The cover picture suggests the integration of various nanotechnology-based solutions in the design of a blended hybrid-wing-body concept for future subsonic commercial aircraft. It represents a radical departure from conventional subsonic aircraft design. Mechanical and thermal insulation properties of the nanocomposite will allow for “morphing” airframe and propulsion structures that can change their shape or properties on demand to improve aerodynamic efficiency and respond to damage. Composite materials derived from low density, high strength carbon nanotube-based fibers and durable nanoporous matrixes will enable the production of ultra-lightweight multifunctional airframes and with embedded lightning strike protection. Nanotexturing will create surfaces that are naturally resistant to ice accretion thereby eliminating the need for runway deicing and in-flight ice mitigation. Replacement of heavy copper wiring cables with carbon nanotube wires will enable significant reductions in aircraft weight. Distributed autonomous networks of nanotechnology based state sensors powered by high efficiency energy harvesting (thermoelectric, piezoelectric, or photovoltaics) will enable real-time monitoring of the overall health and performance of the aircraft leading to reduced emissions and noise and improved safety. The design, developed by NASA and Massachusetts Institute of Technology, is for a 354 passenger aircraft that would be available for commercial use in 2030-2035 and would enable a reduction in aircraft fuel consumption by 54% over a Boeing 777 baseline aircraft. (Courtesy of NASA and MIT)
WTEC Panel Report on

Nanotechnology Research Directions for Societal Needs in 2020
Retrospective and Outlook

September 30, 2010

Editors
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R. D. Shelton
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**Nanotechnology Research Directions for Societal Needs in 2020**

**FOREWORD**

**Impacts, Lessons Learned, and International Perspectives for Nanotechnology to 2020**

The accelerating pace of discovery and innovation and its increasingly interdisciplinary nature leads, at times, to the emergence of converging areas of knowledge, capability, and investment; nanotechnology is a prime example. It arose from the confluence of discoveries in physics, chemistry, biology, and engineering around the year 2000. At that time, a global scientific and societal endeavor was initiated, focused by two key factors: (1) an integrative definition of nanotechnology based on distinctive behaviors of matter at the nanoscale and the ability to systematically control and engineer those behaviors,\(^1\) and (2) articulation of a long-term vision and goals for the transformative potential of nanotechnology R&D to benefit society\(^2\) that included a twenty-year vision for the successive introduction of four generations of nanotechnology products.\(^3\) The definition and long-term vision for nanotechnology paved the way for the U.S. National Nanotechnology Initiative (NNI), launched in 2000, and also inspired sustained R&D programs in the field by Japan, Korea, the European Community, Germany, China, and Taiwan. In fact, over 60 countries established nanotechnology R&D programs at a national level between 2001 and 2004. A new wave of R&D investments by Russia, Brazil, India, and several Middle East countries began after the second generation of nanotechnology products came to market about 2006. The U.S. nanotechnology commitment is significant: cumulative NNI funding since 2000 amounts to more than $12 billion, including about $1.8 billion in 2010, placing the NNI second only to the space program in terms of civilian science and technology investment.\(^4\)

This report outlines the foundational knowledge and infrastructure development achieved by nanotechnology in the last decade and explores the potentials of the U.S. and global nanotechnology enterprise to 2020 and beyond. It aims to redefine the R&D goals for nanoscale science and engineering integration, and to establish nanotechnology as a general-purpose technology in the next decade. The vision for the future of nanotechnology presented here draws on scientific insights from U.S. experts in the field, examinations of lessons learned, and international perspectives shared by participants from 35 countries in 5 international brainstorming meetings hosted or co-hosted by the principal authors of this report.\(^5\) The report was peer reviewed and received input from various stakeholders’ public comments at the website [http://wtec.org/nano2/](http://wtec.org/nano2/). It aims to provide decision makers in academia, industry, and government with a nanotechnology community perspective of productive and responsible paths forward for nanotechnology R&D.

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\(^5\) For more information, see Appendix A. U.S. and International Workshops.
Only ten years after adopting the definition and long-term vision for nanotechnology, the NNI and other programs around the world have achieved remarkable results in terms of scientific discoveries that span better understanding of the smallest living structures, uncovering the behaviors and functions of matter at the nanoscale, and creating a library of nanostructured building blocks for devices and systems. Myriad R&D results include technological breakthroughs in such diverse fields as advanced materials, biomedicine, catalysis, electronics, and pharmaceuticals; and expansion into new fields such as energy resources and water filtration, agriculture and forestry, and integration of nanotechnology with other emerging areas such as quantum information systems, neuromorphic engineering, and synthetic and system nanobiology. New fields have emerged such as spintronics, plasmonics, metamaterials, and molecular nanosystems. “Nanomanufacturing” is already under way and is a growing economic focus. Nanotechnology has come to encompass a rich infrastructure of multidisciplinary professional communities, advanced instrumentation, user facilities, computing resources, formal and informal education assets, and advocacy for nanotechnology-related societal benefit. Communication, coordination, research, and regulation efforts have gained momentum in addressing ethical, legal, and social implications (ELSI) and environmental, health, and safety (EHS) aspects of nanotechnology.

Many nanotechnology breakthroughs have begun to impact the marketplace: 2009 values for nanotechnology-enabled products are estimated at about $91 billion in the United States and $254 billion worldwide. Current developments presage a burgeoning economic impact: trends suggest that the number of nanotechnology products and workers worldwide will double every three years, achieving a $3 trillion market with 6 million workers by 2020. The governance mandate has broadened steadily so that in addition to promoting scientific discovery and technological innovation, it increasingly advances social innovation by proactively addressing many complex issues of responsible development of a new technology. Nanotechnology R&D has become a socio-economic target in all developed countries and in many developing countries—an area of intense international collaboration and competition.

And yet, nanoscale science, engineering, and technology are still in a formative stage, with most of their growth potential ahead and in still-emerging directions. Ambitious goals for several key scientific achievements over the next decade include an increase of about 5,000 times in X-ray source brilliancy for direct measurement of nanostructures and of about 10,000 times in computational capabilities of nanostructures. Key areas of emphasis over the next decade are:

- Integration of knowledge at the nanoscale and of nanocomponents in nanosystems with deterministic and complex behavior, aiming toward creating fundamentally new products
- Better control of molecular self-assembly, quantum behavior, creation of new molecules, and interaction of nanostructures with external fields in order to build materials, devices, and systems by modeling and computational design
- Understanding of biological processes and of nano-bio interfaces with abiotic materials, and their biomedical and health/safety applications, and nanotechnology solutions for sustainable natural resources and nanomanufacturing
- Governance to increase innovation and public-private partnerships; oversight of nanotechnology safety and equity building on nascent models for addressing EHS, ELSI, multi-stakeholder and public participation; and increasing international collaborations in the process of transitioning to new generations of nanotechnology products. Sustained support for education, workforce preparation, and infrastructure all remain pressing needs
Overall, it is predicted that continuing research into the systematic control of matter and a focus on innovation at the nanoscale will accelerate in the first part of the next decade, especially in the next five years, underpinning a growing revolution in technology and society. Nanotechnology already is having a major impact in the development of many sectors, ranging from electronics to textiles; by 2020, it will be a broad-based technology, seamlessly integrated with most technologies and applications used by the masses, driven by economics and by the strong potential for achieving previously unavailable solutions in medicine, productivity, sustainable development, and human quality of life.
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