global Competition

Varied forum participants and experts interviewed made statements to the effect that other nations do more than the United States in terms of government investment in technology beyond the research stage. According to participants, the funding and investment gaps that hamper U.S. nano-innovation (such as the *Missing Middle*) do not apply to the same extent in some other countries—for example, China and Russia—or are being addressed. Multiple participants referred to the European Commission's upcoming Horizon 2020 program, specifically mentioning a key program within Horizon 2020: the European Institute of Innovation and Technology or EIT, which emphasizes the nexus of business, research, and higher education. The 2014-2020 budget for the EIT portion of this European Commission initiative is €2.7 billion (or close to $3.7 billion in U.S. dollars as of January 2014).

Lack of a U.S. Vision for Nanomanufacturing

Multiple forum participants said that the United States lacks a vision or strategy for a nanomanufacturing capability.[12] However, one explained that such a strategy could be designed by (1) proceeding from a vision or goal to the examination of the social, technological, economic, environmental, and political elements of the relevant systems and their interactions with one another; (2) understanding the basic science, engineering, and manufacturing involved; and (3) consulting the full range of stakeholders. This participant said that although systems thinking and the design of a grand strategy, based on a vision, are often employed following a crisis that motivates a nation, such an effort could be usefully pursued in advance of a crisis, using foresight. Such an effort would reflect the statements of another participant who said, in effect, that the future of nanomanufacturing for the United States is limited only by our ability to envision what we want to see realized. This approach would likely draw upon the U.S. federal government to develop and articulate the strategy—in coordination with industry, academia, nonprofits, and state and local governments. Additionally, some federal effort is implied for implementation, but the level of funding and the mix of funding

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[12] Our post-forum communication with an official at the National Science Foundation indicated that although NSF currently funds some centers that focus on new concepts and the development of methods for nanomanufacturing, there is, at this time, no program devoted to supporting nanomanufacturing centers such as these.

sources (not specifically discussed at the forum) would likely be specified as part of developing a vision and strategy for nanomanufacturing.[13]

Other Competitiveness Challenges

Forum participants described further challenges to U.S. competitiveness in nanomanufacturing, including

- the earlier loss of an industry, as discussed above for lithium-ion batteries—or even extensive prior offshoring in some industries, which can be important, in part because, as one participant said: “when we design here [and] ship [manufacturing] abroad, we lose this shop-floor-innovation kind of mentality” and
- threats to U.S. intellectual property on the part of some other countries or entities within those countries—which occur with respect to both university research and private R&D on, for example, manufacturing processes.

Some Key Policy Issues Concerning Nanomanufacturing

Forum participants suggested the need to address policy issues in U.S. research funding, challenges to U.S. competitiveness in nanomanufacturing, and other areas, including environmental, health, and safety (EHS) issues.

U.S. research funding. Forum participants said it is essential for the United States to maintain a high level of investment in fundamental nanotechnology research. This is because (1) some other countries are now making significant investments in R&D and (2) ongoing research breakthroughs will drive the future of nanomanufacturing. One participant emphasized that as nanotechnology increasingly moves into manufacturing, it may be important to consider not only continuing funding for fundamental nanotechnology research, but also targeting some funding to *early stage research on nanomanufacturing processes*.

Challenges to U.S. competitiveness in nanomanufacturing. Forum participants said the United States could improve U.S. competitiveness in nanomanufacturing by pursuing one or more of three approaches, which

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[13] This approach (developing a vision and strategy for U.S. nanomanufacturing) is briefly revisited later in this testimony.

might be viewed either as alternatives or as complementary approaches.[14] These three approaches are described in table 1, below.

Table 1: Three Approaches to Enhancing U.S. Competitiveness in Nanomanufacturing—Proposed Actions and Rationale

Approach	Proposed actions	Rationale
1. strengthen innovation across the U.S. economy	Continue or update policies and programs that help strengthen innovations generally—for example, education and infrastructure.	The U.S. government often acts to supply goods and services critical to innovation when private markets fail to do so; beyond these measures, firms are better able to decide how to allocate resources.
2. promote innovation in U.S. manufacturing	Establish U.S. centers, encourage clusters, or design programs to address the *Valley of Death* or the *Missing Middle* (gaps in U.S. funding or investment).[a]	A strong manufacturing base is essential to the economy and to innovation itself. Addressing the *Valley of Death* and the *Missing Middle* will "level the playing field" and avoid other adverse effects.
3. design a grand strategy for U.S. nanomanufacturing	Define a vision for U.S. manufacturing. Design a grand strategy for achieving this vision—an effort that might be led by the federal government.	Nanomanufacturing may be a future general purpose technology (GPT) and thus is potentially classifiable as a public good with anticipated benefits for the entire society—justifying targeted federal support. It may also create jobs.

Source: GAO analysis of forum information.

[a] Two public-private partnerships that focus specifically on nanomanufacturing are the NASCENT Center at the University of Texas at Austin and the College of Nanoscale Science and Engineering (CNSE) at New York State University, which are discussed later in this testimony.

Other policy areas identified. Forum participants also identified

- the need to remedy the currently insufficient effort by the United States to participate in the international development of basic nanotechnology standards;
- concerns about the reliability of international investment information—and a possible pathway forward: convening international conferences on public investment and other related data; and
- the need for a revitalized, integrative, and collaborative approach to environmental, health, and safety (EHS) issues.

With respect to the third point, above, forum participants said that significant research is needed to discern or anticipate EHS implications of manufacturing with nanomaterials and using nanotechnologies. Participants noted the presence of significant funding—both governmental and private—for nanotechnology research, but one participant suggested that relatively little funding supports research on

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[14] We note that some advocates of particular approaches have raised objections to the others.

EHS implications, an observation that is consistent with our previous reporting on the National Nanotechnology Initiative (GAO, 2012).

Examples of Public-Private Partnerships Designed to Promote Innovation in Nanomanufacturing

Two examples of U.S. public-private partnerships that are designed to promote innovation in nanomanufacturing are housed in universities.[15] A related example with similar goals is a user facility that is located within a federal laboratory.

The NASCENT Center

The Center for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies (NASCENT) was founded at the University of Texas at Austin in 2012, with funding from NSF. Two key objectives are:

- to create processes and tools for manufacturing nano-enabled components for mobile computing, energy, healthcare, and security—as well as simulations for testing potential nanomanufacturing approaches, and
- to provide an ecosystem with computational and manufacturing facilities—for example, large-area wafer-scale and roll-to-roll nanomanufacturing,[16] as well as the university's resources, including faculty, staff, and students.

The Center's overall goal is to facilitate the rapid creation and deployment of new products and to mitigate the risks associated with the *Valley of Death* and the *Missing Middle*. A co-director of NASCENT told us that another goal is to use "10 years of NSF funding to develop the center infrastructure so it will . . . [become] self-supported from industrial partnerships and other [non-NSF] funding sources." Center partners include

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[15] Government funding for one of the university-based centers is provided by a federal grant from the National Science Foundation. For the other, the government portion of the funding is provided primarily by a state government.

[16] See Morse (2011).

- industrial partners—such as toolmakers, materials suppliers, and device makers—that will provide both technical and financial support;
- companies ranging from start-ups to well-established firms that will implement or adopt technology created by the center; and
- “translational research partners” such as technology incubators and technology funds.

The College for Nanoscale Science and Engineering

The College of Nanoscale Science and Engineering (CNSE), established in 2004, is part of the State University of New York and is located in Albany—within the existing regional (Hudson Valley) ecosystem centered on the semiconductor industry. CNSE is designed as a unique research, development, prototyping, and educational public-private partnership for advancing nanotechnology. A chief CNSE partner is SEMATECH—a global consortium of major computer chip manufacturers that coordinates cutting-edge R&D projects on semiconductors and is headquartered at CNSE. CNSE has more than 300 members and strategic partners that include large U.S.- and non-U.S.-headquartered private companies such as IBM, Intel, Samsung, and Global Foundries; small and medium-sized companies; universities from across the United States; and regional community colleges and economic development organizations, as well as government-agency sponsors. CNSE facilities allow the development of semiconductors just short of mass production—which is relevant for companies attempting to transition from an innovative concept to a prototype and to prepare for large-scale production. CNSE has developed models of pre-competitive collaboration among its partners, which use high-tech CNSE equipment that would be too costly for many individual companies to purchase.

The Center for Nanoscale Science and Technology

The Center for Nanoscale Science and Technology (CNST) is hosted by a federal laboratory at the National Institute of Standards and Technology (NIST). CNST is a user facility with baseline sponsorship through the Department of Commerce, which is augmented by external commercial funds in the form of user fees paid by industry, academia, government labs, and states. CNST supports the U.S. nanotechnology enterprise from discovery to production by providing industry, academia, NIST, and other government agencies access to world-class nanoscale measurement and fabrication methods and technology. The CNST’s shared-use nanotechnology-fabrication capability (called NanoFab) gives researchers economical access to and training on a commercial state-of-the-art tool set required for cutting-edge nanotechnology development. The simple application process is designed to get projects started in a few weeks.

Looking beyond the current commercial state of the art, the CNST's nanotechnology-metrology capability offers opportunities for researchers to collaborate on creating and using the next generation of nanoscale measurement instruments and methods.

Concluding Remarks

Based on the views of a wide range of experts, nanoscale control and fabrication are creating important new opportunities for our nation—as well as the need not only to recognize challenges, but also, where challenges exist, to act in response to them. The United States leads in some areas of nanomanufacturing, but faces increasing international competition. Challenges specific to U.S. competitiveness include, among others:

- the U.S. funding gap known as the *Missing Middle*,
- possible weaknesses associated with prior extensive offshoring in some U.S. industries, and
- the lack of a national vision and strategy for the United States to lead or sustain a high level of competitiveness in global nanomanufacturing markets in the years ahead.

Experts outlined three main approaches for responding to these challenges: (1) reviewing and renewing policies that undergird U.S. innovation; (2) supporting public-private partnerships that address U.S. funding gaps—especially as these apply to nanomanufacturing; and (3) defining a vision and strategy for achieving and sustaining a high level of U.S. competitiveness in nanomanufacturing. The potential benefit that experts see in pursuing forward-looking approaches such as these is to help chart a favorable course for the global economic position of the United States as we move further into the twenty-first century.

Chairman Bucshon, Ranking Member Lipinski, and Members of the Committee, this concludes my statement. I would be happy to answer any questions you may have.

GAO Contacts and Staff Acknowledgments

If you or your staff have any questions about this testimony, please contact me at (202) 512-5648 or personst@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this testimony. GAO staff members who made key contributions to this testimony include Judith Droitcour, Assistant Director, and Eric M. Larson, Analyst-in-Charge.

Appendix I: List of Forum Participants

Gene L. Dodaro (Host), Comptroller General of the United States

George Allen, Former U.S. Senator and former Governor of Virginia

Tina Bahadori, Environmental Protection Agency

Sarbajit Banerjee, University at Buffalo, State University of New York

Lynn L. Bergeson, Bergeson & Campbell PC

Bjorn Birgisson, KTH Royal Institute of Technology

Bill Canis, Congressional Research Service

Vicki L. Colvin, Rice University

Joseph DeSimone, University of North Carolina

Bart Gordon, Former Chairman, Committee on Science and Technology, U.S. House of Representatives, and Partner at K&L Gates LLP

John Ho, QD Vision, Inc.

Hamlin M. Jennings, Massachusetts Institute of Technology

Brian David Johnson, Intel Corporation

Michael Liehr, College of Nanoscale Science and Engineering, State University of New York

Scott E. McNeil, Frederick National Laboratory for Cancer Research, and Science Applications International Corporation

Manish Mehta, National Center for Manufacturing Sciences

Celia Merzbacher, Semiconductor Research Corporation

Michael F. Molnar, Advanced Manufacturing National Program Office and the National Institute of Standards and Technology

Matthew Nordan, Venrock

Susan E. Offutt, U.S. Government Accountability Office

Timothy M. Persons, U.S. Government Accountability Office

James M. Phillips, NanoMech Corporation

Robert Pohanka, National Nanotechnology Coordination Office

David Rejeski, Woodrow Wilson International Center for Scholars

Mihail C. Roco, National Science Foundation

Sheila R. Ronis, Walsh College

Françoise Roure, Organisation for Economic Co-operation and Development

Paul Schulte, Centers for Disease Control and Prevention

Charles Wessner, The National Academies

Appendix II: Examples of General Purpose Technologies

Era	Event	Era	Event
9000–8000 BC	Domesticated plants	1800s	Railway
8500–7500 BC	Domesticated animals		Iron steamship
8000–7000 BC	Smelting of ore		Internal combustion engine
4000–3000 BC	Wheel		Electricity
3400–3200 BC	Writing	1900s	Motor vehicle
2800 BC	Bronze		Airplane
1200 BC	Iron		Mass-production, continuous-process factory
Early Medieval	Waterwheel		Computer
1400s	Three-masted sailing ship		Lean production
1500s	Printing		Internet
Late 1700s–early 1800s	Steam engine		Biotechnology
	Factory system	Early 2000s	Nanotechnology[a]

Source: Lipsey et al. (2005, 132).

Note: Lipsey et al. (2005, 98) define a general purpose technology as “a single generic technology, recognizable as such over its whole lifetime, that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects.”

[a] ”Nanotechnology has yet to make its presence felt as a general purpose technology, but its potential is so obvious and developing so quickly that we [Lipsey et al.] are willing to accept that it is on its way to being one of the most pervasive general purpose technologies of the 21st century” (Lipsey et al. 2005, 132).

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