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## NASA'S RELATIONSHIP WITH NANOTECHNOLOGY: PAST, PRESENT, AND FUTURE CHALLENGES

### INTRODUCTION

For more than 50 years, NASA has strived “to reach for new heights and reveal the unknown so that what we do and learn will benefit all humankind” (NASA 2010a). While areas such as robotic exploration, space-based astronomy, Earth observation, and aeronautics have all played a role at NASA, much of its vision and fiscal focus has centered on manned space activities.

Historically, NASA received a moderate budget dedicated to basic and applied research and development (R&D) in support of its efforts to develop a program with far-reaching effects on Earth as well as in space. From 1970 through 2000, NASA was a major center for basic research in climate science, materials engineering, and laser physics in addition to more applied fields in aeronautics and space exploration. During the late 1990s, NASA began to expand its research efforts toward nanotechnology, a broad field that holds tremendous potential for improving spaceflight by reducing the weight of spacecraft and developing smaller and more accurate sensors.

NASA is primarily responsible for cultivating the necessary technologies for successful space-bound endeavors. It focuses on the planning, execution, and completion of specific missions in space. This sets it apart from many U.S. federal science agencies that often support open-ended scientific research. For instance, the National Science Foundation (NSF) funds basic science research and educational outreach while the National Institutes of Health (NIH) funds biomedical studies.

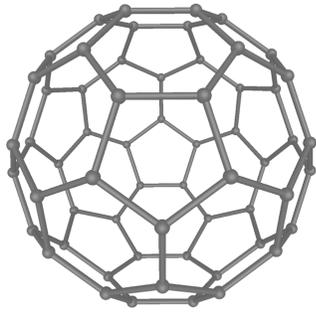
In this report, we review the history of nanotechnology R&D at NASA over the past 15 years. We use nanotechnology to illustrate how

NASA has guided new technology development at its own research facilities and through collaborations with university scientists and laboratories. In particular, nanotechnology serves as an ideal case study of emerging technology development in NASA's long struggle to translate research projects into viable technologies.

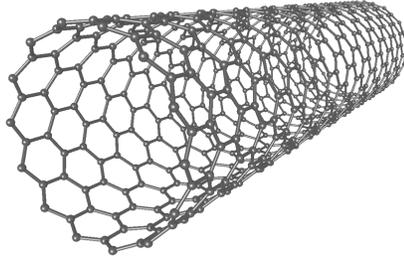
### OVERVIEW OF NANOTECHNOLOGY

Nanotechnology is the study and manipulation of materials on a nanometer-length scale, or the equivalent of one-billionth of a meter. The difference in scale between a nanometer and a meter is roughly comparable to the circumference of a marble versus the circumference of the Earth. In nanoscale systems, the properties of individual or small collections of atoms and molecules become relevant. This often leads to uniquely functional applications not available in their macroscopic equivalents. Nano-engineered devices are designed to exploit the ultralight, ultrastrong, and multifunctional nature of submicroscopic materials—a crucial benefit for space exploration, where weight and physical space are supremely important.

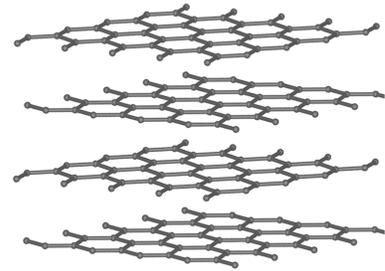
Theoretical physicist Richard Feynman described nanotechnology in 1959. But significant work in the field did not begin until the early 1980s, when three notable advancements in sub-micrometer science were announced: the development of the scanning tunneling microscope (STM) at IBM Research-Zurich in 1981; the discovery of the “buckyball,” or C<sub>60</sub>, in 1985; and the invention of the atomic force microscope by Gerd Binnig, Ph.D., Calvin Quate, Ph.D., and Christoph Gerber, Ph.D., in 1986. The discovery of C<sub>60</sub>, made by a group of future Nobel Prize-



**A.**



**B.**



**C.**

**FIGURE 1.**

Three forms of nanoscale carbon: A)  $C_{60}$ , the “buckyball”; B) a single-walled carbon nanotube (CNT); and C) four sheets of graphene. Note: Each grey ball represents a single carbon atom, and the connecting grey tubes represent carbon-to-carbon bonds. Source for images: [http://en.wikipedia.org/wiki/File:Eight\\_Allotropes\\_of\\_Carbon.png](http://en.wikipedia.org/wiki/File:Eight_Allotropes_of_Carbon.png)

winning scientists led by Robert Curl, Ph.D., Harry Kroto, Ph.D., and the late Richard Smalley, Ph.D., uncovered an entirely new form of carbon known as fullerenes (Figure 1). Fullerene-based systems, including carbon nanotubes (CNT) and graphene, have proven to be particularly valuable in developing nanoscale circuitry, detectors, and novel materials due to their strength, thermal robustness, and extreme lightness (NASA 2012).

U.S. nanotechnology policy is overseen in Congress by the House Committee on Science, Space, and Technology and the Senate Committee on Commerce, Science, and Transportation through the National Nanotechnology Initiative (NNI) (Sargent 2012; Lane and Kalil 2005). Established in 2000 under President Bill Clinton, the NNI coordinates efforts among 26 federal agencies, 15 of which have congressionally appropriated nanotechnology R&D budgets. It also promotes international competitiveness in nano-based industries and informs political bodies on related matters, including health and safety concerns (NNI 2012). Within the executive branch, the Office of Science and Technology Policy (OSTP) manages federal nanotechnology R&D activities through the National Nanotechnology Coordination Office (NNCO), a cabinet-level office that communicates with NNI and provides additional public outreach on its behalf (Holdren 2012).

## **NANOTECHNOLOGY R&D AT NASA FROM 1996 TO PRESENT**

NASA was an early supporter of nanotechnology R&D. By the time NNI was created, NASA had already established the Center for Nanotechnology at the Ames Research Center northwest of San Jose, California. Over the past 15 years, research at Ames has focused on nanocarbon materials and nano-based sensors. This work has resulted in more than 350 nanotechnology-related scientific publications.

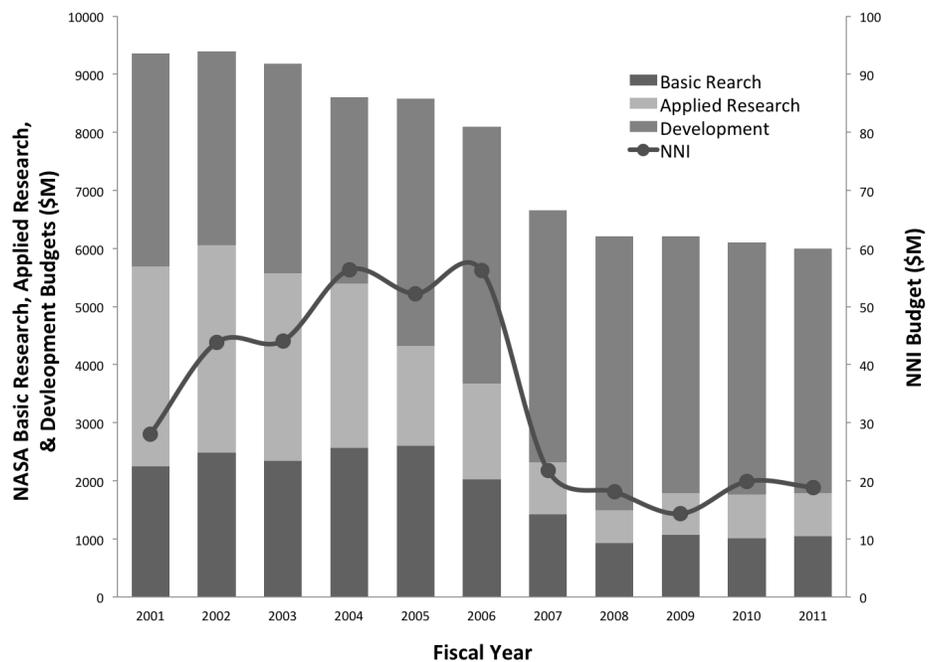
NASA administrator Daniel Goldin oversaw the creation of other nanotechnology efforts, such as at the Glenn and Langley Research Centers, as well as at the Johnson Space Center (JSC) (Venneri, Hirschbein, and Dastoor 2002). At Langley, an early effort in biomimetics, the field of developing mechanical devices or materials based on biological systems, began in 1998 and evolved into a nanotechnology program producing more than 110 publications and resulting in at least three patents. Glenn Research Center produced more than 200 publications, at least three patents, and two R&D 100 Awards—a highly regarded recognition of R&D innovation and advances given by *R&D Magazine*. All of these honors were predominately focused on novel nanomaterials as well as the utilization of nanotechnology for power and energy applications.

In addition to intramural research, NASA has sponsored collaborative projects with universities through its University Research, Engineering, and

Technology Institutes (URETIs). These university-led teams concentrated on cutting-edge research such as biologically inspired nanomaterials—materials created to act similarly to virus, cells, and proteins. Grants from this program were funded for a maximum of \$3 million per year for up to five years. In 2005, there were seven active URETIs, which focused on two camps: bio-inspired nanotechnology and reusable propulsion systems. The NASA URETI program has since been shut down, although many of the projects, most notably the Biologically Inspired Materials Institute at Princeton University and the Texas Institute for Intelligent Bio-Nano Materials and Structures for Aerospace Vehicles at Texas A&M University, have survived through other federally funded grants.

NASA also awarded grants to individual investigators outside of the URETI program. In 1998, the Applied Nanomaterials Group at JSC forged a five-year \$3.8 million collaboration with Smalley’s team for single-walled CNT research via a cooperative agreement. This early effort became a foundation for nanoscale carbon research, generating more than 85 patent applications, 123 publications, 20 Ph.D. theses, numerous commercial spin-offs, and follow-up investment by NASA and other government agencies. Smalley’s research increased CNT production from milligrams-per-day to grams-per-hour, and led to the initial standards for CNT quality control. Due to this success, in 2004 NASA pledged a further \$16 million to Smalley, JSC, and Glenn to develop lightweight, highly conductive “quantum wires” made from CNTs.

Support for nanotechnology began to decline after changes at NASA following the space shuttle *Columbia* accident in 2003. After the tragedy, The National Academies reviewed NASA’s space program and made recommendations for its future. In 2004, NASA received a new mission: President George W. Bush’s “Vision for Space Exploration” (VSE). The VSE called for a new vehicle architecture known as *Constellation*, which included the development of spacecraft to replace the space shuttle; the return to the moon by 2020; and a manned mission to Mars (NASA 2004). Unfortunately, the new directive



**FIGURE 2. TRENDS IN NASA & NNI RESEARCH AND DEVELOPMENT (CONSTANT 2012 DOLLARS)**

Basic research, applied research, and development totals at NASA from FY2001 to FY2011 compared to the NNI total budget. Source: NSF National Center for Science and Engineering Statistics (<http://www.nsf.gov/statistics/>) and the NNI supplement to the president’s budget (<http://www.nano.gov/about-nni/what/funding>)

did not come with additional funding for NASA. Instead it resulted in budget cuts for many other NASA projects, including much of its science and technology R&D (Abbey and Lane 2009). From 2003 to 2010, while the total federal science research budget remained steady between \$60 and \$65 billion (in constant 2012 dollars), NASA’s

research appropriations decreased more than 75 percent, from \$6.62 to \$1.55 billion (Figure 2) (American Association for the Advancement of Science [AAAS] 2012).

With decreased funding for research, NASA stopped work on many promising new technologies. Approximately 300 out of roughly 360 science programs were killed midstream. From 2004 to 2007, NASA reduced annual nanotechnology R&D expenditures from \$47 million to \$20 million, making it the only U.S. federal agency to scale back investment in this area (NNI 2012). The center at Ames rapidly downsized, from a peak of 60 researchers with an \$18 million budget, to approximately 10 researchers and a \$2 million budget funded largely by the U.S. Department of Defense (DOD).

After the inauguration of President Barack Obama in 2009, NASA’s mission and R&D investments in nanotechnology were reassessed by the Augustine Committee (Review of U.S. Human Spaceflight Plans Committee 2009). The final report proposed a number of alternative paths for NASA’s future, including the cancellation of a large part of the *Constellation* program; the completion of the International Space Station; a new emphasis on commercial solutions for in-orbit needs; the development of a new heavy-lift vehicle for future missions; and the revitalization of technology R&D. However, project-specific funding remained in limbo as battles over the FY2011 budget prolonged uncertainty over the allocation of NASA funds. After the budget was passed, short-term plans for manned space exploration were put on hold and the space shuttle was officially retired in 2011. In addition, the *Constellation* program was shut down with the exception of the *Orion* capsule, the crew exploration vehicle for traveling beyond low-Earth orbit. Additionally, due to overruns in the budget for the James Webb Telescope—an infrared space telescope—NASA ended U.S. involvement in another science mission, the European-led ExoMars project (a mission to search for possible biosignatures of life on Mars) when funding for the project was cut from Obama’s FY2013 budget. These decisions, however, did extend the lifetime of the International Space Station until 2020. In part due to the Augustine Committee report,

NASA R&D experienced a resurgence in funding totaling \$9.8 billion in FY2012, a 6 percent increase from FY2010 (AAAS 2012). In FY2013, NASA again restructured its science budget, adding the Space Technology Mission Directorate (STMD), which focuses on “developing breakthrough space capabilities and applications,” including several nano-based research initiatives. In addition to NASA’s increased investment in early-stage “game-changing technologies,” NNI reports a 29 percent increase in NASA nanotechnology-specific R&D in 2012—from \$17 million in 2011 to \$23 million in 2012—that was put toward developing next-generation nanomaterials and nanoscale systems (NNI 2012).

Nevertheless, funding fluctuations at NASA show how the space agency funds R&D. As priorities shift with each budget cycle or presidential term, projects can suddenly start and stop, often leading to partially completed research projects and wasted resources. Repeated program cancellations and the U.S. decision to abandon its manned spaceflight capability highlight a national space policy that fails to ensure the continuity of research and programs that build on existing work.

## CULTURE AND RESEARCH DIFFICULTIES

Maintaining consistent funding levels for high-risk, high-reward scientific R&D has long been a challenge for federal agencies (American Academy of Arts and Sciences 2008). NASA projects by their nature often require long-term investment and continuing technological development. Unfortunately, such research is often relegated to limited, unpredictable, and center-specific discretionary funds. Decentralized funding creates numerous issues, including needless competition and duplication between NASA centers and within the centers themselves. At one point, JSC had a “Microelectrical-mechanical Systems (MEMS) and Nanotechnology Initiative” and an “Applied Nanotechnology Project” competing simultaneously for funding for similar work. This form of competition also discourages communication and collaboration between the “mission” centers (such as JSC) that manage large programs, and the research centers (such as Ames) that specialize in technologies for future missions. Furthermore, uncertain financial support is also

an obstacle to long-term staffing of scientists and researchers, which, combined with poor communication and disorganization, interferes with program advancement.

The versatility of nanotechnology, with applications in areas such as medicine, energy, and materials, does not currently fit into NASA's center- and project-centric hierarchy. Outside of Ames, nanotechnology groups have generally been embedded in a specific branch at their center, effectively isolated from the many other areas of development that could benefit from nanoscale research. In addition, individual NASA centers are inconsistent in their implementation of cooperative agreements, grants, contracts, and other collaborations. Reaching an agreement may be easy at one center, but almost impossible at another. Differences also exist between individual centers and their collaborators in their approach to intellectual property rights and publishing research. For nanoscience to thrive and contribute to the space program, these processes must be simplified and made consistent.

While the success of nanotechnology can already be seen in various aeronautical and low-Earth orbit applications— from advancements in nanocomposites in the secondary structure of the F-35 aircraft to radiation-hardened memory for satellite applications—NASA has had little success applying its nanotechnology R&D to space applications (Yowell and Moloney, forthcoming). The agency successfully integrated nanomaterials developed by Lockheed Martin and Nanocomp Inc. into the *Juno* spacecraft (a robotic mission to Jupiter); however, these innovations were not a result of past NASA R&D efforts. The only example of NASA-developed nanotechnology being successfully applied to spaceflight is the integration of nanosensor technology into the International Space Station in January 2009. This sensor monitors air quality, particularly formaldehyde levels, in the crew cabin (Lu, Meyyappan, and Li 2011).

The bulk of potentially revolutionary nanotechnologies lost funding after 2005, while others have become trapped at the lower end of the nine-point Technology Readiness Level (TRL) scale used to track the maturation of all space-borne materials and technologies. Very few nanoscale technologies developed by the

agency have yet to pass the arduous qualification processes NASA has established for flight readiness. Additionally, due to difficulties implementing new technologies, many nanotechnological advancements are disregarded in favor of older, more familiar technologies. The abandoned nanotechnologies are either forgotten or are eventually co-opted by other entities; for example, the quantum wire project in Smalley's former group has since been revived by the Air Force Research Laboratory.

## THE FUTURE

In order for NASA to succeed in integrating more nanotechnology into spaceflight, the multiple parties governing NASA's budget and its allocation—NASA, the White House (Office of Management and Budget [OMB] and OSTP), and Congress—should establish a long-term plan for investment in basic materials and systems R&D and commit to developing efficient methods for technology transfer. To address R&D problems, NASA's Office of the Chief Technologist (OCT) set out to develop "Space Technology Roadmaps" to guide the agency as it seeks to resolve its most pressing technological needs (NASA 2010b).

NASA typically splits technology development into two categories: "push" and "pull." Historically, the bulk of NASA's research has fallen into the "pull" system, in which engineers request technologies to fit their specific needs. "Push" identifies more general research efforts that are pursued with no specific application in mind. With regard to nanotechnology R&D, "push" and "pull" often overlap; advancements in basic nano-based research can have major technological applications.

The OCT nanotechnology roadmap focuses on these early-stage, potentially transformative technologies by addressing their four principal benefits (push) and identifying five "grand challenges" (pull) that could resolve several major issues in modern spaceflight. The current draft of the OCT nanotechnology roadmaps, published in 2010, lists a series of exciting nanoscale technologies. These projects link NASA's efforts with the more general scientific and technological priorities of the Obama administration, which could stabilize and even increase funding for the agency's nanotechnology program. The OCT

roadmap report presents an in-depth review of four broad areas that nanotechnology could impact. Nanotechnology could reduce vehicle mass; improve functionality and durability of parts; enhance power generation and storage and propulsion; and improve astronaut health management. The OCT roadmap also details the current status, and the potential benefits, of each of the five “grand challenges” underway at NASA facilities: nano-enhanced propellants; nanoscale integrated circuits for power detection and high-speed electronics; nano-based energy harvesting and storage systems; and nanostructured composites for low-weight, high-strength secondary spacecraft components. Graphene-based systems, two-dimensional sheets of hexagonally-arranged carbon atoms, are specifically singled out as a grand challenge for applications in radiation-tolerant, high-speed nanoscale devices (Figure 1).

After their initial publication, The National Academies were requested to review the roadmaps and issued a report in 2011 (National Research Council [NRC] 2012). Using The National Academies’ recommendations, NASA plans to establish both short-term (3-5 year) and long-term (20-30 year) plans for all basic and applied R&D at its research facilities and flight centers. Additionally, NASA intends to regularly update its roadmaps as technologies advance and priorities change.

Unfortunately, the roadmaps neglect to make specific recommendations for funding allocations, funding structure, or possible collaborators. The roadmaps also could have served as an opportunity to address the aforementioned detrimental competition between and within centers, but do not. Furthermore, the roadmaps continue to replicate both the technical and programmatic disconnects between NASA’s research centers and its mission program developers. Overall, the OCT roadmaps lack the insights gleaned from the advances, mistakes, and difficulties of over a decade and \$285 million of previous nanotechnology investments.

Aside from the roadmap initiative, NASA’s OCT intends to emphasize longer-term grants—longer than NASA’s traditional one-year cycle—and funding opportunities for technology development. This promising effort, if

implemented, may help prevent a further loss of expertise within the agency as well as improve its industrial and academic collaborations. If NASA wants to engage academic partners, it should consider grant timeframes similar to those at the NSF and NIH, where the average grant duration lasts 3-5 years, rather than one to two years. Moreover, any successful R&D program effort by NASA should be restructured to encourage competition for the best technologies and solutions while rewarding collaboration between centers. This includes seeking peer-reviews of grants from outside the agency and choosing the most promising projects. OCT should also mitigate the unproductive competition between the individual NASA centers and emphasize idea-sharing.

## CONCLUSION

The United States currently lacks a national space policy that ensures the continuity of research and programs that build on existing capabilities to explore space, nor one that has defined steps for human and robotic exploration of low-Earth orbit, the moon, and Mars. With Congress and the president wrestling over the budget each year, it is vital that NASA present a clear plan for science and technology R&D that is linked to all aspects of the agency. This includes connecting R&D, with nanotechnology as a lead area, to applications related to the agency’s missions. Finalizing the roadmaps and long-term planning were crucial steps that brought all governing bodies of NASA to an agreement on its future. The outcome will depend on the extent of the roadmaps’ impact internally at NASA, and if the R&D departments and flight centers at NASA will implement the guidelines set forth by OCT as well as the more specific recommendations of The National Academies.

OCT is also attempting to improve collaboration between NASA and its academic and industrial partners. In order to effectively engage in new technology R&D, NASA should strengthen its research capacity and expertise by encouraging high-risk, high-reward projects to help support and shape future space exploration, and directing research projects based on the agency’s needs.

However, the current NASA plan fails to provide a particular destination in the cosmos. Without a destination, there is a lack of guidance both for the technologies required for the missions and the R&D NASA should be supporting. By defining future mission requirements and technology challenges and by supporting relevant R&D, NASA can better promote cooperation between programs and centers throughout the agency. NASA should restructure its organization of R&D programs through incentives that encourage competition between best-of-breed technologies, rather than allow the continuation of geographical or center-specific fiefdoms. Failure to make these changes, especially in a political climate of flat or reduced funding, poses substantial risk that the United States will lose its leadership role in space to other countries—most notably China, Germany, France, Japan, and Israel—that make more effective use of their R&D investments. Nanotechnology has the proven capability of revolutionizing most areas of technology that will be critical to NASA’s future missions. The agency needs a bolder plan for R&D to match the requirements of those missions and to recapture its place at the forefront of nanotechnology.

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