Defense Nanotechnology Research and Development Programs

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Department of Defense
Director, Defense Research and Engineering

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EXECUTIVE SUMMARY

The Department of Defense (DoD) has a long history of successfully supporting innovative nanotechnology research efforts for the future advancement of war fighter and battle systems capabilities. Since the 1980s, DoD - including the Defense Advanced Research Projects Agency (DARPA), Office of Naval Research (ONR), Army Research Office (ARO) and the Air Force Office of Scientific Research (AFOSR) - initiated numerous research programs focusing on advancing science and technology below one micron in size. Scientific breakthroughs and advances in the last few years demonstrate the potential for nanotechnology to impact a tremendous number of key aspects for future war fighting: chemical and biological warfare defense; reduction in weight of war fighting equipment; high performance materials for platforms and weapons; high performance information technology; energy and energetic materials; and uninhabited vehicles and miniature satellites.

In support of the National Nanotechnology Initiative, DoD is a member of the Nanoscale Science and Engineering Technology (NSET) subcommittee of the National Science and Technology Council's Committee on Technology. Twenty three federal departments and agencies are members of the NSET, including the Intelligence Community. The NSET meets bimonthly to coordinate the federal government's nanotechnology programs.

The DoD nanotechnology program is summarized by seven program component areas (PCAs), relating to areas of investment that are critical to accomplishing the overall goals of the National Nanotechnology Initiative (NNI): fundamental nanoscale phenomena and processes; nanomaterials; nanoscale devices and systems; instrumentation research, metrology, and standards for nanotechnology; nanomanufacturing; major research facilities and instrumentation acquisition; and societal dimensions. Significant progress has been made toward achieving the goals of these component areas, and the DoD is extremely well positioned to discover and exploit unique phenomena, which occur only at nanoscale dimensions, for the development of novel applications to enhance war fighter and battle systems capabilities.

The DoD investment in each of these seven program component areas is currently sufficient, given the overall DoD research and development budget and the investments being made by ten other government agencies including NSF, DOE, and NIH. In the future, additional investment from DoD is recommended in the areas of nanomaterials and nanomanufacturing. Increased nanomaterials research is recommended in order to enable robust incorporation and design of nanoscale phenomena into advanced materials for a broad spectrum of revolutionary target applications, and due to the fact that significant barriers continue to persist between the discovery of promising nanoscale phenomena and the realization of novel materials properties based on these phenomena. Added support for nanomanufacturing research is recommended by means of the Small Business Innovative Research (SBIR)/Small Business Technology Transfer (STTR) and Manufacturing Technology (MANTECH) programs in order to facilitate transitioning and a sustained supply of nanotechnology-based products for defense technologies. Additionally, while no additional funding support is recommended in the area of environmental health and safety aspects of nanotechnology, it is recommended that the DoD actively monitor this area in order to leverage the investments and expertise of major health agencies worldwide to identify potential health risks and implement optimal and appropriate safety practices for both war fighters and defense product developers.

I. Review of DoD Nanotechnology Programs

The DoD has a history of supporting research and development activities in order to meet its national security mission needs. Included in this effort is support for research in nanoscience and nanotechnology. In the early 1980s, DoD initiated the Ultra Submicron Electronics Research (USER) program that focused on electronic devices well below one micron. In the early 1990s, the Defense Advanced Research Projects Agency (DARPA) initiated a program called Ultra Electronics and Ultra Photonics (ULTRA) that focused on ultra fast and ultra dense electronic devices and chips and scaled photonic devices. At the same time, the Office of Naval Research (ONR) launched an Accelerated Research Initiative on interfacial nanostructures, and the Army Research Office (ARO) launched a nanoscience university research initiative. In the mid-1990s, ONR launched a program on nanostructured coatings, and DARPA launched the Simulation of Bio Systems (SIMBIOSYS) program to focus on bio-info-micro computing which has a major nanotechnology component. Since the mid-1990s, DoD has identified nanoscience as one of six Strategic Research Areas (SRAs) for basic research funding on a long-term basis.

The Fiscal Year 2003 National Defense Authorization Act, Section 246, requires the Director of Defense Research and Engineering (DDR&E) to submit an annual report on the nanotechnology programs within the Department of Defense (DoD) for fiscal years 2004, 2005, 2006, and 2007. These reports are to include the following: (1) A review of the long-term challenges and specific technical goals of the program, and the progress made toward meeting those challenges and achieving those goals; (2) An assessment of current and proposed funding levels, including the adequacy of such funding levels to support program activities; (3) A review of the coordination of activities within the Department of Defense, with other departments and agencies, and with the National Nanotechnology Initiative; (4) An assessment of the extent to which effective technology transition paths have been established as a result of activities under the program; and (5) Recommendations for additional program activities to meet emerging national security requirements.

The 21st Century Nanotechnology Research and Development Act (Public Law 108-153) called for the National Science and Technology Council (NSTC) to prepare a strategic plan for the Federal nanotechnology R&D program. In response to this mandate, the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC, with significant DoD member participation, prepared an updated National Nanotechnology Initiative (NNI) Strategic Plan in December 2004, which is expected to guide the NNI for the next five to ten years. The investment strategy described in the NNI Strategic Plan identifies and defines seven major subject categories of investment, or program component areas (PCAs), relating to areas of investment that are critical to accomplishing the overall goals of the NNI. Since these seven PCAs also constitute a comprehensive taxonomy of the DoD investment, the 2006 review of defense nanotechnology research and development programs will be organized by these PCAs:

1. Fundamental Nanoscale Phenomena and Processes
2. Nanomaterials
3. Nanoscale Devices and Systems
4. Instrumentation Research, Metrology, and Standards for Nanotechnology
5. Nanomanufacturing
6. Major Research Facilities and Instrumentation Acquisition
7. Societal Dimensions

A. Long Term Challenges and Program Goals

Since the DoD is a mission-oriented agency, its nanotechnology programs are distinguished from other federal agencies in that the program activities are simultaneously focused on scientific and technical merit and on potential relevance to DoD. The overall technical objective of these programs is to develop understanding and control of matter at dimensions of approximately 1 to 100 nanometers, where the physical, chemical, and biological properties may differ in fundamental and valuable ways from those of individual atoms, molecules, or bulk matter. The overall objective for DoD relevance is to discover and exploit unique phenomena at these dimensions to enable novel applications enhancing war fighter and battle systems capabilities. Specific long-term challenges and program goals for each of the seven nanotechnology program component areas are described below.

<u>Fundamental Nanoscale Phenomena and Processes</u>

NNI Long-Term Challenges: The discovery and development of fundamental knowledge pertaining to new phenomena in the physical, biological, and engineering sciences that occur at the nanoscale; the elucidation of scientific and engineering principles related to nanoscale structures, processes, and mechanisms.

DoD Program Goals include:

- To discover new phenomena and processes to enable breakthrough advantages for war fighter and battle systems capabilities.
- To develop robust strategies for synthesis, characterization, and assembly of individual nanostructures.
- To explore applications of nanostructures for revolutionary catalysis, scavengers, taggants, and sensors.
- To elucidate fundamental aspects of phonon and electron transport in individual nanowires and two and three dimensional nanostructures as they relate to the development of high performance thermoelectric, thermionic, and photovoltaic devices for advanced solid state power generation, cooling, and thermal management.

<u>Nanomaterials</u>

NNI Long-Term Challenges: The discovery of novel nanoscale and nanostructured materials; the development of a comprehensive understanding of the properties of nanomaterials (ranging across length scales, and including interface interactions); the enabling of design and synthesis, in a controlled manner, of nanostructured materials with targeted properties.

DoD Program Goals include:

- To develop precision nanostructure synthesis techniques required to provide process control over quantum transport characteristics of devices utilizing nanostructured materials.
- To harness biological and biologically inspired processes for low-cost synthesis and templating of designed nanostructures.
- To control and exploit interactions between synthetic and naturally-occurring (biological) materials.

- To develop nanoscale architectures to enhance local diffusion behavior, reaction kinetics, optical properties, and electrical properties.

Nanoscale Devices and Systems

NNI Long-Term Challenges: The application of principles of nanoscale science and engineering to create novel, or to improve existing, devices and systems; the incorporation of nanoscale or nanostructured materials to achieve improved performance or new functionality (note the systems and devices themselves are not restricted to this size).

DoD Program Goals include:

- To utilize breakthroughs in nanotechnology to provide revolutionary devices and systems to advance war fighter and battle systems capabilities.
- To establish a detailed understanding of nanoscale behavior related to electrochemical power source applications (batteries with enhanced discharge rate and energy density; high energy density capacitors; direct thermal-to-electrical energy conversion), fuel cell catalysts, and electrode structures.
- To engage the DoD applied research and development communities to accelerate the transition of science discovery into DoD relevant technologies.
- To work with the Director, Defense Research and Engineering (DDR&E) Advisory Group on Electron Devices (AGED), US Navy groups developing technology plans for Carrier Technology (CARTECH), Submarine Technology (SUBTECH), and Surface Ship Technology (SURFTECH) programs, the U.S. Army Research, Development and Engineering Command (RDECOM) Nanotechnology Integrated Product Team, and the Air Force Research Laboratory Nanoscience and Technology Strategic Technology Team to examine future platform opportunities and requirements.

Instrumentation Research, Metrology, and Standards for Nanotechnology

NNI Long-Term Challenges: The development of tools needed to advance nanotechnology research and commercialization, including next-generation instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems; the development of standards, including standards for nomenclature, materials, characterization and testing, and manufacture.

DoD Program Goals include:

- To develop breakthrough next-generation instrumentation for developing advanced nanotechnology-based materials and devices.
- To extend magnetic force microscopy and enable robust single spin measurement devices.
- To extend new measurement capabilities into innovative sensors for use in defense missions.

Nanomanufacturing

NNI Long-Term Challenges: The enabling of scaled-up, reliable, cost effective manufacturing of nanoscale materials, structures, devices, and systems; the development and integration of ultra-miniaturized top-down processes and increasingly complex bottom-up or self-assembly processes.

DoD Program Goals include:

- To guide and monitor the introduction of nanotechnology into military hardware.
- To identify appropriate opportunities to introduce nanomanufacturing into the DoD Small Business Innovative Research (SBIR)/Small Business Technology Transfer (STTR) and Manufacturing Technology (MANTECH) programs.
- To enable the synthesis, generation, and assembly of individual nanostructures using lessons drawn from biology, including use of viruses and related structures as templates for nanowires and for arrays of inorganic materials of particular interest.
- To develop affordable manufacturing approaches to nanostructured bulk materials.

Major Research Facilities and Instrumentation Acquisition

NNI Long-Term Challenges: The establishment of research facilities, acquisition of major instrumentation, and other activities that develop, support, or enhance the nation's scientific infrastructure for the conduct of nanoscale science, engineering, and technology research and development; the ongoing operation of major facilities and networks.

DoD Program Goals include:

- To provide advanced nanoscience instrumentation via the Defense University Research Instrumentation Program (DURIP).
- To provide DoD facilities and instrumentation capable of contributing to nanoscience research.

Societal Dimensions

NNI Long-Term Challenges: The identification and mitigation of potential risks to health and to the environment posed by nanotechnology (including those resulting from human, animal, or environmental exposure to engineered nanoscale materials, nanostructured materials, or nanotechnology-based devices and their byproducts); the development of relevant nanotechnology materials for schools, undergraduate programs, technical training, and public outreach.

DoD Program Goals include:

- To assure health and safety of war fighters utilizing future nanotechnology-based applications.
- To enable physicochemical characterization and toxicology for water, air and space environments.
- To sustain an investment strategy to enable a multidisciplinary education system capable of sustaining the skilled workforce needed to meet future defense needs.
- To assess, avoid and abate any adverse environmental or health impact from defense utilization of nanotechnology.

B. Progress in Meeting the Challenges and Goals

Significant progress has been made in meeting the long-term challenges and goals described for each of these seven nanotechnology program component areas. Specific accomplishments in each of these areas across the DoD nanotechnology programs are listed below.

Fundamental Nanoscale Phenomena and Processes

DoD research in this program component area (PCA) includes only those 6.1 research projects specifically addressing the synthesis, characterization, properties, or assembly of individual nanostructures.

Program Accomplishments include:

- Established the first direct evidence that the relativistic coupling between the electron spin and the electrons motion (spin-orbit coupling) can lead to the separation of up spin and down spin electrons in a thin film of an otherwise non-magnetic semiconductor, which could dramatically simplify future electron-spin-based devices.
- Developed the first theory that explains the doping mechanism of nanocrystals and proposed a procedure to enable nanocrystal doping.
- New physics theory has been discovered to describe novel chemical detection and molecular adsorption via electric field polarization of molecular adsorbates on the surface of carbon nanotubes.
- Synthesis of a novel photo-electroactive donor-acceptor chain chromophore combined with helical amylase for potential application to light harvesting devices.
- Three-branched DNA molecules have been designed and assembled from oligonucleotide components, constituting a model system for enabling the directed placement of individual nanostructures.

Nanomaterials

DoD research in this program component area (PCA) includes 6.1 and 6.2 nanotechnology research projects.

Program Accomplishments include:

- Demonstrated directed assembly of functionalized nanoparticles in bulk and thin-film block-copolymer templates.
- Nanostructured block copolymers have been integrated with microporous fiber-on-end membranes to produce selectively permeable material systems.
- Developed and demonstrated self-assembly of nano-engineered additives in polyurethane coatings to produce anti-bacterial and anti-fungal surfaces.
- Devised and demonstrated plasma modification of organic fibers to produce nanotextured textile materials with enhanced energy absorption characteristics.
- Developed the first non-linear optical organic polymer materials with non-linear coefficients surpassing 300pm/V, offering tremendous potential for compact, high-speed phased array radar and optical gyroscopes.
- Demonstrated all-optical buffering by slowing down light in a semiconductor medium, which constitutes a significant enabling technology for all-optical switching systems.

- Developed a new nanoenergetic-based formulation of $Al/KMnO_4$ that is orders of magnitude more reactive than traditional energetic formulations.
- Demonstrated reflected intensity lobe patterns from arrays of aligned, multiwalled, carbon nanotubes that capture visible light, providing the basis for a new concept in solar energy conversion and optical communications.

Nanoscale Devices and Systems

DoD research in this program component area (PCA) includes most 6.2 and 6.3 nanotechnology research projects, in addition to 6.1 nanotechnology research projects germane to specific devices.

Program Accomplishments include:

- Nanostructured polymers have been produced and integrated with photonic band-gap fiber optics to increase the sensitivity of prototype TNT sensors.
- Developed a novel mechanism for guiding and switching light using laminar flow of different fluids in micromachined channels, allowing the structure and function of these fluidic optical circuits to be easily modified by changing the type and flow rate of fluids.
- Developed novel neural transponders that can be implanted into peripheral nerve sites and allow spike detection algorithms to read and transmit commands from the central or peripheral nervous system to a prosthetic device.
- Demonstrated an engineered biological regulatory circuit that controls microbial inter- and intra- cellular communication via generation of specific and easily visualized responses to chemical gradients, demonstrating that genetic components can be designed and used to compose biological circuits to regulate intercellular signaling pathways.
- Demonstrated an actuator system that will convert hydrocarbon fuels directly to mechanical work based on mechanically robust, highly conductive, extremely high surface area electrodes fabricated using a carbon nanotube spinning technique.
- Demonstrated the feasibility of integrating protein ion channels in silicon micro-fabricated structures to enable the reading of stochastic sensing signals in a scalable device architecture with enhanced robustness and longevity.
- Developed an array-based platform for studying receptor-ligand binding kinetics at the single or few molecule limit using a bio-functionalized magnetic nanorod and micro-Hall sensor.
- The first self-contained fully functional photovoltaic fiber has been produced based on nanocomposite photovoltaic technology, and enabling unique photovoltaic textiles.
- Novel miniature Hall sensors have been fabricated to capture and actuate bio-functionalized magnetic nanorods.

Instrumentation Research, Metrology, and Standards for Nanotechnology

DoD research in this program component area (PCA) includes Multidisciplinary Research Program of the University Research Initiative (MURI) research projects (6.1) and other significant work on these specific topics.

Program Accomplishments include:

- DoD support for the development of the first ever magnetic resonance force microscope capable of single electron detection formed the bases for starting a new MURI targeting single nuclear spin detection that could dramatically impact future sensor development.
- Demonstrated continuous sampling of the relative phase of two Bose-Einstein condensates with a new technique that probes the phase of each condensate via stimulated photon scattering of a small number of atoms out of the condensates; the results provide great potential to use atom interferometry technology for sensing accelerations and rotations in inertial navigation systems.
- Developed new optical scanning tunneling microscope and optical nanoprobe instruments to measure the light emission and dynamics of quantum dots for enhanced light emitting devices.
- Invention of the thermal DPN (tDPN) method, in which nanostructures can be deposited or written directly onto a substrate by heating the tip of the device.

Nanomanufacturing

DoD research in this program component area (PCA) includes MURI research projects (6.1) focused on nanomanufacturing, and other significant work on this specific topic. It should be noted that Table 1 indicates zero investment in this PCA because individual research efforts addressing nanomanufacturing are primarily focused on other PCAs (i.e., nanomaterials and nanoscale devices and systems).

Program Accomplishments include:

- Optimized the growth conditions for multiwalled carbon nanotubes (MWNTs) using the addition of specific carrier gasses to improve the growth rate and nanotube density.
- Extended nano-imprint lithography methods to 6 nm half-pitch resist lines and $0.04\mu m^2$ SRAM cell metal layers, dramatically exceeding current optical patterning manufacturing capabilities.
- Demonstrated thick Bragg gratings in a photo-thermo-refractive (PTR) glass that enables a new approach to coherent coupling of light between separated semiconductors.
- Developed a fabrication approach based on nano-imprint lithography that will allow molecular electronics cross-bar architectures of less than 30 nanometers with a high degree of registration and low defect rates, enabling high density cost-effective fabrication of memory and logic elements.
- Demonstrated the amplification of a starting single walled carbon nanotube (SWNT) seed population into a larger pool of SWNTs with exactly the same electrical and thermal characteristics as the starting seed population, greatly increasing the potential of SWNTs for a variety of electronic devices.
- Developed a straightforward approach for SWNT assemblies by using aligned surface DNA as a positioning template with excellent application to the fabrication of nanotube nanowires in nanoelectronic circuits.
- A nanocomposite meal bag for the Meals Ready-To-Eat ration has been developed using low density polyethylene/montmorillonite layered silicate, and compounding and film extrusion trials were transitioned to the pilot scale.

Major Research Facilities and Instrumentation Acquisition

DoD research in this program component area (PCA) includes Defense University Research Instrumentation Program (DURIP) grants (6.1) for nanotechnology instruments at Universities, Military Construction (MILCON) for dedicated nanotechnology research buildings, and other significant efforts addressing these specific topics.

Program Accomplishments include:

- Completed the development and installation of unique-in-the-world Naval Research Laboratory Nanomanipulation and Characterization Facility.

Societal Dimensions

DoD research in this program component area (PCA) includes MURI research projects (6.1) focused on health and safety of nanotechnology-based applications and manufacturing.

Program Accomplishments include:

- A special session on nanotechnology and its environmental impact was held at the Strategic Environmental Research and Development Program (SERDP) annual meting to address the possible effects of nanomaterials/nanotechnology on the environment human health, and catalyze collaborations with other agencies in this area.

II. Assessment of Current and Proposed Funding Levels

DoD nanotechnology research programs are carried out both within the DoD laboratories and in extramural research institutions. In both contexts, nanotechnology research is directed by single investigators, multidisciplinary teams, and research centers. Single investigator research represents a critical component of the DoD nanotechnology research effort and is critical to the continued inception and maturation of high risk innovative scientific concepts that will lead to breakthroughs in nanotechnology. Multidisciplinary teams at the intersections of traditional disciplines provide an optimal means of developing the necessary understanding of nanoscale phenomena and identifying promising applications. Research centers provide sustained support and a broad range of expertise focused on key opportunities emerging from nanotechnology research.

Table 1 shows the amount of DoD funding in nanotechnology from FY2005-FY2007 for each of the seven program component areas (PCAs) previously described. The historic DoD investment is also described in Tables 2 and 3. Table 2 shows this DoD investment from FY2005-FY2007 broken out by category: 6.1 (basic research), 6.2 (applied research), and 6.3 (advanced technology development). Table 3 shows the amount of DoD funding in nanotechnology from FY2005-FY2007 for each DoD component.

It should be noted that the data reported in these tables is a result of a comprehensive analysis conducted in FY2006 of all non-SBIR/STTR nanotechnology-relevant DoD research and development efforts (for FY2005-FY2007). Differences between the data shown in Tables 1-3 and those reported in previous Defense Nanotechnology Research and Development Programs reports are due to clarifications and corrections enabled via this extensive analysis process; therefore, the results reported here should be considered the most accurate.

It is important to note that Table 1 indicates zero investment in PCA #5 (nanomanufacturing) because individual research efforts addressing this PCA are primarily focused on other PCAs (i.e., nanomaterials and nanoscale devices and systems). The numerous accomplishments listed in Section IB for this PCA demonstrate that much progress is being made in this area; however, these accomplishments have been made under research efforts that are aligned more closely with the objectives of another PCA.

It should also be noted that the FY2007 program includes an expected increase of approximately $21M for PCA #6 (major research facilities and instrumentation acquisition) in order to develop novel lithography instrumentation for affordable, high performance, low volume, and application-specific integrated circuits (ICs). Furthermore, this new facilities and instrumentation initiative will provide a cost effective manufacturing technology for low volume nanoelectromechanical systems (NEMS) and nanophotonic devices.

Table 1
Historic DoD Investment in Nanotechnology by PCA ($ in Millions)

	FY2005 (Actual)	FY 2006 (Estimate)	FY 2007 (Request)
PCA #1	139.785	159.285	126.663
PCA #2	103.504	149.330	100.107
PCA #3	89.780	111.547	83.641
PCA #4	14.408	11.739	10.768
PCA #5	0.000	0.000	0.000
PCA #6	3.641	3.300	23.300
PCA #7	1.000	1.000	1.000
TOTAL	**352.118**	**436.201**	**345.480**

Note: All totals may not match due to rounding.

PCA #1: Fundamental Nanoscale Phenomena and Processes
PCA #2: Nanomaterials
PCA #3: Nanoscale Devices and Systems
PCA #4: Instrumentation Research, Metrology, and Standards for Nanotechnology
PCA #5: Nanomanufacturing
PCA #6: Major Research Facilities and Instrumentation Acquisition
PCA #7: Societal Dimensions

Table 2
Historic DoD Investment in Nanotechnology by Category ($ in Millions)

	FY2005 (Actual)	FY 2006 (Estimate)	FY 2007 (Request)
6.1	172.660	226.319	174.653
6.2	176.774	194.046	149.857
6.3	2.684	15.836	20.970
TOTAL	**352.118**	**436.201**	**345.480**

Table 3
Historic DoD Investment in Nanotechnology by Agency ($ in Millions)

	FY2005 (Actual)	FY 2006 (Estimate)	FY 2007 (Request)
Army	60.563	66.279	30.332
Navy	42.244	43.945	30.336
Air Force	74.713	90.179	61.963
DARPA	169.599	210.116	209.199
DDR&E	5.000	5.800	5.000
CDBP	0.000	19.882	8.650
TOTAL	**352.118**	**436.201**	**345.480**

Note: All totals may not match due to rounding.

DoD nanotechnology programs are a collection of many individual research and development programs that include a focus on nanotechnology, and are summarized by analyzing a large number of individual program elements. An analysis of the SBIR/STTR investment was also conducted to identify additional efforts supporting nanotechnology research. This analysis identified an additional $41.737M ($13.789M in STTR and $27.948 in SBIR) for FY2005 in nanotechnology research efforts. This data was not included in Tables 1-3 or Section IB, because it was only recently completed and did not include a detailed technical progress review.

Based upon the budgetary information reported in Tables 1-3 and the technical progress reported in Section IB, the funding levels for DoD nanotechnology are found to be adequate to support the defense agency program activities. The overall research and development budget requests for each of the services and DARPA have remained generally stable, although significant decreases in these budgets (particularly for 6.1 basic research) have already been discussed for FY2007. The impact of such a decrease on DoD research and development would be expected to have a broad adverse affect upon defense research and development efforts, including those focused on nanotechnology.

Congressional additions also constitute a significant portion of the DoD research and development budget focused nanotechnology. Historically Congressional additions to the DoD budget have approximately totaled $80M in FY2003, $100M in FY2004, $150M in FY2005, and $130M in FY2006. These additions significantly complicate the assessment of current and proposed funding levels for the DoD investment in nanotechnology, as they are difficult to identify and difficult to evaluate. Identification is difficult due to the large number of program elements that must be investigated to summarize the annual DoD investment, which increases the difficulty of extracting past Congressional additions from the respective appropriated budgets (i.e., a significant portion of the decrease between the FY2006 estimate and the FY2007 request is due to Congressional additions). Evaluation is difficult due to the fact that these programs are Congressionally appropriated, thereby avoiding the standard level of agency technical scrutiny, and often creating inconsistencies with the most current research focus areas of DoD agencies. For these reasons, the DoD nanotechnology investment represented by Tables 1-3 includes some, but not all, of the total Congressional additions; a thorough identification of all Congressional additions for nanotechnology research and development cannot be provided at this time. Nonetheless, it should be noted that the majority of Congressional additions that have been identified from the FY2006 estimate are associated with PCAs #2 and #3 (nanomaterials and nanoscale devices and systems).

III. Coordination within DoD and with Agencies in NNI

In support of the National Nanotechnology Initiative, DoD regularly participates in meetings of the Nanoscale Science and Engineering Technology (NSET) subcommittee of the National Science and Technology Council (NSTC) Committee on Technology. The NSET subcommittee membership consists of representatives from the Office of Science and Technology Policy (OSTP), Office of Management and Budget (OMB), National Science Foundation (NSF), DoD, National Institute of Standards and Technology (NIST), Department of Commerce (DoC), Department of Energy (DoE), Department of Homeland Security (DHS), Department of Transportation (DoT), Department of Justice (DoJ), Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), National Institutes of Health (NIH), Department of Agriculture (USDA), Department of State (DoS), Food and Drug Administration (FDA), National Institute of Occupational Safety and Health (NIOSH), Patent and Trademark Office (USPTO), Nuclear Regulatory Commission (NRC), International Trade Commission (ITC), Department of the Treasury (DoTr), Consumer Product Safety Commission (CPSC), as well as a representative from the Intelligence Community. The NSET subcommittee meets bimonthly at the National Science Foundation to coordinate all federal government programs in the NNI with the National Nanotechnology Coordination Office (NNCO). Additionally, appropriate coordination of the overall DoD investment in nanotechnology is assured through DoD reliance panels, the Naval Working Group on Nanoscience, the Air Force Research Laboratory Nanoscience and Technology Strategic Technology Team, and the U.S. Army RDECOM Nanotechnology Integrated Product Team.

The NSET has created working groups with various industrial sectors named Consultative Boards to Advance Nanotechnology (CBAN). Along with other appropriate NSET agencies, the DoD is participating in CBAN addressing information technology and chemicals. Future CBAN activities, with anticipated DoD participation, continue to be under discussion for future applications to the automotive, aerospace and biotechnology sectors.

In addition, the following are specific examples of the many ongoing collaborative efforts directly between individual agencies participating in the National Nanotechnology Initiative:

DoD, NSF, DoE:	Ongoing collaborative research efforts in nanostructured materials
DoD, DoE, NASA, NIST, NSF:	Coordinated research efforts focused on the realization of robust quantum computing

DoD, NASA, DOE:	Coordinated research efforts in directed energy conversion
DoD, NASA, NSF:	Coordinated development of modeling and simulation tools for predicting properties of nanoscale materials and for developing and optimizing processes for nanomaterials fabrication
DoD, DoE, NASA:	Cooperative efforts on materials and device development and modeling for direct thermal-to-electrical energy conversion (thermoelectric, thermophotovoltaics, and thermionics)
DoD, DoE:	Cooperative efforts to develop monolithic absorber/bolometric sensors for terahertz detectors
DoD, NSF, NIST:	Coordination of program plans and program reviews for nanomanufacturing R&D efforts, including four NSF Nanoscale Science and Engineering Centers (NSECs) and the DoD MURIs, and for development of R&D partnerships
DoD, NSF, NASA, DoE:	Plans and activities at NSF's National Nanotechnology Infrastructure Network (NNIN) and Network for Computational Nanotechnology (NCN) have been coordinated with complementary centers funded by DoD, NASA, and DoE
DOD, NIH:	Synthesis of nanometer-scale materials with an optical response tunable from visible to infrared wavelengths, enabling (via joint support from DOD and NIH) R&D on non-invasive destruction of tumors
DOD, DOE, NASA, NSF:	Coordinated programs for nanostructured electrodes and catalysts for fuel cells and batteries
DOE, EPA, USDA:	Collaboration in the area of pervaporation, specifically membranes constructed of a polymer-zeolite matrix with nanoscale pores
DoD, NSF:	Joint funding of Materials Research Science and Engineering Centers (MRSECs), and co-funding of two Nanoscale Science and Engineering Centers (NSECs)
DoD, DoE:	The Defense Threat Reduction Agency's (DTRA) Joint Science & Technology Office (JSTO) for Chemical/Biological Defense finalized a memorandum of agreement with the Center for Integrated Nanotechnologies (CINT), a DoE user facility managed by Sandia National Laboratories and Los Alamos National Laboratory.

IV. Effective Technology Transition Paths

Nanotechnology is still very much emerging and at the early stages of development; for this reason, the majority of the effort is currently focused on basic research and exploration. Nonetheless, significant research results have been transferred to technology development, both within DoD laboratories and in industry. DoD agencies are exploring nanotechnology successes as sources of potentially disruptive innovations in order to accelerate transition of these discoveries into future platforms, and increasing emphasis is being given to transitioning research discoveries in nanoscale materials into development through 6.2, 6.3, SBIR/STTR, and MURI programs.

Each of the defense services have established research teams to explore nanotechnology and identify rapid and effective technology transition paths (i.e., the Naval Working Group on Nanoscience, the Air Force Research Laboratory Nanoscience and Technology Strategic Technology Team, and the U.S. Army RDECOM Nanotechnology Integrated Product Team). Additionally, while not analyzed exhaustively, a significant increase in SBIR/STTR (i.e., product-based) programs focusing on nanotechnology has been identified over the past few years. Furthermore, analysis of the technical progress reported in section IB, particularly for PCAs #3 (Nanoscale Devices and Systems) and #5 (Nanomanufacturing), reveals considerable progress in establishing effective technology transition pathways as a result of activities under the DoD research and development efforts focused on nanotechnology. Additionally, annual DoD sponsored conferences, such as “Nanomaterials for Defense Applications,” have established a regular forum to establish linkages between DoD funded research and development efforts and commercial/defense product developers.

V. Recommendations for Program Activities

Nanotechnology research covers many science and technology areas that are of primary interest to DoD. Nonetheless, because basic research in nanotechnology involves high-risk efforts with the potential for extremely high payoffs, major advances in the application of nanotechnology to the military are often unpredictable. For this reason, it is critical to maintain a balanced and stable research investment portfolio (relative to the overall DoD research and development budget) in order to identify and capture the critical technological breakthroughs needed to provide revolutionary advantages for war fighter and battle systems capabilities. The current DoD nanotechnology programs represent a balanced and dynamic investment portfolio addressing both near-term national security needs and long-term challenges. As a part of the reliance process, DoD will continue to coordinate its nanotechnology programs amongst the services, DARPA, and other federal agencies to maximize leveraging and avoid duplication and redundancy.

As basic research in nanotechnology continues to mature, it is anticipated that the results will be transitioned to applied research and advanced technology development and to industry. Increasing emphasis is being put on effective transitioning of research to technology development for the services, which will require more effective coupling between the different funding categories, and between the basic research programs and SBIR/STTR and MANTECH programs. The DoD will work with the NSTC Interagency Working Group in its joint efforts with the NNI to augment the Federal program in nanomanufacturing.

Nanotechnology research remains a major national initiative, with DoD playing a major role since its inception. Considerable scientific knowledge is yet to be learned, and DoD guidance is critical to assure both the optimum direction of ongoing research efforts and the optimum leveraging of this knowledge to advance war fighter and battle systems capabilities. Furthermore, DoD’s sustained investment in nanotechnology basic research funding over the long term will ensure that we can meet the challenges and goals set out in this report.

1. Fundamental Nanoscale Phenomena and Processes:
Sustained support is recommended to ensure the discovery of new phenomena and processes necessary for breakthrough advantages in DoD systems, particularly in the areas of: chemical/biological sensing; electronic phenomena; and energetics.

2. Nanomaterials:
Increased support and attention is recommended in order to enable robust incorporation and design of nanoscale phenomena into advanced materials for a broad spectrum of revolutionary target applications. Significant barriers continue to persist between the discovery of promising nanoscale phenomena and the realization of novel materials properties based on these phenomena.

3. Nanoscale Devices and Systems:
Sustained support is recommended to assure the continual development of novel devices and systems to enhance DoD capabilities, particularly in the areas of: chemical/biological defense; information technology; energy storage; multifunctional materials and devices; and health monitoring and sensing.

4. Instrumentation Research, Metrology, and Standards for Nanotechnology:
Sustained support is recommended to ensure appropriate involvement, guidance, and leveraging by DoD in this area to enhance research and development progress in all other component areas.

5. Nanomanufacturing:
Increased support is recommended by means of the SBIR/STTR and MANTECH programs in order to facilitate transitioning and the sustained supply of research results for defense technologies. While the SBIR/STTR programs have experienced a significant increase in the past few years, further increases in SBIR/STTR activities and significant MANTECH investments are recommended in order to achieve the greatest success.

6. Major Research Facilities and Instrumentation Acquisition:
Sustained support is recommended to ensure continual development of advanced instrumentation and opportunities for leveraging of unique capabilities in these areas by other agencies.

7. Societal Dimensions:
Sustained support is recommended to assure the health and safety of war fighters utilizing future nanotechnology-based applications. While no additional funding support is recommended in the area of environmental health and safety aspects of nanotechnology, it is recommended that the DoD actively monitor this area in order to leverage the investments and expertise of major health agencies worldwide to identify potential health risks and implement optimal and appropriate safety practices for both war fighters and defense product developers.

VI. References

1. Basic Research Plan, Director of Defense Research and Engineering, February 2003.
2. Joint Warfighting Science and Technology Plan, Office of the Deputy Under Secretary of Defense (Science and Technology), February 2003.

3. Defense Technology Area Plan, Office of the Deputy Under Secretary of Defense (Science and Technology), February 2003.
4. National Nanotechnology Initiative, Research and Development Supporting the Next Industrial Revolution, 2004.
5. The National Nanotechnology Initiative Strategic Plan, December 2004.