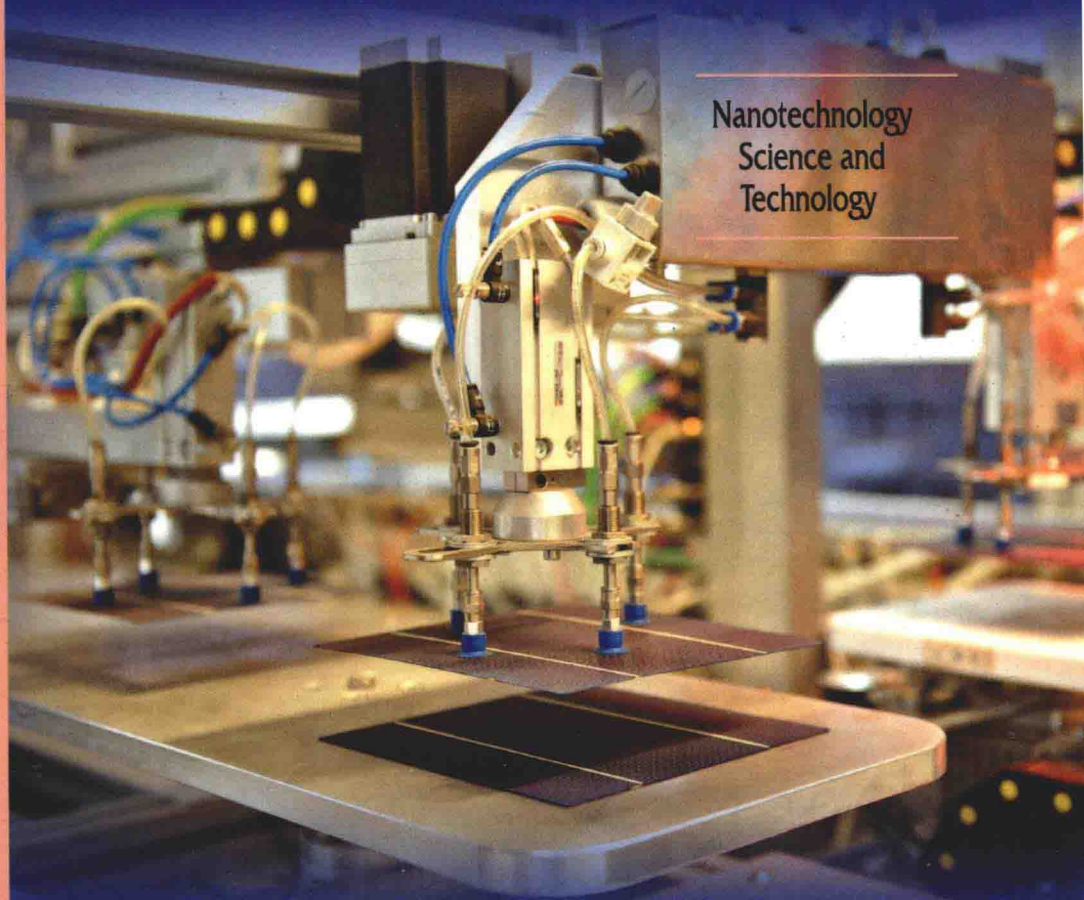
Nanomanufacturing

An Emerging Megatrend and Implications for the United States



Nanotechnology Science and Technology

Brad D. McReynolds
Editor

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NANOTECHNOLOGY SCIENCE AND TECHNOLOGY

NANOMANUFACTURING

AN EMERGING MEGATREND AND IMPLICATIONS FOR THE UNITED STATES

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NANOTECHNOLOGY SCIENCE AND TECHNOLOGY

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PREFACE

Nanoscale science, engineering, and technology—commonly referred to collectively as nanotechnology—is believed by many to offer extraordinary economic and societal benefits. Congress has demonstrated continuing support for nanotechnology and has directed its attention primarily to three topics that may affect the realization of this hoped for potential federal research and development (R&D) in nanotechnology; U.S. competitiveness; and environmental, health, and safety (EHS) concerns. This book provides an overview of these topics, and two others which are nanomanufacturing, and public understanding of and attitudes toward nanotechnology.

Chapter 1 - Nanoscale science, engineering, and technology—commonly referred to collectively as nanotechnology—is believed by many to offer extraordinary economic and societal benefits. Congress has demonstrated continuing support for nanotechnology and has directed its attention primarily to three topics that may affect the realization of this hoped for potential: federal research and development (R&D) in nanotechnology; U.S. competitiveness; and environmental, health, and safety (EHS) concerns. This report provides an overview of these topics and two others: nanomanufacturing and public understanding of and attitudes toward nanotechnology.

The development of this emerging field has been fostered by significant and sustained public investments in nanotechnology R&D. Nanotechnology R&D is directed toward the understanding and control of matter at dimensions of roughly 1 to 100 nanometers. At this size, the properties of matter can differ in fundamental and potentially useful ways from the properties of individual atoms and molecules and of bulk matter. Since the launch of the National Nanotechnology Initiative (NNI) in 2000 through FY2013, Congress has

appropriated approximately $18 billion for nanotechnology R&D. President Obama has requested $1.7 billion in NNI funding for FY2014. More than 60 nations have established similar programs. In 2010, total annual global public R&D investments reached an estimated $8.2 billion, complemented by an estimated private sector investment of $9.6 billion. Data on economic outputs used to assess competitiveness in mature technologies and industries, such as revenues and market share, are not available for assessing nanotechnology. Alternatively, data on inputs (e.g., R&D expenditures) and non-financial outputs (e.g., scientific papers, patents) may provide insight into the current U.S. position and serve as bellwethers of future competitiveness. By these criteria, the United States appears to be the overall global leader in nanotechnology, though some believe the U.S. lead may not be as large as it was for previous emerging technologies.

Some research has raised concerns about the safety of nanoscale materials. There is general agreement that more information on EHS implications is needed to protect the public and the environment; to assess and manage risks; and to create a regulatory environment that fosters prudent investment in nanotechnology-related innovation. Nanomanufacturing—the bridge between nanoscience and nanotechnology products—may require the development of new technologies, tools, instruments, measurement science, and standards to enable safe, effective, and affordable commercial-scale production of nanotechnology products. Public understanding and attitudes may also affect the environment for R&D, regulation, and market acceptance of products incorporating nanotechnology.

In 2003, Congress enacted the 21st Century Nanotechnology Research and Development Act (P.L. 108-153) providing a legislative foundation for some of the activities of the NNI, addressing concerns, establishing programs, assigning agency responsibilities, and setting authorization levels. Efforts to reauthorize the act have been unsuccessful. As of the date of this report, no reauthorization legislation had been introduced in the 113th Congress. In October 2013, the ranking member of the House Committee on Science, Space, and Technology circulated a draft reauthorization of the America COMPETES Act that included a "Reauthorization of the National Nanotechnology Initiative" subtitle. The majority version of the 2013 America COMPETES Act reauthorization bill does not include a nanotechnology reauthorization provision.

Chapter 2 - 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.

The U.S. National Nanotechnology Initiative (NNI), begun in 2001 and focusing primarily on R&D, represents a cumulative investment of almost $20 billion, including the request for fiscal year 2014. As research continues and other nations increasingly invest in R&D, nanotechnology is moving from the laboratory to commercial markets, mass manufacturing, and the global marketplace—a trend with potential future import that some compare to history's introduction of technologies with major economic and societal impact, such as plastics and even electricity. Today, burgeoning markets, innovation systems, and nanomanufacturing activities are increasingly competitive in a global context—and the potential EHS effects of nanomanufacturing remain largely unknown.

At the July 2013 forum, participants from industry, government, and academia discussed the future of nanomanufacturing; investments in nanotechnology R&D and challenges to U.S. competitiveness; ways to enhance U.S. competitiveness; and EHS concerns. Participants reviewed a summary of forum discussions, and two experts (who did not attend the forum) independently reviewed a draft of this report. Their comments were incorporated in this report as appropriate.

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Chapter 1

NANOTECHNOLOGY: A POLICY PRIMER*

John F. Sargent Jr.

SUMMARY

Nanoscale science, engineering, and technology—commonly referred to collectively as nanotechnology—is believed by many to offer extraordinary economic and societal benefits. Congress has demonstrated continuing support for nanotechnology and has directed its attention primarily to three topics that may affect the realization of this hoped for potential: federal research and development (R&D) in nanotechnology; U.S. competitiveness; and environmental, health, and safety (EHS) concerns. This report provides an overview of these topics and two others: nanomanufacturing and public understanding of and attitudes toward nanotechnology.

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* This is an edited, reformatted and augmented version of a Congressional Research Service publication, CRS Report for Congress RL34511, from www.crs.gov, prepared for Members and Committees of Congress, dated December 16, 2013.

NNI funding for FY2014. More than 60 nations have established similar programs. In 2010, total annual global public R&D investments reached an estimated $8.2 billion, complemented by an estimated private sector investment of $9.6 billion. Data on economic outputs used to assess competitiveness in mature technologies and industries, such as revenues and market share, are not available for assessing nanotechnology. Alternatively, data on inputs (e.g., R&D expenditures) and non-financial outputs (e.g., scientific papers, patents) may provide insight into the current U.S. position and serve as bellwethers of future competitiveness. By these criteria, the United States appears to be the overall global leader in nanotechnology, though some believe the U.S. lead may not be as large as it was for previous emerging technologies.

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OVERVIEW

Congress continues to demonstrate interest in and support for nanotechnology due to what many believe is its extraordinary potential for delivering economic growth, high-wage jobs, and other societal benefits to the

nation. To date, the Science and Technology Committee in the House and Senate Committee on Commerce, Science, and Transportation have directed their attention primarily to three topics that may affect the United States' realization of this hoped for potential: federal research and development (R&D) investments under the National Nanotechnology Initiative (NNI); U.S. international competitiveness; and environmental, health, and safety (EHS) concerns. This report provides a brief overview of these topics—which are discussed in greater detail in other CRS reports[1]—and two other subjects of interest to Congress: nanomanufacturing and public attitudes toward, and understanding of, nanotechnology.

Nanotechnology research and development is directed toward the understanding and control of matter at dimensions of roughly 1 to 100 nanometers. At this size, the physical, chemical, and biological properties of materials can differ in fundamental and potentially useful ways from the properties of individual atoms and molecules, on the one hand, or bulk matter, on the other hand.

In 2000, President Clinton launched the NNI to coordinate federal R&D efforts and promote U.S. competitiveness in nanotechnology. Congress first funded the NNI in FY2001 and has provided increased appropriations for nanotechnology R&D in each subsequent year. In 2003, Congress enacted the 21st Century Nanotechnology Research and Development Act (P.L. 108-153). The act provided a statutory foundation for the NNI, established programs, assigned agency responsibilities, authorized agency funding levels for FY2005 through FY2008, and initiated research to address key issues.

Federal R&D investments are focused on advancing understanding of fundamental nanoscale phenomena and on developing nanomaterials, nanoscale devices and systems, instrumentation, standards, measurement science, and the tools and processes needed for nanomanufacturing. NNI appropriations also fund the construction and operation of major research facilities and the acquisition of instrumentation. Finally, the NNI supports research directed at identifying and managing potential environmental, health, and safety impacts of nanotechnology, as well as its ethical, legal, and societal implications.

Most current applications of nanotechnology are evolutionary in nature, offering incremental improvements in existing products and generally modest economic and societal benefits. For example, nanotechnology is being used in automobile bumpers, cargo beds, and step-assists to reduce weight, increase resistance to dents and scratches, and eliminate rust; in clothes to increase

stain- and wrinkle-resistance; and in sporting goods, such as baseball bats and golf clubs, to improve performance.

In the longer term, nanotechnology may deliver revolutionary advances with profound economic and societal implications. Potential applications discussed by the technology's proponents involve various degrees of speculation and varying time-frames. The examples below suggest areas where such possible revolutionary advances may emerge, and early research and development efforts that may provide insights into how such advances may be achieved.

- *Detection and treatment technologies for cancer and other deadly diseases.* Current nanotechnology disease detection efforts include the development of sensors that can identify biomarkers, such as altered genes, that may provide an early indicator of cancer. One approach uses carbon nanotubes and nanowires to identify the unique molecular signals of cancer biomarkers. Another approach uses nanoscale cantilevers—resembling a row of diving boards—treated with molecules that bind only with cancer biomarkers. When these molecules bind, the additional weight bends the cantilevers indicating the presence and concentration of these biomarkers. Nanotechnology holds promise for showing the presence, location, and/or contours of cancer, cardiovascular disease, or neurological disease. Current R&D efforts employ metallic, magnetic, and polymeric nanoparticles with strong imaging characteristics attached to an antibody or other agent that binds selectively with targeted cells. The imaging results can be used to guide surgical procedures and to monitor the effectiveness of non-surgical therapies in killing the disease or slowing its growth. Nanotechnology may also offer new cancer treatment approaches. For example, nanoshells with a core of silica and an outer metallic shell can be engineered to concentrate at cancer lesion sites. Once at the sites, a harmless energy source (such as near-infrared light) can be used to cause the nanoshells to heat, killing the cancer cells they are attached to.[2] Another treatment approach targets delivery of tiny amounts of a chemotherapy drug to cancer cells. In this approach the drug is encapsulated inside a nanoshell that is engineered to bind with an antigen on the cancer cell. Once bound, the nanoshell dissolves, releasing the chemotherapy drug, killing the cancer cell. Such a targeted delivery approach could reduce the amount of chemotherapy

drug needed to kill the cancer cells, reducing the side effects of chemotherapy.[3]

- *Clean, inexpensive, renewable power through energy creation, storage, and transmission technologies.* Nanoscale semiconductor catalysts and additives show promise for improving the production of hydrogen from water using sunlight. The optical properties of these nanoscale catalysts allow the process to use a wider spectrum of sunlight. Similarly, nanostructured photovoltaic devices (e.g., solar panels) may improve the efficiency of converting sunlight into electricity by using a wider spectrum of sunlight. Improved hydrogen storage, a key challenge in fuel cell applications, may be achieved by tapping the chemical properties and large surface area of certain nanostructured materials. In addition, carbon nanotube fibers have the potential for reducing energy transmission losses from approximately 7% (using copper wires) to 6% (using carbon nanotube fibers), an equivalent annual energy savings in the United States of 24 million barrels of oil.[4]
- *Universal access to clean water.* Nanotechnology water desalination and filtration systems may offer affordable, scalable, and portable water filtration systems. Filters employing nanoscale pores work by allowing water molecules to pass through, but prevent larger molecules, such as salt ions and other impurities (e.g., bacteria, viruses, heavy metals, and organic material), from doing so. Some nanoscale filtration systems also employ a matrix of polymers and nanoparticles that serve to attract water molecules to the filter and to repel contaminants.[5]
- *High-density memory devices.* A variety of nanotechnology applications may hold the potential for improving the density of memory storage and accelerate access speed to stored data.[6]
- *Higher crop yield and improved nutrition.* Higher crop yield might be achieved using nanoscale sensors that detect the presence of a virus or disease-infecting particle. Early, location-specific detection may allow for rapid and targeted treatment of affected areas, increasing yield by preventing losses.[7] Nanotechnology also offers the potential for improved nutrition. Some companies are exploring the development of nanocapsules that release nutrients targeted at specific parts of the body at specific times.[8]

- *Self-healing materials.* Nanotechnology may offer approaches that enable materials to "self-heal" by incorporating, for example, nanocontainers of a repair substance (e.g., an epoxy) throughout the material. When a crack or corrosion reaches a nanocontainer, the nanocontainer could be designed to open and release its repair material to fill the gap and seal the crack.[9]
- *Sensors that can warn of minute levels of toxins and pathogens in air, soil, or water.* Microfluidic and nanocantilever sensors (discussed earlier) may be engineered to detect specific pathogens (e.g., bacteria, virus) or toxins (e.g., sarin gas, hydrogen cyanide) by detecting their unique molecular signals or through selective binding with an engineered nanoparticle.[10]
- *Environmental remediation of contaminated sites.* The high surface-tovolume ratio, high reactivity, and small size of some nanoscale particles (e.g., nanoscale iron) may offer more effective and less costly solutions to environmental contamination. By injecting engineered nanoparticles into the ground, these characteristics can be employed to enable the particles to move more easily through a contaminated site and bond more readily with targeted contaminants.[11]

Nanotechnology is also expected by some to make substantial contributions to federal missions such as national defense, homeland security, and space exploration and commercialization.

U.S. private sector nanotechnology R&D is now estimated to be twice that of public funding. In general, the private sector's efforts are focused on translating fundamental knowledge and prototypes into commercial products; developing new applications incorporating nanoscale materials; and developing technologies, methods, and systems for commercial-scale manufacturing.

Many other nations and firms around the world are also making substantial investments in nanotechnology to reap its potential benefits. Between 2001 and 2004, more than 60 countries established nanotechnology programs at the national level.[12]

With so much potentially at stake, some Members of Congress have expressed interest and concerns about the U.S. competitive position in nanotechnology R&D and success in translating R&D results to commercial products. This has led to an increased focus on potential barriers to commercialization efforts, including the readiness of technologies, systems,