Defense Nanotechnology Research and Development Program

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EXECUTIVE SUMMARY

The Department of Defense (DoD) has a long history of successfully supporting innovative research and development 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 and development programs focusing on advancing science and technology below one micron in size. Scientific breakthroughs and advances in the last ten years demonstrate the potential for nanotechnology to impact a tremendous number of key capabilities for future war fighting: chemical and biological warfare defense; high performance materials for platforms and weapons; unprecedented information technology; revolutionary 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.

Based upon an analysis of the planned research and development activities and the progress reported for the past year, the funding levels for DoD nanotechnology are found to be adequate to support the defense agency program activities. Substantial progress has been demonstrated toward each of the long term DoD program goals, and no deficiencies or oversights were identified within the current funded program. It is critical for DoD to maintain a stable (relative to the overall DoD research and development budget) and strategic (relative to the worldwide investment) nanotechnology research and development investment portfolio in order to identify and capture the critical technological breakthroughs needed to provide revolutionary advantages for war fighter and battle systems capabilities.

In the future, additional investment from DoD is recommended in the area of nanomanufacturing via 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. This area remains a significant barrier to the commercialization of nanomaterials and nanotechnology-based products, and additional future investments will be necessary to achieve the greatest success and technology transition. Increased attention is recommended in the area of nanomaterials to realize strategies for robust incorporation and design of nanoscale phenomena into advanced materials for a broad spectrum of revolutionary target applications. Additionally, strong support is recommended for the newly formed Nanomaterials Working Group under the Emerging Contaminant Governance Board, in order to address emerging international attention on the potential environmental health and safety aspects of nanotechnology.

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. A longstanding commitment to innovative basic research made possible support for research in nanoscience and nanotechnology from before the inception of these initiatives. 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) established the Institute for Soldier Nanotechnology (ISN). In the mid-1990s, ONR launched a program on nanostructured coatings, and DARPA launched a Biological-Informational-Micro initiative which included a number of efforts exploiting advances in nanotechnology focused on interfacing biological systems with microelectronics.

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 2007 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 relevance to DoD. The technical objective of defense nanotechnology programs is defined as:

> *To develop understanding and control of matter at dimensions of approximately one to one hundred nanometers, where the physical, chemical, and biological properties may* ***differ*** *in fundamental and valuable ways from those of individual atoms, molecules, or bulk matter.*

In terms of relevance to DoD, the objective of defense nanotechnology programs is defined as:

> *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:

- 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, sensors, thermoelectrics, thermionics, and photovoltaics.

<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:

- 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.

<u>Nanoscale Devices and Systems</u>

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: systems and devices themselves are not restricted to this size).

DoD Program Goals:
- 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.

<u>Instrumentation Research, Metrology, and Standards for Nanotechnology</u>

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:
- 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.

<u>Nanomanufacturing</u>

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 ultraminiaturized top-down processes and increasingly complex bottom-up or self-assembly processes.

DoD Program Goals:

- 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.

<u>Major Research Facilities and Instrumentation Acquisition</u>

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 Goal:

- To provide DoD facilities and instrumentation capable of contributing to nanoscience research.

<u>Societal Dimensions</u>

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:

- 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

Program Accomplishments:

- A new mode of cellular burning instability has been discovered using nanoscale aluminum particles for nanoenergetics.
- Room temperature current induced spin polarization has been demonstrated for nanoelectronics.
- New single layer self-assembled monolayers have been developed and shown to effectively passivate nanoscale reactive particles for nanoenergetics.
- The coupling of two InAs quantum dots (that individually behave as pseudo atoms) have been shown to form a quantum dot "molecule" with multiple optically accessible ground and excited states for nanoelectronics and sensing.

Nanomaterials

Program Accomplishments:

- Unique optoelectronic fibers with nanoscale structural features have been developed and demonstrated to detect light or heat at any axial location.
- Attachment of biomolecular receptors on high surface area nanofibers has been achieved for multifunctional fibers and sensors.
- Nanocrystalline quantum dots have been synthesized and shown to detect infrared light without the need for cooling below room temperature.
- Nanomagnetic materials have been synthesized and demonstrated for high sensitivity DNA detection and characterization, and control of intra-cellular biochemical signaling pathways.
- Nanostructured materials have been fabricated with record electro-optic coefficients of more than 450 pm/V.
- Nanomagnetic and nanowire mediated three-dimensional engineered tissue constructs have been developed.

Nanoscale Devices and Systems

Program Accomplishments:

- A novel detector has been developed, via the introduction of a tunneling barrier into a quantum dot detector, which has been verified to selectively reduce the noise current, significantly increasing the signal to noise ratio.
- Patterned ink-jet printing of nanocomposite photovoltaic dyes onto a flat substrate has been demonstrated to produce two-color, functioning photovoltaic cells.
- Nanoporous chip arrays have been developed for stabilization and sensing of protein ion channels, and demonstrated for sensing of water born toxins.
- The record smallest individual organic light-emitting diode has been fabricated by filling a 60 nm diameter, 100 nm deep hole with a light-emitting (electroluminescent) polymer.

- The first ever propagating condensate atom interferometer on an atom chip has been produced.
- Electrical spin injection has been achieved and measured in nanoscale semiconductor material.
- The record highest Q mechanical resonators have been developed from nanocrystalline diamond.

Instrumentation Research, Metrology, and Standards for Nanotechnology

Program Accomplishments:

- Optical trapping of nanostructures has been achieved via successful manipulation of 10 nm nanoparticles with < 1 mW laser power.
- Single photon production and detection has been demonstrated in alkali vapor cells.
- The first near-field Raman imaging of buried carbon nanotubes has been achieved.
- A new metrology system (ZT meter) to directly measure thermoelectric material performance has been established, based on an impedance spectroscopy transmission line model.

Nanomanufacturing

Program Accomplishments:

- A novel method using supercritical fluid at extreme pressure (Rapid Expansion of Supercritical Solution, RESS) has been demonstrated for nanoparticle fabrication.
- A unique continuous process for production of tailored nanoscale materials in narrow size distributions has been developed.
- For packaging, a nanocomposite meal bag for the meal ready-to-eat (MRE) ration has been developed and demonstrated at the pilot scale using a low density polyethylene/ montmorillonite layered silicate formulation.
- First ever samples of 3-dimensional braid reinforcement solely made of drawn-twisted continuous carbon nanotube yarns have been fabricated.
- A new thermal dip pen nanolithography technique to directly write metallic nanowires on a substrate in air or vacuum has been established.

Major Research Facilities and Instrumentation Acquisition

Program Accomplishments:

- A maskless, direct write lithography tool to address both the DoD's need for affordable, high performance, low volume Integrated Circuits (ICs) and the commercial market's need for highly customized, application-specific ICs has been developed.
- The U.S. Army Research Laboratory's Nanoelectronics Laboratory has been established and includes a turbopumped scanning electron microscope based nanomanipulator/ nanoelectronic probe, enhanced electron beam pattern generator, long working distance optical microscope, spin processor, 6-arm vacuum cryogenic DC-40GHz probe station with atmospheric test and optical probe capability, carbon nanotube (CNT) growth furnace, CNT imaging and analysis software, scanning probe microscope with dip-pen nanolithography and electrical characterization capability, field controlled electromagnet, and an array of high-precision electronic instrumentation for nanoelectronic testing including a 3Hz-50GHz spectrum analyzer and semiconductor parametric characterization system. The focus of the Nanoelectronics Laboratory's research is to develop low-power nanoscale sensor and

communications devices suitable for individual combatant protection and novel survivability concepts including true microscale networked autonomous mobile sensor/electronic systems and electronic textiles.

- A world-class local-electrode atom probe (LEAP) microscope and complementary pulsed-laser enhancement capable of 80-nm resolution and data acquisition rates of up to 1.2M atoms per minute enabling confident, quantitative 3-D tomography of material structure has been acquired.

Societal Dimensions

Program Accomplishments:

- The DoD Nanomaterials Working Group has been established under the Emerging Contaminant Governance Board. The group's charter includes addressing the need to develop internal procedures for assessing environmental, safety, and occupational health implications from DoD unique engineered nanomaterials, and for managing future potential environmental, safety and occupational health liabilities.

II. Assessment of Current and Proposed Funding Levels

The DoD nanotechnology program is a direct result of sustained support for highly adaptive and innovative research and development programs within the department of defense. These sustained research and development programs (which include basic research, applied research, and advanced technology development efforts) led to the establishment of nanotechnology as a major research thrust internationally. Furthermore, the DoD nanotechnology research and development program is defined as the assembly of individual efforts within the overall DoD research and development program that are categorized as nanotechnology (i.e., according to the objectives defined previously in this report).

Nanotechnology research and development efforts are carried out both within the DoD laboratories, and in extramural research institutions. In both contexts, nanotechnology efforts may be directed by single investigators, multidisciplinary teams, or research centers. Single investigator research represents a critical component of the DoD research program and is critical to the continued inception and maturation of high risk innovative scientific concepts that will lead to breakthroughs in science and engineering (including 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 research and development funding that supports the nanotechnology objectives during FY 2006-FY 2008, subdivided into the seven program component areas (PCAs) previously defined. It should again be noted that these funding amounts are a collection of many individual research and development efforts that focus on the DoD nanotechnology objectives, and the data are created from detailed analysis of a large number of individual program elements within the DoD budget. Table 2 shows the amount of this funding that has been identified as congressional additions (for FY 2006 and FY 2007 only). The historic DoD investment is also described in Tables 3 and 4. Table 3 shows the DoD research and development funding that supports the nanotechnology objectives from FY 2006-

FY 2008 subdivided by category: 6.1 (basic research), 6.2 (applied research), and 6.3 (advanced technology development). Table 4 shows these funding amounts from FY 2006-FY 008 subdivided by DoD agency component.

It should be noted that the FY 2007 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.

Program Component Areas (PCA):
- 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 1
Historic DoD Investment in Nanotechnology by Program Component Area ($ in Millions)

	FY 2006 (Actual)	**FY 2007 (Estimate)**	**FY 2008 (Request)**
PCA #1	184.597	180.998	179.124
PCA #2	109.709	84.776	91.683
PCA #3	110.447	107.535	70.638
PCA #4	10.772	9.513	8.259
PCA #5	3.120	4.839	1.000
PCA #6	4.313	28.606	22.978
PCA #7	1.000	1.000	1.000
TOTAL	**423.958**	**417.267**	**374.682**

Table 2
Congressional Additions to DoD Investment in Nanotechnology by Program Component Area ($ in Millions)

	FY 2006 (Actual)	**FY 2007 (Estimate)**
PCA #1	33.781	33.492
PCA #2	17.467	3.068
PCA #3	21.586	23.145
PCA #4	2.730	1.371
PCA #5	0.000	1.916
PCA #6	0.000	0.000
PCA #7	0.000	0.000
TOTAL	**75.564**	**62.992**

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

	FY 2006 (Actual)	FY 2007 (Estimate)	FY 2008 (Request)
6.1	199.781	211.064	197.245
6.2	191.574	152.817	125.384
6.3	32.603	53.386	52.053
TOTAL	**423.958**	**417.267**	**374.682**

Table 4
Historic DoD Investment in Nanotechnology by Agency ($ in Millions)

	FY 2006 (Actual)	FY 2007 (Estimate)	FY 2008 (Request)
Army	64.012	66.984	34.136
Navy	45.460	45.188	27.140
Air Force	89.907	70.855	63.817
DARPA	195.377	219.320	212.458
DDR&E	5.800	5.000	7.200
CBDP	19.882	9.650	29.801
MDA	3.520	0.270	0.130
TOTAL	**423.958**	**417.267**	**374.682**

The research and development funding amounts in support of nanotechnology for each of the services and DARPA are characterized by fluctuations resulting from regular initiation and completion of new research and development focus areas, but have generally remained stable. It should be noted that the sizeable decrease between FY 2006 or FY 2007 budgets and those of FY 2008 are largely due to the congressional additions reported in Table 2. Further, the large relative fluctuations in the Chemical and Biological Defense Program (CBDP) and Missile Defense Agency (MDA) budgets for FY 2006 through FY 2008 are also generally explained by the presence of congressional additions.

As shown in Table 2, Congressional additions constitute a significant portion of the DoD research and development budget focused nanotechnology. Congressional additions significantly complicate the assessment of current and proposed funding levels for the DoD investment in nanotechnology, since these Congressionally appropriated programs commonly avoid the standard agency technical scrutiny. Furthermore, Congressional additions are often inconsistent with, or even in direct opposition to, the technical focus areas and directions of DoD agencies.

Based upon the budgetary information reported in Tables 1-4 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. Substantial progress has been demonstrated in each of the program component areas, and toward each of the long term DoD program goals. Furthermore, no deficiencies or oversights were identified within the current funded program. While the defense nanotechnology research and development portfolio is still predominantly comprised of basic research and applied research efforts, as opposed to advanced technology development, this remains consistent with the current maturity of most nanotechnology research efforts – while scientific and technological advances are regularly being made and demonstrating great promise, robust and mature products will generally require considerably more time to be realized.

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 office of one of the participating agencies 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 also formed five working groups to address areas of specific interest across all federal agencies. These groups are focused on: Nanotechnology Environmental and Health Issues (NEHI), Nanotechnology Innovation and Industry Liaison (NILI), Nanomanufacturing, Nanotechnology Public Engagement Group (NPEG), and Global Issues in Nanotechnology (GIN).

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, 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, 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 Multidisciplinary University Research Initiatives (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
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 Chemical and Biological Defense Program is operating under a memorandum of understanding with the Center for Integrated Nanotechnologies (CINT), a DoE user facility managed by Sandia National Laboratories and Los Alamos National Laboratory
DoD, NASA:	Collaborative efforts and information exchange for nanocomposite photovoltaic fibers and fiber batteries

IV. Effective Technology Transition Paths

As DoD's research and development efforts continually advance and mature the state-of-the-art in nanotechnology, scientific and technical progress is made across a broad range of application areas. As this progress occurs, a more accurate identification of the most (and least) promising application areas to target with future nanotechnology efforts is also realized. While the majority of the defense nanotechnology research and development effort currently remains focused on basic research and application exploration, significant research results have been transferred to technology development, both within DoD laboratories and in industry. DoD agencies continue to explore 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 Multidisciplinary University Research Initiative (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, both the SBIR/STTR and MANTECH (i.e., product and manufacturing technology based) programs are poised to transition breakthrough results to military and commercial products. While not analyzed as part of this report, it should be noted that the SBIR/STTR program has shown a significant investment in nanotechnology-based products during the past few years, and this amount is expected to increase. 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,” continue to provide 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 remains a major national initiative, and DoD remains at the forefront as a major contributor, as it has even before the inception of this initiative. 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.

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 efforts in nanotechnology continue to mature, it is anticipated that the results will be transitioned to applied research efforts and advanced technology development in both the military and industry sectors. Increasing emphasis is being put on communication and 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. Also, DoD is continuing to work with the NSTC Interagency Working Group to augment the federal program in nanomanufacturing, since this area remains a significant barrier to the commercialization of nanomaterials and nanotechnology-based products.

Current research and development programs in support of nanotechnology span a broad range of science and technology areas that are of primary interest to DoD. Because these programs are inherently high risk with the potential for extremely high payoff, major advances in the application of nanotechnology to the military are often unpredictable (particularly when attempting to assess basic research and early applied research efforts). For this reason, it is critical to maintain a stable (relative to the overall DoD research and development budget) and strategic (relative to the worldwide investment) nanotechnology research and development investment portfolio in order to identify and capture the critical technological breakthroughs needed to provide revolutionary advantages for war fighter and battle systems capabilities. It is essential that breakthroughs in nanotechnology be exploited for these capabilities, but also that DoD's support for highly adaptive and innovative research and development (which helped conceive the current international nanotechnology focus) not be restricted by a singular focus on nanotechnology (or any other single area).

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:
Sustained support and increased attention is recommended to realize strategies for 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 (particularly bulk) 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 a sufficient supply of materials and devices for defense technologies. While the SBIR/STTR programs have demonstrated significant support for nanotechnology-based products during the past few years, further increases in SBIR/STTR activities and significant MANTECH investments are strongly encouraged 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, particularly in terms of the newly formed Nanomaterials Working Group under the Emerging Contaminant Governance Board, in order address emerging international attention on the potential environmental health and safety effects of nanotechnology. Additionally, this working group is expected to enhance DoD's ability to collaborate with other agencies in this area, to leverage the investments and expertise of major health agencies worldwide, to identify potential health risks, and to 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.
6. Classification Order 1850, United States Department of Commerce, Patent and Trademark Office, November 2005.