Nanotechnology in Support of Aviation Safety

Prepared for the Federal Aviation Administration, under contract DTFA01-01-C-00039

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August 18, 2003

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Executive Summary

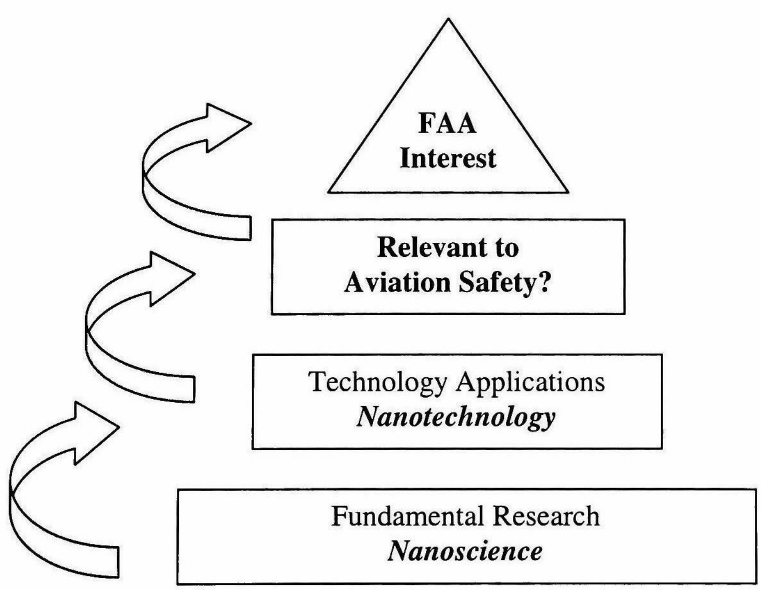
Overview

Nanotechnology may be defined as the creation of functional materials, devices and systems through control of matter at the scale of .1 to 100 nanometers and the subsequent exploitation of the novel properties and behavior of materials at that scale. The emerging field of nanotechnology offers the potential to develop dramatic new innovations and capabilities with applications across a wide spectrum of industries. There is clearly great applicability of prospective developments in nanotechnology for transportation; nowhere is this more promising than in aviation.

Objectives and Methodology

There is significant and growing interest in the U.S. in nanoscale research and development (R&D). The National Nanotechnology Initiative, which represents the federal government's strategic plan to support nanoscale science, engineering and technology, is pouring greater than $700 million annually into these efforts. It is highly likely that civil aviation will benefit materially from these efforts. The objective of this study is to identify and describe a representative set of nanoscience and nanotechnology endeavors having prospective relevance to the civil aviation sector, with emphasis on identifying safety-related applications of interest to the FAA. Figure 1 below provides an overview of the steps in the process.

Figure 1



More specifically, the process involved:

- **Development of a "catalog" of nanoscale R&D efforts in the U.S.** Projects at more than 90 academic institutions, government labs and agencies and private sector organizations were reviewed and their nanoscale R&D programs summarized. (See Appendix 1)
- **Nanotechnology panel meetings.** Two panel meetings with representatives from industry and academia were conducted at the Transportation Center at Northwestern University. These meetings served as a forum to obtain additional information about nanoscience research initiatives underway, as well as to survey the opinions and insights of people in the aerospace industry as to their interests in nanotechnology and how it may benefit civil aviation, especially as it pertains to safety.
- **Determination of the relevance of nanotechnology research efforts.** From the information gathered through the catalog entries and panel meetings, those research efforts that appeared to hold promise for enhancing civil aviation safety were identified and discussed. In addition, government research priorities to support nanoscale R&D to enhance aviation safety have been suggested.

Overview of Results

Through this process, several generic categories of nanotechnology of relevance were identified. These were found to have the potential to provide the basis for dramatic new capabilities and innovations, many of which may enhance civil aviation safety. These categories are *structural materials, coatings, lubricants, sensors*, and *electronic devices*. Highlights of potential safety-related applications include:

- Novel nanoscale materials such as carbon nanotubes and "buckyballs," nanoscale metals, and nanoclays that can be used in composites to improve a wide variety of materials properties including greater strength, reduced weight, improved flame retardancy and improved catalysts to name a few.
- Nanoscale materials that can be incorporated into coatings for wear-, erosion-, corrosion-, and abrasion-resistance. This will protect aircraft structures and systems from the stresses of flying.
- Lubricants incorporating nanoscale particles for reducing friction between parts and thus improving performance and reliability of aircraft and engine parts.

- Highly intelligent and sensitive sensors at very small scale for health- and condition-monitoring of aircraft components and systems; such sensors have the potential to provide advanced warning of impending failure.
- Electronic devices with the capability of making components (such as sensors) smaller, faster, more powerful and more reliable.

Implications for FAA

While nanotechnology offers much promise, the field is very much in its infancy and it is highly uncertain as to how long it will take for many relevant applications to be developed. The time to development of useful applications will be measured in years, if not decades. The following table summarizes the estimated time to market introduction for the nanotechnology categories discussed in this study.

TABLE 1

Nanotechnology Category	Estimated Time to Market Introduction
Structural Materials	5 – 10 years
Coatings	5 – 8 years
Lubricants	5 – 8 years
Sensors	10 – 15 years
Electronic Devices	10 – 20 years

As a result of important developments in nanotechnology, there are a number of implications for the FAA, given its role in aviation safety and certification, discussed below.

First, it is necessary for the FAA to set priorities on its interests in nanoscale R&D outcomes. Those efforts that result in improvements in aviation safety should be supported, while those that focus on cost-reducing outcomes are likely to be well supported by industry. In addition, establishing the focus of research areas and programs can minimize unwise duplication of efforts.

Second, the FAA should consider creating or strengthening partnerships with other government agencies and with academia in order to leverage financial and other resources and thereby support nanoscale R&D efforts in areas of common interest. This can effectively leverage FAA resources. For example, NASA efforts in nanoscale R&D are likely to hold great interest and applicability for FAA. In particular, NASA's initiatives in developing new materials with dramatically improved properties for use in space vehicle applications are likely to have similar applications to aircraft. Also, the National Institute of Standards and Technology (NIST), which undertakes and promotes research into methods, processes and standards that will allow nanotechnology to develop, is an important area for FAA to watch. Given FAA's role in certification, much work should be done that will enable FAA to understand nanomaterials and certify the devices and systems that incorporate nanotechnology, as well as the manufacturing processes and inspection methods related to them. This should be done in a timely way, i.e. without delaying industry's application of such materials and processes. NIST could be of great assistance in this area.

Third, the FAA should recognize the barriers the agency has often set before innovation. In particular, the FAA should be aware of its regulatory role and mitigate the use of regulatory processes and policies that can slow worthwhile nanotechnology development and deployment. Several panel members expressed concern that the FAA is too slow and the certification process too onerous, and that this may delay the development and adoption of aviation-related nanotechnology applications. As a result, the FAA should take measures to ensure that its role as regulator does not hinder the innovation process.

Finally, FAA should monitor research efforts in other countries. Nanoscience and nanotechnology is a global phenomena; many foreign countries have established significant nanoscale R&D efforts, some of which have very focused programs. An example is Taiwan's program related to nanoscale electronics. Other countries and regions to watch include Japan, Western Europe and Hong Kong.

1. Introduction

1.1. Background

The emerging fields of nanoscience and nanoengineering – the ability to work precisely at the atomic and molecular levels – are leading to unprecedented understanding of and control over the fundamental building blocks of all physical objects. (National Nanotechnology Initiative, 2000) This ability to control matter may one day allow science and engineering to exploit the novel properties that occur at nanoscale, and the potential exists to eventually tailor the desired chemical, physical, and biological properties and phenomena associated with nanoscale structures. Research is underway to develop applications based on nanoscience such as new advanced materials, corrosion-resistant coatings and extremely sensitive and low-cost sensors that could be used for assessing the structural integrity of vehicles. Thus, there is clearly great applicability of prospective developments in nanotechnology for transportation; nowhere is this more promising than in aviation.

1.2. Objectives

While nanoscale research and development (R&D) holds great promise for civil aviation, to date there has been no systematic attempt to relate outcomes of present and prospective research to the aviation sector. The objective of this study is to identify and describe a representative set of nanoscience and nanotechnology R&D efforts having prospective relevance to the civil aviation sector, with an emphasis on safety-related applications. To the extent possible, the likely timing of relevant nanotechnology applications will also be addressed. In addition, while nanoscale R&D is a global phenomenon, the focus will be on efforts in the United States. The results of the study will provide early guidance for FAA's decision making with regard to its resources available to be deployed to support nanoscale R&D that will benefit civil aviation. (As time passes, of course, such guidance will have to be reviewed and modified as appropriate.)

1.3. Methodology

A multi-step approach was used in collecting data to support the study. In particular, the steps in the process included:

- **Development of a "catalog" of nanoscale R&D efforts in the United States.** Over 90 government laboratories and agencies, academic institutions and organizations in the private sector involved in nanoscale R&D were reviewed. Through searches of relevant literature and Internet resources, information was compiled into "catalog entries" (attached as an appendix to this report). Each catalog entry summarizes, to the extent possible, the nature of the research program and specific projects, stated objectives of the research, stated potential industrial applications that may result from the research, and personal contact information for selected researchers. In addition, there was on-going review of other literature and Internet resources for information about nanotechnology, including scientific and professional journals, government reports and personal contact with nanotechnology researchers in both the public and private sectors.
- **Nanotechnology panel meetings.** Two panel meetings with representatives from industry and academia were conducted at the Transportation Center at Northwestern University. The panel meetings served as a forum to obtain additional information about nanoscience research initiatives underway, as well as to survey the opinions and insights of people in several civil aviation enterprises as to their interests in nanotechnology and how it may benefit civil aviation. Airframe, engine, and component manufacturers, as well as aircraft operators, were represented at the meetings.
- **Determination of the relevance of nanotechnology research efforts.** From the information gathered through the catalog entries and the panel meetings, those research efforts that appear to hold promise for enhancing civil aviation safety are identified and discussed. In addition, government research priorities to support nanoscale R&D to enhance aviation safety are suggested.

2. General State of Research and Technology Development at Nanoscale

2.1. Distinction between Nanoscience and Nanotechnology

Nanotechnology may be defined as the creation of functional materials, devices and systems through control of matter at the scale of .1 to 100 nanometers, and the exploitation of novel properties and phenomena at that scale (1 nm = 1 billionth of a meter). Nanoscience may be defined as the pure science and research that will form the basis for new nanotechnologies. Much of the fundamental research that is occurring in the nation's academic institutions and government laboratories can be considered nanoscience. Such research consists largely of the measurement and characterization of the various properties of nanoscale materials, as well as studies of the phenomena, processes and tools necessary to control and manipulate matter at nanoscale in order to form a scientific knowledge base. Nanotechnology itself is not an industry, but an emerging field of potentially "disruptive" technologies based on knowledge learned from nanoscience that may have relevance and applications across a wide range of industries.

At the nanometer scale, the classical laws of physics change, and new behaviors (such as quantum mechanics, size confinement, and others) emerge. In fact, a wide variety of properties change – optical, structural, electrical, mechanical and chemical – for nearly every material when shrunk to the nanoscale. (Fellman, 2002) Thus, nanotechnology is not just concerned with fabricating materials and devices on a smaller scale, but also with exploiting the novel properties that occur at nanoscale. This suggests that the potential exists to discover and eventually tailor to specific purposes the desired chemical, physical, and biological properties and phenomena associated with individual and assembled nanostructures. It is important to note that nanoscience is inherently interdisciplinary with much of the research being carried out in research centers and laboratories that bring together scientists with backgrounds in physics, chemistry, engineering, materials science, and biology.

2.2. Relationship of MEMS and Nanotechnology

It is appropriate to comment on the distinction between micro-electro-mechanical systems (MEMS) and nanotechnology, as the two are related, yet fundamentally different in their approach. MEMS devices, which fall between today's machines and "nanomachines" in size, are already at work in the "real" world. Prominent examples can be found in the auto industry, such as tire pressure sensors and accelerometers for the deployment of airbags, as well as MEMS gyroscopes for military and aerospace applications. MEMS represents incremental change, making devices smaller and smaller (and potentially more efficient, reliable, and less expensive). (Gillmor, 2002) MEMS devices are often fabricated using existing technology such as lithography techniques that are used today to fabricate computer chips and integrated circuits.

Nanotechnology, however, is about radical or "disruptive" change and typically approaches the problem from the bottom-up – through the manipulation and control of matter at the scale of atoms and molecules. Nanotechnology seeks to exploit the novel properties that occur in matter at the nanoscale and thereby seeks to build materials and devices with remarkable new and different properties. However, there is substantial potential for nanoscale materials and devices to be incorporated within MEMS. For example, an application area anticipated for carbon nanotubes is their use in MEMS devices as components such as bearings, actuators, and electrodes. Thus, the field of MEMS could benefit substantially from nanotechnology. Ultimately, there may even be nano-electro-mechanical systems, or NEMS, devices.

2.3. Research and Development

While the field of nanotechnology is considered in its infancy, global efforts in nanoscale R&D have grown rapidly in recent years. By 2001 it was estimated that more than 30 countries had activities or plans in nanotechnology, including broad general science programs, such as those in the U.S. and France, to industry-focused programs like Taiwan's in electronics. (Moore, 2002) According to the National Science Foundation (NSF), the proposed funding for nanoscale R&D in the U.S. in 2003 would make up about 30% of the estimated $2.15 billion worldwide government spending on nanotechnology. This would put the U.S. behind Japan, but ahead of Western Europe in government spending. Table 2.1 summarizes approximate historical government spending on nanotechnology (in U.S. $ millions).

TABLE 2.1

Region	1997	1998	1999	2000	2001	2002	2003
U.S.	$116	$190	$255	$270	$422	$604	$710
Japan	120	135	157	245	465	650	
W. Europe	126	151	179	200	225	400	
Others	70	83	96	110	380	520	

(Source: Moore, 2002)

Growth in nanoscale R&D is made possible in part by the advances in tools and processes that allow scientists and researchers to measure and manipulate structures at the nanoscale. According to Zhong Wang, director of Georgia Tech's Center for Nanoscience and Nanotechnology, five advances make nanoscience possible: (Micromagazine.com, 2001)

- The development of scanning and transmission electron microscopes, as well as scanning tunneling and atomic force microscopes.
- The introduction of new structures such as carbon nanotubes and fullerenes.
- An understanding of quantum mechanics and device structures such as quantum dots that tap into this understanding.
- Powerful computers and advanced software for simulations.
- The challenge of nanoscale devices and engineering posted on ITRS (International Technology Roadmap for Semiconductors).

Given the growth in funding for nanoscale R&D, it is not surprising that there are some fairly bold predictions about the potential market for innovations and technologies based on nanoscience. The NSF, for example, predicts that the market for products incorporating nanotechnology will be worth $1 trillion by 2015, while the NanoBusiness Alliance, a nanotechnology industry organization, believes the overall market for nanotech products could reach $225 billion by 2005. (Maneva, 2002) The NanoBusiness Alliance also estimates that venture capital investment in nanotechnology will rise to $1.2 billion in 2003 from $100 million in 1999. (Maneva, 2002) Nanotechnology applications are likely to occur in a wide variety of industries, aerospace and aviation among them, with the potential for significant enhancements to safety.

The following sections describe in more detail research efforts in the U.S., beginning with an overview of the National Nanotechnology Initiative and continuing with a discussion of the three primary sectors carrying out nanoscale R&D: academic institutions, government laboratories and agencies and private sector organizations.

2.3.1 National Nanotechnology Initiative

Driving the field of nanotechnology in the U.S. is the federal government's National Nanotechnology Initiative (NNI). The initiative, launched by former President Clinton in 2000, reflects the government's strategic plan to support research and infrastructure for nanotechnology development, and is the umbrella program coordinating nanotechnology research for multiple government agencies.

The NNI provides for a research strategy balanced across five types of activities (NNI, 2000):

- Fundamental research: Provides for sustained support for individual investigators and small groups doing fundamental research leading to discoveries of the phenomena, processes, and tools necessary to control and manipulate matter at the nanoscale.
- Grand challenges: Provides support for fundamental research with an emphasis on achieving long-term objectives in areas perceived to be important to federal agency applications. Examples of these objectives include nanomaterials by design, nanoelectronics, opto-electronics and magnetics that have implications for healthcare, energy, manufacturing, nanoscale processes and environment, microcraft and robotics, and chemical, biological, radiological and explosive detection and protection.
- Centers and networks of excellence: Provides for the creation of nanotechnology research centers to encourage networking and shared academic user's facilities. This includes six NSF-funded nanotechnology institutes at Northwestern, Harvard, Cornell, Columbia, Rice, and Renssaeler Polytech.
- Research infrastructure: Provides funding for metrology, instrumentation, modeling and simulation, and user facilities, with a goal to develop a flexible and enabling infrastructure so that U.S. industry can rapidly commercialize the new discoveries and innovations.
- Ethical, legal, and societal implications: Provides support for workforce education and training efforts and research to study the societal implications of nanotechnology.

Funding for nanoscience research has grown more than five-fold since 1997, when approximately $116 million was allocated for such research. The NNI allocated roughly $270 million for nanoscience and nanotechnology research efforts in FY 2000, and that grew to $604 million in FY 02. President Bush's FY 03 budget request for the NNI was $710 million, a 17%

increase over FY 02. Resources would be divided between various government agencies as follows (along with major areas of interest in nanotechnology): (Brown, 2002)

- National Science Foundation: $221 million for fundamental research on novel phenomena, synthesis, processing and assembly at nanoscale; instrumentation, modeling; materials by design; biostructures and bio-inspired systems; nanosystem architecture; infrastructure and education.
- Department of Defense: $210 million for information acquisition, processing, storage and display; materials performance and affordability; chemical and biological warfare and defense.
- Department of Energy: $139 million for basic energy science and engineering with research relevant to energy efficiency, defense, environment, and nuclear proliferation.
- Department of Commerce: $44 million for measurement science and standards, including methods, materials, and data.
- National Institutes of Health: $43 million for biomaterials (such as material-tissue interfaces, biocompatible materials); devices (biosensors, research tools); therapeutics (such as drug and genetic material delivery); infrastructure and training.
- NASA: $22 million for lighter and smaller spacecraft; biomedical sensors and medical devices; powerful computers that are smaller and consume less power; radiation tolerant electronics; thin film materials for solar sails.
- EPA: $5 million for research focused on risk assessment and risk management related to human health and environmental effects.
- Department of Transportation: $2 million primarily for research into improving methods of detecting explosives and biological and chemical weapons to ensure the security of the U.S. air transportation system.
- Department of Justice: $1 million for DNA research incorporating nanotechnology.

2.3.2 Academic Institutions

Given that roughly 70% of NNI funding is allocated to university-based fundamental research in nanoscience, the nation's academic institutions are at the heart of nanoscale R&D (NNI, 2000). Many colleges and universities have established programs in nanoscience and nanotechnology, sometimes in partnership with government labs and private sector organizations. Over the past five years, numerous 'nanotechnology institutes' have been created as umbrella organizations within universities to bring together faculty from a variety of academic disciplines, such as materials science, chemistry, engineering, biology, and others, to conduct nanoscale research. Often these institutes are funded with million of dollars from government resources (such as the NNI) and additional money from state and other public- and private-sector sources.

Among the largest of the academic programs in nanotechnology is the creation of six Nanoscale Science and Engineering Centers (NSECs), funded by the NSF with greater than $10 million each over a five-year period. These six universities have assembled multidisciplinary research teams to focus on a particular area of nanotechnology:

- Northwestern University: Center for Integrated Nanopatterning and Detection Technologies. The Center will focus on developing nanopatterning capabilities for soft materials, with potential applications in the design of chemical and biological sensors. The objective of the research is to develop novel biological and chemical sensor modalities (recognition and signal transduction) based on an understanding of biorecognition and the chemistry, physics, and engineering of functional surface architectures with nanometer features.
- Harvard University: Center for the Science of Nanoscale Systems and Device Applications. The goal of the program is to explore the properties of nanostructures for novel electronic and magnetic devices, including potential applications in quantum information processing.
- Cornell University: Center for Nanoscale Systems in Information Technologies. The focus on research at the Center will be on understanding and controlling the nanoscale properties of materials and looking at devices based on those properties that can be put together to make successful new systems for ultrahigh-performance processing, storage, and transmission of information.
- Columbia University: Center for Electronic Transport in Molecular Nanostructures. The Center collaborates with national laboratories and industrial partners to research and gain a

fundamental understanding of how electrons move through molecules and through structures of molecules on the scale of a nanometer. The goal of the research is to establish the foundation for new paradigms for information processing through the development of a fundamental understanding of charge transport phenomena unique to the character of nanoscale molecular structures.

- Rice University: Center for Biological and Environmental Nanotechnology. Research activities will explore the interface between nanomaterials and aqueous systems at multiple-length scales, including interactions with solvents, biomolecules, cells, whole organisms and the environment. This will serve as foundational knowledge for designing biomolecular/nanomaterial interactions, solving bioengineering problems with nanoscale materials and constructing nanoscale materials useful in solving environmental engineering problems.
- Rensselaer Polytechnic Institute (RPI): Center for Directed Assembly of Nanostructures. Areas of research include directed assembly of nanostructures to create gels and polymer nanocomposites, nanostructured biomolecule architectures, multi-scale theories and models, and characterized nanostructured materials.

These institutions are leading the way in nanoscience research that may result in important developments in the field, and potentially the development of applications of nanotechnology that contribute to the enhancement of aviation safety.

Of course, numerous other universities have established or are planning to establish meaningful programs in nanoscale R&D that can also lead to important developments in nanotechnology. Following are a few examples:

- Purdue University: Construction is underway on a new $51 million facility to be known as the Birck Nanotechnology Center. Research groups are exploring the science of nanostructures and new materials, as well as the design and fabrication of nanoelectronic devices. Also, Purdue was named in 2002 as one of three NASA-funded University Research, Engineering and Technology Institutes, and will focus on nanoelectronics and computing with about $3 million in funding each year for five years.

- University of California at Los Angeles (UCLA) and at Santa Barbara (UCSB): The California NanoSystems Institute, a multi-million dollar initiative involving collaboration between UCLA and UCSB, plans to develop research programs in a variety of areas of nanoscience. In addition, it will promote and facilitate the transfer of nanosystems innovation to the marketplace. Also, UCLA was named in 2002 as one of three NASA-funded University Research, Engineering and Technology Institutes and will focus on the fusion of bio-nanotechnology and information technologies. Government funding is about $3 million a year for five years.
- Princeton University and Texas A&M: Named in 2002 as one of three NASA-funded University Research, Engineering and Technology Institutes, the partnership between these two schools will focus on bio-nanotechnology materials and structures for aerospace vehicles, with about $3 million in funding a year for five years.
- University of North Carolina: The Center for Nanoscale Materials is performing research in new materials synthesis and fabrication as well as studies of the mechanical, electronic, magnetic, and optical properties of new materials such as carbon nanotubes.
- University of Texas (Austin): The Center for Nano and Molecular Science and Technology is conducting research in a variety of areas including bioelectronic materials, molecular nanoscale electronic materials and quantum dot and quantum wire materials.

More detailed information about these and many other academic research programs can be found in the catalog entries attached to this report as Appendix 1.

2.3.3 Government Agencies and Laboratories

While many government organizations act as funding vehicles allocating resources to academic institutions to perform research, there are numerous important research projects underway at some government labs and agencies. Prominent examples include:

- NASA: In addition to funding the new university programs in nanotechnology mentioned above, the Center for Nanotechnology at NASA Ames Research Center employs about 50 full-time scientists and is extensively involved in nanoelectronics research involving carbon nanotubes, molecular electronics, inorganic nanowires for sensors and devices, and other areas. The goal of the program is to develop novel concepts in nanotechnology for NASA's future needs in electronics, computing, sensors, and advanced miniaturization of all systems.

- Argonne National Laboratory: This lab has strong research capabilities in the materials science area, including work on corrosion-resistant coatings, and has numerous partnerships with universities (including the University of Chicago and University of Illinois) and private sector companies.
- Brookhaven National Laboratory: The Center for Functional Nanomaterials is one of several centers established by the Department of Energy to form an integrated national program of Nanoscale Science Research Centers (NSRCs). This particularly center will focus on research into oxides, magnetic nanoassemblies, nanocatalyst materials, charge injection and transport, and other areas.
- Lawrence Berkeley National Laboratory: The Materials Science Division performs significant research into advanced materials, including carbon nanotubes and other materials that could be incorporated into MEMS devices.
- Los Alamos National Laboratory and Sandia National Laboratory: The Center for Integrated Nanotechnologies, a joint venture between Los Alamos and Sandia, is one of several centers established by the Department of Energy to form an integrated national program of NRSCs. Science themes at this center are to include complex functional materials, nanomechanics, nano/bio/micro interfaces and nanoelectronics/nanophotonics.
- Oak Ridge National Laboratory: Another DOE lab that focuses on nanostructured materials, including carbon nanotube-based electronic devices and other designer nanoscale materials.
- Pacific Northwest National Laboratory: Another DOE lab that is pursuing nanoscience research in the nanomaterials and nano-biology areas.
- National Institute of Standards and Technology (NIST): An important goal of NIST is to develop the new measurements, standards and data needed to turn fundamental nanotechnology discoveries into new technologies with applications in a wide variety of areas.
- Naval Research Lab (NRL): Various components of this lab, including the Chemistry, Surface Nanoscience and Sensor Technology sections perform research in numerous areas, including surface science, nanoelectronics and the structural and chemical analysis of materials.

More detailed information about these and other specific research programs can be found in the catalog entries attached to this report as Appendix 1.

2.3.4 Private Sector Organizations

As corporate R&D typically focuses on more near-term projects with an expected payoff, organizations in the private sector are focusing on those areas of nanoscience that may find its way into more near-term technology applications. It is encouraging that companies such as Boeing and GE are devoting sizable resources (financial and other) to aid in the long-term development of nanotechnology. GE, for example, is making nanotechnology a priority in its R&D program and is undertaking many projects that are not expected to have a bottom-line impact for at least 10 years. (Stein, 2002) Numerous other companies, from large, multi-nationals such as Hewlett-Packard and IBM to smaller "pure play" nanotechnology companies are also making long-term investments in nanoscience research. Following are some examples of important research programs and products under development in the private sector:

- Carbon Nanotechnologies Inc.: This company is an important producer advanced materials such as carbon nanotubes, based on technology developed at Rice University. The company states that applications for its products include high-strength and novel composite materials, as well as electronic devices.
- Inframat Corp.: Under funding from the U.S. Navy, the company is developing nanostructured materials and multifunctional coatings to improve material properties and performance for a broad range of engineering applications. In particular, thermal spray nanocomposite coatings of alumina and titania appear to offer improved hardness and corrosion-resistance.
- InMat Inc.: The company is developing flexible barrier coatings incorporating nanoclays – nanometer sized platelets of clay materials – which provide a chemical barrier and improve air retention. The barrier coatings may have applications to tires (including aircraft tires), with benefits including improved air retention and reduced weight and oxidation resulting in extended tire life.
- Nanocor: The company is a leader in the development of nanoclays specifically designed for plastic nanocomposites. Such nanocomposite products are likely to improve barrier, flame resistance, thermal and structural properties of many plastics and could have applications to aircraft materials, particularly for flame retardancy.

- Nanophase Technologies Corp.: The company has developed processes to create controlled mixtures of nanomaterials that provide abrasion- and wear-resistance, as well as nanocrystalline particles that can be dispersed in a wide range of formats to tailor the particles to meet a variety of customer applications. Stated applications include ceramics for use in a wide range of demanding environments based on nanocrystalline aluminum oxide and ZTA (zirconia-toughened alumina).
- NanoPowders Industries: A producer of nanosized metal powders in the 20-80 nm range, the company's products can be used as additives in plastics and coatings for improved mechanical properties and corrosion resistance.
- Reactive NanoTechnologies Inc.: Through the use of nanotechnology, the company is developing a revolutionary advance in materials joining. Applications could result in metal-to-ceramic bonding and may prevent damage to heat-sensitive components during the joining process.
- Technanogy: The company is a producer of high-quality, highly energetic ultra-pure aluminum powder at the nanoscale. The nano-aluminum powder may offer significant performance improvements in energetic applications, such as aviation fuel, that could offer improved fuel economy and reduced emissions.
- Zyvex Corp.: Under funding from the NIST Advanced Technology Program, the company is undertaking research to develop prototype micro-scale assemblers using MEMS, and to extend the capabilities to nanometer geometries. The program is structured to develop systems providing highly parallel micro- and nano-assembly for real-world, high-volume applications.

More detailed information about these and many other private sector research programs can be found in the catalog entries attached to this report as Appendix 1.

3. Applications of Nanotechnology

3.1. Specific Areas Being Addressed with Nanotechnology

This study has identified several generic categories of nanotechnology that have the potential to provide dramatic new capabilities and innovations, many of which may enhance civil aviation safety. These categories are:

- Structural Materials
- Coatings
- Lubricants
- Sensors
- Electronic Devices

The following sections describe the potential nanotechnology applications that may arise in these categories that are also relevant to civil aviation, based on both the nanoscience research that is occurring in these areas and the interest in such applications by the "user" community (i.e., aircraft and engine manufacturers and operators).

3.1.1 Structural Materials

Nanostructured materials is considered to be perhaps the largest opportunity area within nanotechnology, and it is highly likely that new advanced materials will play a large part in the aerospace industry of the future. Nanotechnology may fundamentally change the way materials are produced, allowing for the ability to assemble nanoscale building blocks into larger structures with unique properties and functions. According to In Realis, a technology consulting firm, a profile of the current nanotechnology focus among 300 firms shows that "materials" is the largest area for expenditure (46% of total), followed by electronics (24%), biotech (16%), and tools (14%). (Glapa, 2002)

Carbon Nanotubes and the Fullerenes

Perhaps one of the most exciting and promising developments in the materials area is the discovery of a novel form of carbon, C-60, in 1985 by Dr. Richard Smalley of Rice University, and the subsequent discovery and engineering of carbon nanotubes in 1991. Carbon nanotubes are a part of a relatively new class of molecules known as fullerenes, which are molecules of carbon formed in a hollow, hexagonal or pentagonal shape. Much of the work on fullerenes is focused on C-60, which is a naturally occurring form of carbon in a soccer ball shape consisting of 60 carbon atoms (such carbon is often referred to as "buckyballs"). (Nanotechplanet.com,

2001) Carbon nanotubes are perfect, hollow molecules of pure carbon linked together in a hexagonally-bonded network to form a hollow cylinder that can be either single- or multi-walled, typically with a diameter of about 1 nm. These nanomaterials are considered to have vast potential for the generation of new, organic compounds. (Nanotechplanet.com, 2001)

Carbon nanotubes and buckyballs are promising because of their unique properties. Therefore they represent an important building block for nanotech materials and devices. Properties of carbon nanotubes include (NNI, 2000 / Bailey, 2002):

- Strength approximately 50 to 100 times greater than steel at approximately one-sixth its weight (they are among the stiffest and strongest materials known).
- Durability greater than diamond.
- Full range of electrical and thermal conductivity properties (they are believed to conduct heat better than any other known material).

This suggests that new materials with remarkable properties are possible and there is potential for their use in a wide range of applications. These properties also suggest that they have numerous applications relevant to aviation and aviation safety. Bob Gower, CEO of nanotube producer Carbon Nanotechnologies, Inc., states that single-wall carbon nanotubes are "ideal for aerospace" when incorporated into composites. (Stuart, 2002) Such composites could be the basis of stronger and lighter aircraft materials.

Currently, carbon nanotubes are expensive to make and cannot be produced in large quantities, with worldwide production of C-60 fullerenes in 2001 estimated at just 100 to 200 kilograms. (Waga, 2002) In addition, production of nanotubes has frustrated researchers with their tendency to clump together in solution, thereby inhibiting the ability to manipulate and control their dispersion. However, numerous companies are pioneering methods to produce larger-scale quantities, including Carbon Nanotechnologies, Inc. Progress is also being made to address the problem of aggregation. For example, the University of Pennsylvania is testing surfactants that may prevent nanotubes from clinging to one another. (Nanoelectronicsplanet.com, 2003) Thus, the research community remains hopeful that carbon nanotubes will in fact lead to new advanced materials with applications in a wide variety of industries. While it is difficult to say when carbon nanotubes will be used in aviation-related applications, one panel member suggested that they will first be incorporated into component structures in about seven years.

Potential Applications Identified

More likely near-term applications of advanced materials will be the use of nanoscale materials within existing materials (such as fillers for polymers) to improve various properties of existing materials such as strength, hardness, corrosion resistance, electrical or thermal conductivity and others. Longer-term applications are more likely to be new materials used to build devices and systems, and perhaps eventually "smart" materials that can sense their health and even self-repair. Following are a few highlights of possible applications of nanomaterials that may enhance aviation safety:

- **Composite materials.** New composite materials are being developed through the use of nanoparticles – particularly carbon nanotubes – embedded in materials such as polymers and metal alloys for the creation of advanced materials with improved strength and reduced weight characteristics. In addition to carbon nanotubes, ceramics based on nanocrystalline aluminum oxide and zirconia-toughened alumina may offer improved materials properties that are useful for structures operating in harsh environments, such as aircraft engine components. These new composite materials are likely to find their way into aircraft materials and structures that make aircraft components and systems stronger and lighter, and therefore more reliable and resistant to failure.
- **MEMS components.** Carbon nanotubes may offer promise for use as building blocks in MEMS devices. For example, bearings, actuators and electrodes could be made from carbon nanotubes. MEMS devices may benefit significantly from improved strength and reduced failure rates of components enhanced by nanotechnology. Such devices may be used in a variety of ways to enhance aviation safety, such as highly reliable aircraft systems components or as sensors that monitor the performance of aircraft structures, systems and engines that can provide early warning of possible failure.
- **Flame-resistant materials.** Greatly improved flame-resistant materials appear to be possible through the incorporation of nanometer-sized clay particles into a variety of plastics, particularly polyolefins. Such nanocomposites use smaller quantities of traditional flame retardant additives (with resulting environmental benefits) while achieving greater

strength. (Flame Retardancy News, 2002) Such flame-retardant properties could prove useful for various aircraft materials, including interior materials and possibly wiring. Nanocor, a leader in nanoclay technologies, has a research and development program devoted to incorporating nanometer-sized flame-resistant clay particles into plastics for use in a variety of industrial applications, including aviation.

- **Catalysts.** Nanoscale structures have inherently large surface-to-volume ratios which provide the capability for a more complete reaction and makes nanoparticles useful as catalysts. Nanoparticles of aluminum powder may offer significant performance improvement in energetic applications, such as aviation fuel, that could offer improved fuel economy and reduced emissions. Technanogy is a producer of high-quality, highly energetic ultra-pure aluminum powder at nanoscale for use in various energetic applications.

3.1.2 Coatings

Another very promising area for nanotechnology applications is that of coatings. Protective coatings are widely used now in a number of aviation applications, and nanotechnology has the potential to create new and dramatically improved coatings. The objective of coatings is to create a surface where the attributes differ from that of the underlying material, thus improving such characteristics as wear-, erosion-, abrasion-, and corrosion-resistance. (Legg, 2002) Coatings also show promise when used for friction, optical, electronic and magnetic, decorative, and specialized military purposes. The main advantage of nanotechnology-enhanced coatings is that one can harness the benefits of nanomaterials without making the whole part from the expensive material. (Legg, 2002)

Several panel members expressed a strong interest in nanotechnology-enhanced coatings, and many believe that coatings offer a most promising opportunity area for nanotechnology applications. Such interest included barrier and hard coatings for improved strength and corrosion-resistance of aircraft components and structures, as well as thermal barrier protection for components exposed to high temperatures as in engines. There is also substantial interest in glare- and scratch-resistant coatings for windows and canopies to extend window life, as well as friction-resistant coatings for aircraft structures to reduce drag and improve performance. Some panel members also suggested that the coatings area could be a more near-term application, because existing technology and infrastructure can be used in large part to create coating materials incorporating nanoparticles.

Potential Applications Identified

Specialized coating applications that may promote aviation safety include:

- **Corrosion-resistant coatings.** Use of nanomaterials, particularly nanoscale-sized particles of metals such as aluminum and titanium, may dramatically improve the effectiveness of coatings that offer corrosion-resistance. Inframat Corp. has developed, under funding from the U.S. Navy, thermal spray nanocomposite coatings of alumina and titania, originally designed for shipboard use for corrosion-resistance. It is likely that there will be some related aerospace applications of such a corrosion-resistant coating for certain aircraft structures and components to reduce the probability of failure and extend to the life of the component or structure.
- **Hard and thermal barrier coatings.** Use of nanomaterials can also improve the properties of hard and thermal barrier coatings. In particular, thermal sprayed coatings incorporating nanostructures such as alumina/titania ceramics, tungsten carbide cobalt metal ceramics and ceramic-toughened zirconia may improve wear- and erosion-resistance, as well as hardness for the protection of aircraft components. Also, coatings incorporating nanoparticles of yttria-stabilized-zirconia may offer improved thermal barrier protection, useful for the protection of hot section engine components. Organizations undertaking R&D into these areas include Inframat Corp., the University of Connecticut and the Defense Advanced Research Projects Agency (DARPA), as well as others.
- **Flexible barrier coatings.** InMat Inc. is developing flexible barrier coatings incorporating nanometer-sized platelets of clay materials ("nanoclays") that provide a chemical barrier and improve air retention. The barrier coatings could have applications to aircraft tires, with benefits including improved air retention and reduced weight and oxidation, resulting in improved safety and extended tire life.
- **Coatings for electronic shielding.** The electrical conductivity properties of carbon nanotubes suggest their usefulness as fillers in composites and coatings with applications for electronic devices aboard aircraft for EMI and RFI shielding in order to improve communications systems.

- **Hydrophobic coatings.** Several glass manufacturers have demonstrated that a surface layer coating of titanium dioxide particles so small that they are transparent can repel water and loosen dirt in the presence of ultraviolet light. (Geracimos, 2002) Such treatments could be applied to aircraft windows and canopies for improved pilot visibility. Also, U.S. Global Aerospace, Inc. recently acquired a super hydrophobic surface treatment, dubbed 'Nanosil,' that produces surfaces that are designed to repel water completely. Atoms of silicon are incorporated into a molecular structure to change the electrical nature of a polymer material so that water repellency can be "tuned" for optimum performance. Surfaces treated with the product, such as aircraft windows, radomes and flight surfaces may exhibit anti-icing and anti-fogging properties. (Nanoinvestornews.com, 2002)

3.1.3 Lubricants

Lubrication is particularly important to many aircraft structures; nanomaterials have the potential to improve substantially the properties of lubricants. Nanotechnology-enhanced lubrication will dramatically reduce friction between moving parts, minimizing wear and improving overall machine performance while reducing maintenance costs. This can be particularly important for very small devices with moving parts, such as MEMS devices, where friction and shear can be particularly strong. Many such devices can be found in aviation.

Potential Applications Identified

- **Nanoparticle-based lubricants.** Applied NanoMaterials, Inc., is developing a solid lubricant ("NanoLub") based on nanoparticles of inorganic compounds which lubricate by rolling like miniature ball bearings. The lubricant can be used as an additive to oil and grease lubricants, thin film coatings and material for impregnating self-lubricating parts. It is expected that a solid lubricant such as this will reduce friction and improve machine performance and reliability, and will likely have application to aerospace systems. (Kanaan, 2002)

3.1.4 Sensors

Nanotechnology may lead to advances in sensing through the convergence of advanced materials and nanoelectronics capabilities that allow for the creation of highly sensitive and intelligent sensors at very small scale. Today, MEMS devices are currently used in various sorts of sensors and their capabilities will continue to expand in the near term as they are further developed. Nanomaterials may be used in MEMS, and ultimately in nano-electro-mechanical systems (NEMS). Major potential application areas of nanotechnology to sensing include sensors for condition and health monitoring of vehicle structures and components, and chemical, biological, radiological, and explosives detection, all relevant to aviation.

While sensors incorporating nanoscale components offer much promise, there are some major challenges that need to be addressed before such sensors become effective and economically viable. Several panel members noted that, while the technology for the sensors may be on the horizon, the "communications network" behind them, and the ability to interrogate information from sensors, is a problem that dominates cost and performance considerations. Improved processing and computation methods are therefore necessary to gather, transmit, and process the data and information to determine when a signal represents some type of failure. The ability of sensors to discriminate, or to detect the types of problems they are designed to reflect, is still a major challenge and points to the need for a high level of reliability. Other important challenges include the power consumption of sensors, the placement and number of sensors necessary to "instrument" large structures and the risk of data overload. Research efforts to address these challenges would therefore be appropriate.

Potential Applications Identified

The following are several potential applications that have been identified as having the promise of enhancing aviation safety:

- **Sensors for condition monitoring.** Work is being carried out at various research institutions, including NASA's Langley Research Center, on carbon nanotube-based stress sensors embedded in aircraft structures and components. Such sensors would be designed to detect fractures, corrosion, and other signs of failure in aerospace materials by using nanotubes as circuits that give off electrical signals at a sign of failure. (Stuart, 2001) Ultimately, integrated nanoscale sensor systems may be possible for collecting, processing, and communicating large amounts of data with minimal size and power consumption. Such systems would utilize advances in nanoscale electronics and may be used to monitor the condition of numerous aircraft components and systems.

- **Sensors for chemical, biological, radiological, and explosives detection.** Given the importance of homeland security in the U.S., the National Nanotechnology Initiative recently initiated a "Grand Challenge" relating to chemical, biological, radiological and explosives detection and protection. Advances in nanoelectronics may allow for new portable, highly sensitive, automated, chemical and biological sensors, with potential uses for drug, chemical, and explosives detection aboard aircraft and in airports. In particular, novel chemical detectors based on nanoscale and MEMS components, such as integrated circuits, could be used to sense trace amounts of explosives and chemical or biological weapons. Such nanotechnology-based sensor technologies may offer benefits such as improved sensitivity and selectivity, reduced weight, and improved reliability over current systems.

3.1.5 Electronic Devices

In the area of computing and electronic devices, nanostructured materials such as carbon nanotubes offer the potential to make devices smaller, faster, more powerful, and eventually less costly. Researchers at various institutions (including UCLA, Hewlett-Packard Labs, IBM, and others) have already demonstrated the potential use of carbon nanotubes as electronic circuitry that may one day replace silicon crystals as the building blocks for ultra-fast, ultra-small computers. (Rotman, 2002) The use of nanotubes or related materials (such as nanowires) as tiny electronic switches suggests that nanotubes could have a big impact on computer memory and logic. In fact, "carbon nanotubes are, in theory at least, the ideal material for building tomorrow's nanoelectronics." (Rotman, 2002) Thus, nanomaterials are potential building blocks for molecular electronic and opto-electronic devices, which could lead to applications that enhance aviation safety.

Potential Applications Identified

Following are some examples of potential applications relevant to aviation:

- **Flat Panel Displays.** The high electrical conductivity of carbon nanotubes, combined with the sharpness of their tips, mean that they are among the best known electron field emitters of any material. (Carbon Nanotechnologies, Inc., 2003) Thus, use of carbon nanotubes in next-generation cathode ray tubes (CRTs) and flat panel displays may provide improved resolution for avionics and cockpit displays.

- **Molecular electronics.** Molecular electronic devices based on nanostructures, particularly carbon nanotubes, could lead to the creation of novel electrical, semi-conducting and thermal conductivity properties that improve processing and transmission speeds of electronic devices. This would improve the speed and reliability of avionics and on-board computer systems of the future, while reducing their power consumption. It also has positive implications for electronics used in air traffic management.
- **Antenna and radar.** MEMS-based phased-array radar using radio frequency (RF) photonics may provide for lower weight, lower cost RF transmission and improved communications systems.

3.1.6 Tools, Standards and Methods

Before nanotechnology can be fully developed, characterization and manipulation of matter at the nanoscale must be possible. The development of scanning probe microscopes and scanning tunneling microscopes has enabled some basic nanoscience research to be carried out. However, new and improved experimental tools need to be developed to broaden the capability to measure and control nanostructured materials, including the development of new standards of measurement. The mission of NIST is to support the development of measurement and standards infrastructure to support U.S. industry development and commercialization of nanotechnology. More specifically, R&D at NIST will support:

- New atomic scale measurements for length, mass, chemical composition and other properties.
- New nanoscale manufacturing technologies to be used by industry in assembling new devices at the atomic level.
- New standard methods, data, and materials to transfer NIST nanotechnology to industry and assure the quality of nano-based products.

4. Motives for Pursuing Nanotechnology Applications

A variety of motives exist for pursuing nanoscale R&D and a review of these motives and interests across the aviation supply chain can help identify those applications that are most likely to be developed earlier rather than later. Information about motives and interests on the part of airframe, engine, and component manufacturers, as well as aircraft operators, was primarily obtained from the two nanotechnology panel meetings held at the Transportation Center. As mentioned earlier, representatives from each of these areas were surveyed about their interests in nanotechnology and their beliefs as to how nanotechnology can enhance aviation safety in general, and benefit their firms specifically.

4.1. Airframe Manufacturers

Of primary interest to airframe manufacturers are technologies that improve the strength and reduce the weight of materials used to build airplanes. Such improvements may lead to significant aircraft performance improvements, as well as improved safety and reliability. Intelligent micro- and nano-scale sensors for health and condition monitoring of aircraft structures and systems were also identified, as was the use of nanoparticles as "nanoenergetics," or catalysts, in fuels. The use of nanoparticles in fuels can improve fuel economy and reduce emissions. Finally, the continued development of tools and standards that promote nanotechnology development, as well as to improve quality control and inspection methods, were highlighted as of critical importance. As new technologies often must be certified, the proper tools and standards must be in place to monitor their performance.

Several panel members also noted that the economics of new technologies are very important. Until the cost of new nanotechnologies (such as nanoparticles) becomes reasonable, it is unlikely that they will find their way into the commercial side of aviation manufacturing.

4.2. Engine Manufacturers

Of primary importance to engine manufacturers are advanced materials that offer an improvement over the properties of existing materials, as well as materials such as nanoparticles that can be incorporated into coatings and lubricants for the protection of engines and components that are used in harsh environments. For example, coatings that provide improved oxidation and corrosion resistance, as well as thermal barrier coatings for engine hot section walls are greatly desired. In addition, it was mentioned that sensors for engine health and condition monitoring is an important area and could be coupled with maintenance systems to provide early warnings of engine problems and thus increase reliability and reduce maintenance costs.

4.3. Aircraft Operators

From an aircraft operators' perspective, those technologies that improve operations through increased reliability and safety, as well as those that contribute to reduced costs are desired. Potential nanotechnology applications identified include:

- Anti-ice coatings incorporating nanoscale particles for wing applications to reduce – even eliminate – the need for aircraft de-icing or anti-icing.
- Scratch-resistant, anti-reflective coatings for windows and canopies.
- Sensors for health- and condition-monitoring of aircraft components and systems for early warning of problems and reduced maintenance costs.
- "Nanoenergetics" to improve fuel economy and reduce environmentally undesirable emissions.

4.4. Other Suppliers

Other suppliers, such as avionics, component and systems manufacturers may be equally interested in utilizing new nanotechnologies that improve the performance of their products. An avionics producer, for example, may be particularly interested in advanced materials and nanoparticles such as carbon nanotubes for use in CRTs and LEDs for improved resolution of cockpit displays and reduced power consumption. Also of interest to avionics manufacturers may be new, ultra-small electronic devices that improve on-board computing processing speed and data storage capabilities, while reducing weight and space requirements on the aircraft. Other component manufacturers, such as landing gear makers, are likely to be interested in advanced materials that improve the strength of metal alloys while reducing weight.

While many second-tier suppliers to the aerospace industry may not have the R&D capabilities and financial resources that primary suppliers do, it is likely that partnerships will form between these suppliers and their primary supplier customers, as well as with academia. It is important that nanoscale R&D knowledge and capability be extended broadly to suppliers if the aviation industry is to get the full benefits from developments in nanotechnology.

4.5. Government (i.e., FAA in Safety and Certification Roles)

Government (i.e., FAA) is interested in both on- and off-aircraft technologies that contribute to improved safety and efficiency. Just one example: enhanced airport security involving nanoscale sensors for hazardous materials detection and protection could be of great interest to FAA and TSA. As a result, FAA must approach nanoscience and nanotechnology on two levels. First, as a customer for certain "hardware," as in ATM and in test and inspection devices, FAA should maintain currency with respect to the field in order to know when nanoscale products and components can improve FAA's own performance. This may require that FAA, on occasion, actually pursue nanotechnology development for its own account. Second, FAA will have to consider for approval (i.e., certification) a growing number of devices, components and materials incorporating nanoscale elements and to do this in a timely, efficient and confident manner. FAA must establish and maintain an expanding stock of intellectual capital about nanoscience and nanotechnology.

5. Implications for FAA and DOT

While nanotechnology offers great promise, the field is very much in its infancy and it is highly uncertain how long it will take for many relevant applications to be developed. The time to development of useful applications will be measured in years, if not decades. As a result, there are a number of implications for the FAA, given its role in aviation safety and certification. The following sections describe some of these implications in more detail, including the need to set R&D priorities, develop and strengthen partnerships, and the need to recognize and avoid barriers to innovation.

5.1. Setting R&D Priorities

First, it is necessary for FAA to set priorities on its interests in nanoscale R&D outcomes. Those efforts that result in improvements in aviation safety should be supported, while those that focus on cost-reducing outcomes are likely to be well-supported by industry. In addition, an understanding of the existing focus of research areas and programs can reduce unwarranted duplications of efforts.

More specifically, several panel members have suggested a number of research priorities that they believe the government (including FAA) should pursue, including:

- Studies of the environmental effects of the use of nanoparticles in aviation fuels.
- Studies of tools and inspection techniques in areas that are relevant to the types of nanotechnologies that may be adopted by civil aviation.
- A stronger focus on technology development and less focus on pure research.

5.2. Develop and Strengthen Partnerships

The FAA should consider establishing or strengthening partnerships with other government agencies, as well as academia, to leverage financial and other resources, and thereby support nanoscale R&D efforts in areas of common interest. For example, NASA initiatives in nanoscale R&D are likely to hold great interest and applicability for FAA. NASA's strengths in materials science and development at nanoscale is particularly relevant to FAA interests in such advanced materials that could improve the safety and performance of aircraft structures and components. The FAA should ensure that they are aware of NASA's R&D efforts and be capable of leveraging the knowledge created at NASA.

The National Institute of Standards and Technology (NIST), which undertakes and promotes research into methods, processes and standards that will allow nanotechnology to develop, is another important agency for the FAA to survey. Given FAA's role in certification, much work will need to be done in the area of understanding and certifying new materials, devices and systems that incorporate nanotechnology, as well as manufacturing processes and inspection methods related to these new technologies. NIST could prove of great assistance in this area.

Also, given that a substantial portion of total nanoscale R&D is occurring in the nation's academic institutions, the FAA should monitor the results of research from this sector. (The catalog entries attached as Appendix 1 to this report represent a beginning in this respect.) The FAA should then consider establishing or strengthening partnerships with those institutions that are performing research relevant to aviation. Perhaps a valuable role the FAA could serve in this capacity is in facilitating the transfer of fundamental knowledge created in academic institutions to valuable technology applications that can be adopted by industry.

Finally, FAA should continually monitor research efforts in other countries. Nanoscience and nanotechnology are global phenomena; many foreign countries have established significant nanoscale R&D efforts, some of which have very focused programs, such as Taiwan's in nanoscale electronics. Other countries and regions to watch include Japan, Western Europe and Hong Kong.

5.3. Recognizing and Avoiding Barriers to Innovation

Regulation

In the context of manufacturing, monitoring and certification, government (i.e., FAA) regulation arises as an important issue with the potential to delay nanoscale innovations. Several panel members expressed concern that the FAA is too slow and the certification process is too onerous, and that this will delay aviation-related applications. In short, many fear FAA processes will discourage and delay the adoption of nanotechnology applications. As a result, some panel members expect that many relevant nanotechnology applications will occur first in non-aviation industries. FAA should make every attempt to avoid those processes that will unnecessarily hinder the development and adoption of nanotechnology applications.

Tools, Standards and Inspection Techniques

A big challenge to nanotechnology is the creation of tools and standards for quality control and inspection. Characterization of properties is very important at the early stage, and currently there is no ability to do nanoscale inspection of macroscale parts because the proper tools have yet to be developed. This area is very new to the FAA and the aviation industry, and the proper standards relating to nanotechnology application development, manufacturing, certification, and inspection will have to be developed. The National Institutes of Standards and Technology (NIST) will likely play a big role in this and the FAA should work collaboratively with NIST.

Economics

At microscale, economics is an important issue, and the MEMS industry has not driven down cost as much as many had expected. Several panel members noted that there is not much flexibility in MEMS manufacturing and this drives up cost. To make manufacturing of many MEMS devices worthwhile, a massive market and long production runs are needed. However, this is not characteristic of aviation; it better describes other industries, such as manufacturing of automobiles, household appliances and electronics, all of which have taken advantage of MEMS to a greater degree than has aviation.

At nanoscale, it is currently very expensive to produce certain types of nanoparticles, particularly carbon nanotubes. For nanomaterials to find their way into aviation-related applications, the cost will have to come down significantly, as aerospace companies are typically cost-sensitive and demand both *better* and *cheaper* from new technologies.

Culture of Aerospace Companies

Several panel members suggested that the conservative nature of the aviation and aerospace industries suggest that these industries are "followers," not "leaders" in innovation. Since safety is such an important issue for aviation, reliability must be demonstrated first, and many expect that most nanotechnology innovations will appear in other industries first. However, this does lead to ample opportunity for still other industries to benefit from (piggyback) R&D occurring in the former settings.

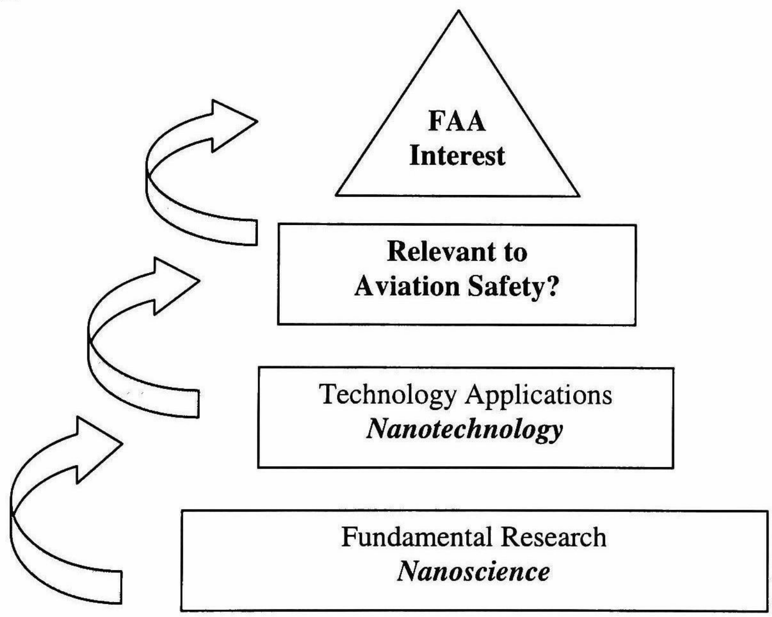
Lack of Human Capital

Nanotechnology is inherently interdisciplinary as it represents a convergence of biology, chemistry, physics, materials science, engineering and other disciplines. Nanotechnology researchers therefore require a broad array of skills and talents, as well as an ability to work collaboratively with researchers from various backgrounds and disciplines. It has been suggested by many that companies and other research entities have found it difficult to find talent with the requisite knowledge, background and skills. The NNI is attempting to address this as part of the annual funding is allocated to programs in workforce training and education.

6. Summary and Conclusions

Given the substantial investment in nanoscale R&D on the part the federal government and others in the public and private sectors, it is highly likely that new and innovative nanotechnologies will be developed with applications in a wide variety of industries, including civil aviation. The goal of this study has been to identify and describe a representative set of nanoscience and nanotechnology efforts having prospective relevance to the civil aviation sector, with an emphasis on identifying safety-related applications of FAA interest. Figure 7.1 provides an overview of the steps in the process.

Figure 6.1



Through this process, several generic categories within nanotechnology are identified that have the potential to provide dramatic new capabilities and innovations, many of which may enhance civil aviation safety. These categories are *structural materials, coatings, lubricants, sensors*, and *electronic devices*. Highlights of potential safety-related applications include:

- Novel nanoscale-sized materials such as carbon nanotubes and "buckyballs," nanoscale metals and nanoclays that can be used in composites to improve a wide range of materials properties including greater strength, reduced weight, improved flame retardency, and improved catalysts to name a few.

- Nanoscale-sized materials that can be incorporated into coatings for wear-, erosion-, corrosion-, and abrasion-resistance and for protection of aircraft structures and systems.
- Lubricants incorporating nanoscale particles for reduced-friction between parts and improved performance and reliability of aircraft parts.
- Highly intelligent and sensitive sensors at very small scale for health- and condition-monitoring of aircraft components and systems, with the potential to provide advanced warning of impending failure.
- Electronic devices with the potential to make devices such as sensors smaller, faster, more powerful and more reliable.

While nanotechnology offers great promise, the field is very much in its infancy and it is highly uncertain how long it will take for many relevant applications to be developed. The time to development of useful applications will be measured in years, if not decades. The following table summarizes the estimated time to market introduction for the nanotechnology categories discussed in this study.

TABLE 6.1

Nanotechnology Category	Estimated Time to Market Introduction
Structural Materials	5 – 10 Years
Coatings	5 – 8 Years
Lubricants	5 – 8 Years
Sensors	10 – 15 Years
Electronic Devices	10 – 20 Years

As a result of important developments in nanotechnology, there are a number of implications for the FAA, given its role in aviation safety and certification, discussed below.

First, it is necessary for the FAA to set priorities in its interests in supporting nanoscale R&D efforts. Those projects that result in enhancements in aviation safety should be supported, while those focusing on cost-reducing outcomes are likely to be well-supported by industry. In addition, an understanding of nanoscale R&D endeavors undertaken by others in both the public and private sectors in the U.S. and elsewhere can best assure unwarranted duplication of efforts.

Second, the FAA should consider establishing or strengthening partnerships with other government agencies and academia to leverage its financial and other resources and to support nanoscale R&D efforts in areas of common interest. For example, NASA nanoscale R&D projects are likely to hold great interest and applicability for FAA. Also, the National Institute of Standards and Technology (NIST), which undertakes and promotes research into methods, processes and standards that will allow nanotechnology to develop, is an important area for the FAA to monitor. Given FAA's role in certification, much work will need to be done to assure its timely understanding of nanotechnology. Only in this way can FAA become capable of certifying new materials, devices and systems incorporating nanotechnology in such as way as to avoid discouraging or delaying nanotechnology-based innovation. This also applies to manufacturing processes and inspection methods related to these new technologies. (NIST could be of great assistance in this latter area.)

Third, to address the immediately preceding issue, the FAA should recognize barriers it has sometimes erected to innovation. In particular, the FAA should be aware of its role in regulation of the air transportation system and its participants, and design regulatory processes and policies that will not slow nanotechnology development and adoption unduly. Several panel members expressed concern that the FAA is too slow and the certification process is too onerous, and that this may delay the development and adoption of aviation-related nanotechnology applications.

Finally, FAA should monitor research efforts in other countries. Nanoscience and nanotechnology are global phenomena and many foreign countries have established significant nanoscale R&D efforts, some of which are very focused programs, such as Taiwan's in nanoscale electronics. Other countries and regions to monitor include Japan, Western Europe and Hong Kong.

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