Market Relevance Study of Nanotechnology for the Railroad Industry

Prepared for the Federal Railroad Administration, under contract

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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, including the railroad industry.

The Transportation Center at Northwestern University (NUTC) recently completed a study for the Federal Aviation Administration (FAA) in which present and prospective nano-scale research and development (R&D) having relevance to aviation safety was identified and described. The work included the creation of a "catalog" summarizing nano-scale R&D programs at various government laboratories, academic institutions, and private sector organizations, as well as an assessment on the relevance of such research programs to promote civil aviation safety. The catalog is attached to this report as Appendix B. The body of knowledge developed in connection with that project can naturally be extended to a similar study for the railroad industry.

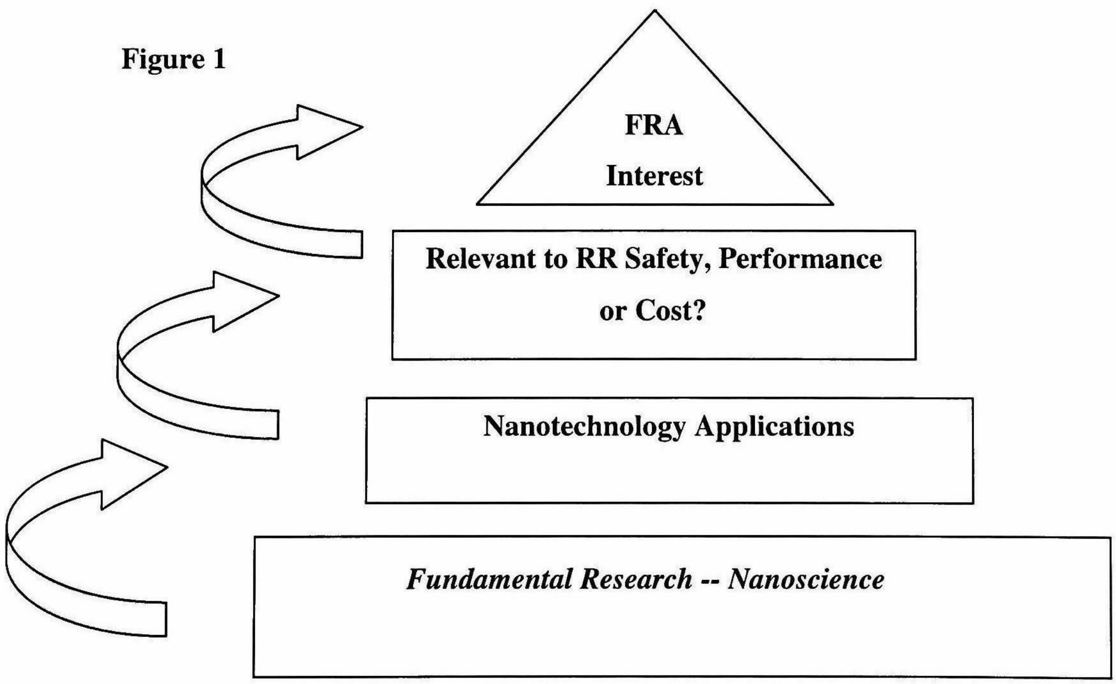
This report reviews essential conclusions from the work performed for the FAA, and draws upon it for findings related to the categories of physical science and technology likely to be most affected by progress in research at the nano-scale over the next two decades. We then apply findings to the R&D needs and opportunities facing railroads. At the broadest level, we conclude nanotechnology will have important impacts on railroads, but the *direction* of these influences will differ greatly between the short run and the long run. In the long run, nano-scale developments will allow substantial weight reductions in existing materials and will drive the development of new, high value, products that will want to move by the swiftest means of transportation available – and that is unlikely to be by rail. In the long run, therefore, nanotechnology is likely to have a strongly deleterious effect on railroads.

In the short run however – as soon as five to eight years from now – new coatings, sensors, electromagnetic devices, and communications components will be developed that may yield large benefits in railroad safety, security, and operating efficiency. Some of these advances appear to be near enough, and promising enough in application, that FRA might begin devoting a portion of its R&D funding to projects employing nano-materials or principles.

Objectives and Methodology

There is significant and growing interest in the U.S. in nano-scale research and development (R&D). The National Nanotechnology Initiative, which represents the federal government's strategic plan to support nano-scale science, engineering and technology, is investing more than $700 million annually into these efforts. It is highly likely that the transportation industry, including the railroad sector, 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 railroad industry, with emphasis on identifying commercially viable applications that will promote safety, improve performance or reduce costs (or a combination thereof) of railroad components and systems. Figure 1 below provides an overview of the steps in the process.

Figure 1



More specifically, the NUTC study process involved two major phases:

- **Survey and catalog nano-scale R&D efforts in the U.S.** In connection with the earlier study undertaken by the NUTC for the FAA, a "catalog" summarizing nano-scale R&D efforts in the U.S. was created. Projects at more than 90 academic institutions, government labs and agencies and private sector organizations were reviewed and their nano-scale R&D programs summarized. (See Appendix B) This catalog was then reviewed by TC researchers in order to identify promising potential applications of nanotechnology that might be generally relevant to the railroad industry.

- **Apply to Railroad Research and Technology Opportunities.** After completing the review, we investigated whether or not nanoscience and nanotechnology might benefit the railroad industry by examining specific technology "needs" and opportunities . We have not separately developed a complete encyclopedia of railroad research needs for this report, but we are familiar with (and in numerous cases have participated in) many of the expert panels formed to set railroad R&D priorities over the years. We also reviewed FRA's own *Five-Year Strategic Plan for Railroad Research, Development, and Demonstration* (2002). These resources are the knowledge base against which we have applied the less familiar and more speculative, but truly exciting, new information TC recently gathered on the future of nanotechnology.

Overview of Results

In the first phase of this process, several generic categories of nanotechnology of relevance to transportation were identified. These were found to have the potential to provide the basis for dramatic new capabilities and innovations, many of which may enhance the safety, reliability and cost performance of the railroad industry. Important categories are:

- **Structural materials.** Novel nano-scale materials such as carbon nano-tubes and "buckyballs," nano-scale metals, and nano-clays that can be used in composites to improve a wide variety of properties including greater strength and reduced weight.

- **Coatings.** Nano-scale materials that can be incorporated into coatings for resistance to wear, erosion, corrosion, and abrasion.
- **Lubricants**. Nano-scale particles used in lubricants to reduce friction and thus improve performance and reliability of railcar parts and infrastructure systems.
- **Sensors.** Highly sensitive sensors at very small scale for health- and condition-monitoring of rail components and systems; such sensors have the potential to provide advanced warning of impending failure.
- **Electronic devices.** Used in a variety of components to make them smaller, faster, more powerful and more reliable.

Which nanotechnology advances are most promising for early commercial application to railroads?

Coatings and lubricants containing nano-scale particles will perhaps appear first. They will protect from corrosion various surfaces to which they can be applied. Some of these surfaces are painted now (e.g. most rolling stock); some are not (e.g. the interior of hoppers). Such materials will be very durable and protective; they can also discourage graffiti (or at least make it easy to remove) on rolling stock and structures. We expect certain railcar and other surfaces to be treated with anti-friction coatings, which will reduce loading and unloading times; examples include hopper car slope sheets and loading chutes. There is great promise for use of tell-tale nano-particles for detection of incipient failures. For example, introduction of such particles into lubrication oil can supplant labor-intensive spectrographic analysis of these substances and probably give results on a continuous and more comprehensive basis. This could be deployed in five-to-to ten years.

Use of nano-scale materials to strengthen structural characteristics of light-weight materials such as plastics is possible within ten years. Nano-materials are likely to be used in improving the performance of both batteries and electromagnetic devices (including by making them lighter). These new "hybrid" materials will be rapidly commercialized once they are available, enabling continuation of the amazing progress made in miniaturization of electronic devices over the past few decades. We detail in the report a number of ways in which these advances will assist railroads. Likely applications are in micro-generators and low power-draw transmitter/receivers that might be mass produced at low cost for use in advanced electronic braking and positive train control systems.

Stand-alone (self-communicating) sensors constructed at the nano-scale will be deployed widely in the transportation and logistics fields, including railroads, but they will come in a second wave – perhaps 10 to 20 years out. Preceding such sensors will be MEMS (micro-scale) devices that can be expected to preempt nano-scale applications for some time to come. Also, sensors embedded in critical structures and components will be able to monitor their condition (e.g. corrosion, cracking, other deterioration), perhaps on a near-continuous basis. This is likely to emerge in ten-to fifteen years. As costs come down, nano-sensors will also be deployed to monitor the "environment" in which goods are transported with more precision than ever before. Parameters such as temperature, humidity and shock can be recorded and stored routinely, thus pinpointing damage liability and or identifying specific locations causing problems that can then be addressed.

Long Run Implications

Over the course of the next 15 to 20 years, all modes of transport except pipelines can expect to see some shifts in the nature of the products they are called upon to move. For example, there will be functionally equivalent or, perhaps, better-performing products that are dramatically smaller in size and lower in weight than they are today. While some merchandise rail freight will not be affected significantly (e.g. canned goods, lumber, steel products), others will be – to the point that they will require less transport "effort" and may well shift to other modes or methods. For railroads, it is likely that intermodal traffic will be most affected.

Similarly, there is much value to truckers in nanotechnology. Historically, motor carriers have had a greater propensity to exploit technology when it is ready than the railroads, because it can be acquired incrementally in, single units. This is true even for implementation of state on national policy changes such as size and weight regulations. By contrast, in railroading, technology deployment often requires *development and maturization of industry interoperability standards*. Even then, the new railroad technology may require replacement of an entire *system* at the train level (e.g., electronic braking) or a large territory (e.g., positive train control), if not the entire industry (track gauge) obviously, but also radio frequency (RF) technological and messaging specifications. A related factor is that in trucking, vendors typically develop the new technology and make it available *off the shelf* to any carrier; in railroading, new technology development is likely to have required substantial company or industry involvement at the R&D standards settings and testing stages, and deployment may be significantly *customized* to individual railroad firms. These factors imply serious consequences for the railroads' competitive position if they are not aggressive in pursuing industry standards and do not invest significant resources in R&D and testing.

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A caveat must be registered with respect to this report. NUTC can engage in technology forecasting and broadly suggest promising commercial applications of new science. We are not, however, the regulators nor the investors! To suggest the possibility of an application is not to determine its feasibility, its compliance with regulatory standards, nor its cost-effectiveness compared with alternatives. It would be a disservice to the sponsor of this research and the railroad industry if the reader were to ignore this caveat.

1. Introduction[1]

"You can observe a lot just by watching." -- *Attributed to Yogi Berra*

1.1. Background

The emerging fields of nanoscience and nano-engineering – 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 novel properties of elements and compounds that occur at nano-scale. The potential exists eventually to tailor the desired chemical, physical, and biological properties and phenomena associated with nano-scale structures for commercial applications. Research is underway to develop nanotechnologies that can be incorporated in new advanced materials, corrosion-resistant coatings, and extremely sensitive and low-cost sensors designed for use in assessing the structural integrity of vehicles. There is clearly great applicability of prospective developments in nanotechnology for transportation, including the railroad industry.

The Transportation Center at Northwestern University (NUTC) recently completed a study for the Federal Aviation Administration (FAA) in which present and prospective nano-scale research and development (R&D) having relevance to aviation safety was identified and described. The work included the creation of a "catalog" summarizing nonsocial R&D programs at various government laboratories, academic institutions, and private sector organizations, as well as an assessment on the relevance of such research programs to promote civil aviation safety. The body of knowledge developed in connection with that project can be extended naturally to a similar study for the railroad industry.

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[1] Note: Chapters 1, 2, 3, 5 and the Apppendices drew heavily from the Transportation Center at Northwestern's recent report for the Federal Aviation Administration 9FAA). We have not made detailed citations to the earlier report in this document.

1.2. Objectives

While nano-scale research and development (R&D) holds great promise for the transportation sector in general, to date there has been no systematic attempt to relate outcomes of current and prospective research to the railroad sector. The objective of this study is to identify and describe a representative set of nanoscience and nanotechnology R&D efforts having prospective commercial relevance to the railroad industry. Those potential applications of nanotechnology that appear most promising to the railroad industry will be highlighted, and promising areas for further research will be suggested. Finally, the FRA's potential role will be examined, such that the results of the study will provide early guidance for FRA's decision making with regard to its resources available for support of nano-scale R&D of benefit to the railroad industry.

1.3. Methodology

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

1.3.1. Survey and Catalog Nano-scale R&D Efforts in the United States.

In connection with the earlier study undertaken by the NUTC for the FAA, a "catalog" summarizing nano-scale R&D efforts in the U.S. was created. Over 90 government laboratories and agencies, academic institutions and organizations in the private sector involved in nano-scale R&D were reviewed. Through searches of relevant literature and Internet resources, information was compiled into catalog entries (attached as Appendix B 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. This catalog was used to identify those applications having the greatest potential market relevance to the railroad industry.

1.3.2. Apply to Railroad Research and Technology Opportunities.

After completing the survey, issues related to why nanoscience and nanotechnology is so promising and valuable to the railroad industry were examined, and the relevance and potential benefits of certain nano-scale R&D outcomes were identified. Since the literature gives us little to build upon, we have taken what we learned about nanotechnology and what we already knew about railroad R&D priorities, and drew the necessary connections. This is classic procedure in national security intelligence analysis or business competitive research. We are putting rare events or unknowns up against knowledge we have to a near certainty. In the case of intelligence or competitive strategy, the unknown is what the "other side" will do – or even what its real motivations are. In the world of technology forecasting, the unknown is what scientific and engineering breakthroughs might be achieved in the future.

In both cases, we have reasonably good understanding of what our own capabilities and vulnerabilities are, but we often misestimate the impact of our own actions on the "other side." The better the applications, the more likely the fundamental research needed to make them possible will be conducted. This can be viewed as an application of the famous Heisenberg Uncertainly Principle, or what modern industrial engineers call the Hawthorne Effect – we affect the ultimate outcome because we are not truly external to the performance of the system – those being watched know we are looking at them and change their behavior as a result. In the case of defense intelligence or competitive research, this argues for secrecy as to what we are doing. But in the case of technology forecasting, it argues for advertising the promise and the potential public benefits of the applications, so that more effort might be put into fundamental research.

We have not separately developed a complete encyclopedia of railroad research needs for this report, but the principal investigator has spent a career researching and practicing in this field. He has participated in many of the expert panels formed to set railroad R&D priorities over the years. We are also familiar with FRA's own report, Five-Year Strategic Plan for Railroad Research , Development, and Demonstratrion (2002). These resources are the knowledge base against which we have applied the less familiar and more speculative, but truly exciting, new information we have recently gathered on the future of nanotechnology.

2. General State of Research and Technology Development at the Nano-scale

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 nano-technologies. 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 nano-scale materials – as well as studies of the phenomena, processes, and tools necessary to control and manipulate matter at nano-scale – in order to form a scientific knowledge base. *Nanotechnology* is an emerging field in which knowledge learned from nanoscience can be developed into useful applications across a wide range of industries.

At the nanometer scale, the Newtonian 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, magnetic mechanical, and chemical – for nearly every material when explored at the nano-scale. (Fellman, 2002) Nanoscience is rather like a modern version of alchemy – turning ordinary commodities into new, more valuable substances. By extension, nanotechnology is not just concerned with fabricating materials and devices on a smaller scale, but also with exploiting the novel properties that occur at nano-scale. A fascinating example is work involving development of films only a few molecules[2] thick that have hydrophilic properties on one side and hydro-phobic

[2] *Molecule* comes from Latin words meaning "little mass." A molecule is made up of two or more atoms bearing a stable relationship with one another. How small is a molecule? As reported by Bill Bryson in *A Short History of Nearly Everything* (2003), at sea level and the freezing point of water, one cubic centimeter (about the size of a sugar cube) of air contains some *45 billion billion* molecules (p. 133-134).

properties on the other. A coating made of this material would adhere like super-glue to a surface and then repel it like a film of grease anything trying to stick to this suggest 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 nano-structures.

It is important to note that nanoscience is inherently interdisciplinary, with much of the basic scientific investigation 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 "nano-machines" 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. An application has also been made in the railroad industry, as a MEMS laser ring-gyro heading indicator is integrated into the design of at least one train *location determination system* for positive train control (PTC). 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 nano-scale and thereby seeks to build materials and devices with remarkable new and different properties. However, there is substantial potential for nano-scale materials and devices to be incorporated within MEMS. For example, an application area anticipated for carbon nano-tubes 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 nano-scale 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 nano-scale 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

Year/ 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 nano-scale 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 nano-scale. 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 tunneling and atomic force microscopes.
- The introduction of new structures such as carbon nano-tubes 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 nano-scale devices and engineering posted on ITRS (International Technology Roadmap for Semiconductors).

Given the growth in funding for nano-scale 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. Closer to the present, a nanotechnology industry organization called the NanoBusiness Alliance estimates that venture capital investment in nanotechnology will rise to $1.2 billion in 2003 from $100 million in 1999 (Maneva, 2002). The NanoBusiness Alliance also believes the overall market for nano-tech products could reach $225 billion by 2005 (Maneva, 2002). Nanotechnology applications are likely to occur in a wide variety of industries, including transportation industries, with the potential for significant enhancements to safety and performance.

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 nano-scale R&D: academic institutions, government laboratories and agencies and private sector organizations

2.4. 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 nano-scale.

- 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:

    - nano-materials by design,
    - nano-electronics,
    - opto-electronics and magnetics that have implications for healthcare, energy, and manufacturing,
    - nano-scale processes and environments,
    - micro-craft and robotics, and
    - chemical, biological, radiological and explosives 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 Rensselaer Polytechnic Institute.

- 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 nano-scale; instrumentation, modeling; materials by design; bio-structures and bio-inspired systems; system-system 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.

2.5. 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 nano-scale 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 Nano-scale 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 patterning-patterning 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 bio-recognition 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 nano-structures 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 nano-scale properties of materials and looking at devices based on those properties that can be put together to make successful new systems for ultra-high performance processing, storage, and transmission of information.

- Columbia University: Center for Electronic Transport in Molecular Nano-structures. 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 nano-scale molecular structures.

- Rice University: Center for Biological and Environmental Nanotechnology. Research activities will explore the interface between nano-materials and aqueous systems at multiple- length scales, including interactions with solvents, bio-molecules, cells, whole organisms and the environment. This will serve as foundational knowledge for designing bio-molecular/material-material interactions, solving bioengineering problems with nano-scale materials and constructing nano-scale materials useful in solving environmental engineering problems.

- Rensselaer Polytechnic Institute (RPI): Center for Directed Assembly of Nano-structures. Areas of research include directed assembly of nano-structures to create gels and polymer nano-composites, structured-structured bimolecular architectures, multi-scale theories and models, and characterized structured-structured 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 railroad industry.

Numerous other universities have established or are planning to establish meaningful programs in nano-scale 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 nano-structures and new materials, as well as the design and fabrication of nano-electronic devices. Also, Purdue was named in 2002 as one of three NASA-funded University Research, Engineering and Technology Institutes, and will focus on nano-electronics 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 nano-systems 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 nano-tubes.

- University of Texas (Austin): The Center for Nano and Molecular Science and Technology is conducting research in a variety of areas including bio-electronic materials, molecular nano-scale 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 B.

2.6. 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 nano-electronics research involving carbon nano-tubes, molecular electronics, inorganic nano-wires 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 nano-assemblies, nano-catalyst materials, charge injection and transport, and other areas.

- Lawrence Berkeley National Laboratory: The Materials Science Division performs significant research into advanced materials, including carbon nano-tubes 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, mechanics-mechanics, micro/bio/micro interfaces and nano-electronics/nano-photonics.
- Oak Ridge National Laboratory: Another DOE lab that focuses on nano-structured materials, including carbon tube based electronic devices and other designer nano-scale materials.
- Pacific Northwest National Laboratory: Another DOE lab that is pursuing nanoscience research in the nano-materials 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, nano-electronics 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 B.

2.7. 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 their 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 nano-tubes, 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 nano-structured materials and multifunctional coatings to improve material properties and performance for a broad range of engineering applications. In particular, thermal spray nano-composite coatings of alumina and titania appear to offer improved hardness and corrosion-resistance.
- InMat Inc.: The company is developing flexible barrier coatings incorporating nano-clays – nano-meter sized platelets of clay materials – which provide a chemical barrier and improve air retention. The barrier coatings may have applications to 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 nano-clays specifically designed for plastic nano-composites. Such nano-composite products are likely to improve barrier, flame resistance, thermal and structural properties of many plastics and could have applications to railcar materials, particularly for flame retardation.
- Nanophase Technologies Corp.: The company has developed processes to create controlled mixtures of nano-materials that provide abrasion- and wear-resistance, as well as nano-crystalline 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 nano-crystalline aluminum oxide and ZTA (zirconia-toughened alumina).

- NanoPowders Industries: A producer of nano-sized 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 nano-scale. The nano-aluminum powder may offer significant performance improvements in energetic applications, including various types of 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 B.

3. Generic Categories of 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 railroad safety, performance, reduce costs or a combination thereof. 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 relevant to the railroad industry, based on both the nanoscience research that is occurring in these areas and the interest in such applications by the "user" community (railcar manufacturers and other suppliers and operators of rail equipment and infrastructure).

3.1. Structural Materials

Nano-structured 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 railroad industry of the future. Nanotechnology may fundamentally change the way materials are produced, allowing for the ability to assemble nano-scale 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 Nano-tubes 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 nano-tubes in 1991. Carbon nano-tubes 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 nano-tubes 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 nano-materials are considered to have vast potential for the generation of new, organic compounds. (Nanotechplanet.com, 2001)

Carbon nano-tubes and buckyballs are promising because their unique properties enable their employment as building blocks within nano-tech materials and devices. Properties of carbon nano-tubes 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 diamonds.
- 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 the railroad industry. Use of carbon nano-tubes in composites could be the basis of stronger materials used in railroad components exposed to extreme pounding forces, such as crossing diamonds, or extreme temperatures, such as brake shoe linings.

Currently, carbon nano-tubes 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 nano-tubes 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 nano-tubes from clinging to one another: (Nanoelectronicsplanet.com, 2003)

Potential Applications Identified

Likely near-term applications of advanced materials will be the use of nano-scale 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 nano-materials that may enhance railroad safety, reliability or cost performance:

- **Composite materials.** New composite materials are being developed through the use of nano-particles – particularly carbon nano-tubes – 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 nano-tubes, ceramics based on nano-crystalline aluminum oxide and zirconia-toughened alumina may offer improved materials properties that are useful for structures operating in harsh environments. These new composite materials are likely to find their way into materials and structures that make railroad components and systems stronger and lighter, and therefore more reliable and resistant to failure. In particular, use of composite materials incorporating nano-particles in railcar rolling and braking gear may offer significant operating benefits. Unless the cost of nano-inspired components can be reduced dramatically, they are unlikely to be cost-beneficial except in very specific applications.

- **MEMS components.** Carbon nano-tubes may offer promise for use as building blocks in MEMS devices. For example, bearings, actuators and electrodes could be made from carbon nano-tubes. 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 railroad safety and performance, such as highly reliable systems components or as sensors that monitor the performance of rail 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 nano-composites 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 railroad materials, including interior railcar materials for those cars that carry passengers or flammable or hazardous cargo. Nanocor, a leader in nano-clay 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.

3.2. Coatings

Another very promising area for nanotechnology applications is that of coatings. Protective coatings are widely used in a number of applications outside the railroad industry, including automotive and aviation-related 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, magnetic, decorative, and specialized military purposes. The main advantage of nanotechnology-enhanced coatings is that one can harness the benefits of nano-materials without making the whole part from the expensive material. (Legg, 2002)

Potential Applications Identified

Specialized coating applications that may promote railroad safety include:

- **Corrosion-resistant coatings.** Use of nano-materials, particularly nano-scale-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 nano-composite coatings of alumina and titania, originally designed for shipboard use for corrosion-resistance. It is likely that there will be some related railroad applications of such a corrosion-resistant coating for certain structures and components to reduce the probability of failure and extend the life of the component or structure. In particular, corrosion-resistant coatings for metal bridges could improve strength and extend life, as well as coatings for premium rail specialty track work and various components of railcars.

- **Hard and thermal barrier coatings.** Use of nano-materials can also improve the properties of hard and thermal barrier coatings. In particular, thermal sprayed coatings incorporating nano-structures 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 nano-particles of yttrium-stabilized-zirconia may offer improved thermal barrier protection, useful for the protection of hot section engine components. It is possible that there will be applications of these types of coatings, particularly to the locomotive. 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 that provide a chemical barrier and improve air retention. The barrier coatings could have applications to tires, with benefits including improved air retention and reduced weight and oxidation, resulting in improved safety and extended tire life.

- **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 railcar windows for improved 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 windows, radomes and other surfaces may exhibit anti-icing and anti-fogging properties. (Nanoinvestornews.com, 2002) One particular area of rail infrastructure that may benefit from these types of coatings is switches, which can be prone to problems due to ice buildup.

3.3. Lubricants

Lubrication is particularly important to many railcar structures; nano-materials 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.

Potential Applications Identified

- **Nano-particle based lubricants.** Applied NanoMaterials, Inc., is developing a solid lubricant ("NanoLub") based on nano-particles of inorganic compounds that 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 rail systems. (Kanaan, 2002)

3.4. Sensors

Nanotechnology may lead to advances in sensing through the convergence of advanced materials and nano-electronics 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 the passenger railroad industry.

While sensors incorporating nano-scale components offer much promise, there are some major challenges that need to be addressed before such sensors become effective and economically viable. In the work TC performed for the FAA, 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 be valuable for acceleration of nanotechnology applications.

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 nano-tube based stress sensors embedded in structures and components. Such sensors would be designed to detect fractures, corrosion, and other signs of failure in materials by using nano-tubes as circuits that give off electrical signals at a sign of failure. (Stuart, 2001) Ultimately, integrated nano-scale sensor systems may be possible for collecting, processing, and communicating large amounts of data with minimal size and power consumption. Such sensor systems could eventually have railroad-related applications, such as to monitor the condition of numerous components and systems.

- **Sensors for chemical, biological, radiological, and explosives detection.** Given the importance of homeland security, the National Nanotechnology Initiative recently initiated a "Grand Challenge" relating to chemical, biological, radiological and explosives detection and protection. Advances in nano-electronics may allow for new portable, highly sensitive, and automated chemical and biological sensors, with potential uses for drug, chemical, and explosives detection aboard passenger rail cars and in rail yards and shipping ports. In particular, novel chemical detectors based on nano-scale 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, selectivity, and reliability over current systems. The potential for nanotechnology in security-related applications is significant.

3.5. Electronic Devices

In the area of computing and electronic devices, nano-structured materials such as carbon nano-tubes 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 nano-tubes as electronic circuitry that may one day replace silicon crystals as the building block for ultra-fast, ultra-small computers. (Rotman, 2002) The use of nano-tubes or related materials (such as nano-wires) as tiny electronic switches suggests that nano-tubes could have a big impact on computer memory and logic. One observer believes, "carbon nano-tubes are, in theory at least, the ideal material for building tomorrow's nano-electronics." (Rotman, 2002) Nano-materials are potential building blocks for molecular electronic and opto-electronic devices, which could lead to applications that enhance railroad safety and reliability.

Potential Applications Identified

Following are some examples of potential applications relevant to railroads:

- **Flat Panel Displays.** The high electrical conductivity of carbon nano-tubes, 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 nano-tubes in next-generation cathode ray tubes (CRTs) and flat panel displays may provide improved resolution for displays used in locomotive on-board systems and at centralized rail operations centers. In addition, signal lights and warning message board displays could also be improved.

- **Molecular electronics.** Molecular electronic devices based on nano-structures, particularly carbon nano-tubes, 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 on-board computer systems of the future, while reducing their power consumption. It also has positive implications for electronics used in rail traffic management.

3.6. Tools, Standards and Methods

Before nanotechnology can be fully developed, characterization and manipulation of matter at the nano-scale 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 nano-structured 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 nano-scale 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. Railroad Industry Opportunities for Applying Nanotechnology

4.1. Locomotives

State of the art locomotives generate over 4000 horsepower and cost over $2 million. While reliability has improved in recent years, some parts are prone to failure and it is difficult to keep locomotives operating at peak efficiency. If tuning is off only marginally, a large penalty is incurred in lost power, wasted fuel, and/or additional emissions. Indeed, railroads currently acquire locomotives that may not be truly "state-of-the-art," because economic value is greater for the more reliable model than for the model with the most advanced features.

4.1.1. Improvements in Conventional Diesel-Electric Locomotives

4.1.1.1. Engine Maintenance and Operating Efficiency

The promise of nanotechnology for improved locomotive performance is in several areas. An early success might be found in small sensors that could be introduced in the fuel stream and retrieved from exhaust emissions to report diesel engine internal condition and fuel efficiency performance.

Modern diesel-electric locomotives gain a large power boost from the turbocharger, which runs off the prime-mover exhaust stream and compresses air for forced introduction to the diesel engine, allowing it to burn more fuel efficiently. Turbochargers are critical to overall locomotive performance, and they are a key maintenance expense item. Special nano-coatings might be used on the fans of turbochargers to increase their durability, and perhaps to emit tell-tale signatures if turbochargers are reaching a point of incipient failure.

4.1.1.2. Emissions

Railroads, like truckers and others, are under federal mandate to improve engine emissions such as NOX, CO, and particulates. Building locomotives with emissions control devices, keeping locomotives tuned properly, using the "greenest" locomotives in the most sensitive air quality environments, and using low-sulfur diesel fuels are some of the current mitigation strategies, but all are expensive and may be ephemeral. Nano-scale fuel additives that have properties with the potential to improve locomotive emissions might extend the life of current engine models and have direct emission reduction benefits in the worst air quality attainment areas, such as the Los Angeles Basin and Houston.

4.1.1.3. Lubrication / Friction Reduction

Diesel engines are self-lubricating in some respects but not all. Nanotechnology advances in improved mechanical lubricants would be welcome in many aspects of railroading, not least of which is the main power plant. The idea of nano-scale "ball bearings" that would be incorporated in standard lubricants to reduce friction is intriguing.

We understand that progress has been made in designing heavy mechanical assemblies using the principle of electro-magnetic repulsion to suspend, for example, the weight of a motor rotor otherwise requiring lubricated bearings. Nanotechnology breakthroughs that would dramatically increase the attractive and repulsive power of conventional magnets would have important applications for railroads, starting with the locomotive.

4.1.2. New Diesel-Electric Locomotive Traction Motor and Control Designs

Directly related to the issues just presented, at least one electric motor designer we know of through the High Speed Rail IDEA program envisages use of permanent magnets on the armature of DC traction motors to eliminate the need for carbon brushes and wire windings on the rotor, thus reducing its weight and solving a maintenance headache. We cannot evaluate the feasibility of the idea, but we imagine that if there were anything to the idea, it would only be better with improvements to permanent magnets that might come from nano-scale research and materials.

4.1.3. Fuel Cell Locomotive Power

Railroads are a likely test-bed for fuel cell technology development, because locomotive fueling is done away from population concentrations at locations with privately controlled access. Moreover, some investigators believe that locomotives develop and use electric power on what would be an efficient scale for fuel cell applications. Diesel-electric locomotives are already a "hybrid" engine system, as all vehicles powered by fuel cells are likely to be. We are unsure as to all of the implications of nanotechnology for fuel cell development, but we suspect there will be many important implications, starting with the nano-scale coatings needed to make hydrogen storage containers impervious to "osmosis" of the fuel into the atmosphere. Nanoscience may also result in new catalysts or materials for filters that make production of elemental hydrogen from petroleum or coal more economically attractive.

4.1.4. Locomotive Flywheel Materials

Modern locomotives employ "dynamic braking" principles and equipment. These systems convert some of the kinetic energy of a braking train to electric power by using the locomotive's traction motors as generators. Unfortunately, the power thus generated cannot today be stored feasibly in a battery or other device and reused to power the train – except in the case of electric locomotives that return power through a pantograph to a catenary (overhead power distribution system). Diesel-electric locomotives simply waste the power as heat generated on a resistance grid. There has been some experimentation in the industry with the idea of using the electric power from regenerative braking to turn a flywheel connected to the main generator. In this way the regenerated energy could be stored in the flywheel and subsequently used to power the train.

Recently proposed designs for the flywheel feature carbon fiber construction. Containment of a failed flywheel is a significant issue. If nanoscience is able to produce materials of extraordinary strength and density for the flywheel and / or containment vessel, the flywheel-based regenerative braking hybrid locomotive may eventually be commercially viable.

4.2. Railcars, Train Systems, and Containers

4.2.1. Freight Car Structural Materials and Coatings

Freight cars have evolved from little more than iron and wood farm wagons on flanged wheels to steel and aluminum cars that can carry 115 tons of lading. Each car has power (pneumatic) braking equipment, semi-automatic coupling operation, a pair of radio frequency (RF) I.D. transponders, and other appurtenances. It may be specially designed to carry new automobiles, liquid chemicals, or lumber. It may be covered to protect a cargo of grain and fitted with bottom-dumping gates or rotating couplers to enable upside-down emptying. Light weight is not much of a premium-earning value in a heavy rail car, but aluminum competes evenly with steel for coal hoppers because the lighter tare weight of the car permits more lading tonnage within the overall weight-on rails restriction (typically 286,000 lbs.).

One of the early applications of nanotechnology to railroads is likely to be in the area of new coatings that contain nano-scale particles. These coatings will help protect from corrosion various surfaces to which they can be applied. Some of these surfaces are painted now (e.g. most rolling stock); some are not (e.g. the interior of hoppers). Such materials will be very durable and protective; they can also discourage graffiti (or at least make it easy to remove) on rolling stock and structures. We expect certain railcar and other surfaces to be treated with anti-friction coatings, which will reduce loading and unloading times; examples include hopper car slope sheets and loading chutes.

New structural materials incorporating fiber reinforcement for strength and anti-corrosion properties have long been sought, but they would have to be extremely cheap to compete with traditional materials. Nano-scale materials might eventually have a market in production of strong, corrosion free plastics, and these in turn might be economically feasible for construction of recyclable cradles or/mini-containers used in handling automotive and consumer durables.

4.2.2. Freight Car Running Gear

4.2.2.1. Trucks / Bogies

The two-axel swivel bogie was one of the great innovations in early American railroad history, enabling faster speeds and greater weight on tracks of lower quality than their European counterparts. European car designs are only recently catching up. Meanwhile, the next step technologically (and economically) is to radial trucks that automatically "steer" the bogie into curves to minimize lateral track forces, save fuel, and make derailment less likely. Is there a commercial opportunity for nanotechnology in this arena? Perhaps, but we must be skeptical. Radial trucks are a good idea, but the systems engineering challenge is great, and the freight-car fleet cannot be replaced for decades. As long as a significant number of cars in the fleet have conventional track-train dynamics, train operation and track tolerances will have to accommodate those forces pretty much as they are. A closer-in opportunity might exist if nano-scale materials can be used in high wear-bearing surfaces within the freight car truck and if permanent lubricants are developed to reduce the high friction and impact exposure these parts must bear.

4.2.2.2. Wheels & Axels

A broken wheel or axel can cause a devastating derailment. From time to time FRA and the railroads have had to remove certain wheel designs from service or take other extraordinary steps to deal with catastrophic wheel or axel failure. There is currently no ability to conduct a complete scientific inspection of wheels or axels without removing the equipment from service. High on the industry's technology wish-list is a system that would enable an automated rolling inspection of mounted wheels and axels while the freight car is still in the train consist – for example, as part of an outbound final inspection for a train leaving a yard. The most likely technology for incorporation in such a system is ultra-sound, as the industry has much experience with metallurgical acoustic signatures. Improvements would have to be made, however, in coupling the acoustic ping source to the inspection target and the acoustic wave receiving apparatus.

Is there an application for nanoscience in this important area? We are unsure, but the prospect may warrant further investigation.

4.2.2.3. Bearings

Great progress has been made in the design of tapered roller bearings for railcars and the seals and lubricants that prevent "hot-boxes" (overheated journal bearings), which were one of the seven scourges of the industry half a century ago; "burned-off journals" remain a significant concern today, because if not detected in time, they can cause a train derailment. Even if detected before the heat causes the wheel and axel to "freeze-up," a hotbox means the train must stop and the faulty car must be set out of the train consist.

The promise of nanotechnology in this area is to develop even better lubricants and seals for journal bearings. The idea of designing carbon "buckyballs" that would be, in effect, *ball bearings within the lubricant for the railcar's roller bearings*, is an exciting prospect.

4.2.2.4. Condition Monitoring & Incipient Failure Reporting

Nano-sensors may be developed that would warn of incipient failures within the journal, or would sense an abnormal audio or temperature signal from outside the journal and pass that information to an on-board train health monitoring system. The engineering of such a system would be complex, since there is no "emissions stream" out of the journal from which to capture nano-sensors that have been "switched" to report incipient failure. Alternative designs using embedded fibers to sense temperature anomalies or metal fatigue (or to sample directly the state of nano-sensors inserted into the lubricant) may be possible.

Once detected outside the journal, reporting of abnormalities could be accomplished through a wireless car-to-car-to-locomotive communications network, itself made practical by advances in battery power and micro-transmitters using first-generation nanotechnology developments. External journal bearing temperature sensing can be done by conventional means for reporting to the train health monitoring system; the advantage of receiving reports from sensors embedded *within* the journal is that failures might be detected before reaching the point of disabling the car and necessitating its removal from service.

4.2.3. Passenger Cars & Passenger Security

The implications of nanoscience advances affecting structural improvements in passenger car components and designs, such as radial trucks, brake shoes, journals, or wheels and axels, would follow the same patterns just described for freight rolling stock. Protection and comfort of passengers traveling by rail, however, represents a different class of innovations that could possibly profit from nano-scale developments.

4.2.3.1. Explosives Detection

Immediately after the September 11 attacks, there was much discussion of whether transit, rail commuter, or Amtrak passengers needed to be put through security screening in a manner analogous to airline passengers. Gradually there grew to be recognition that the open boarding characteristics of rail passenger service could not be adapted to meet the airline screening model. Interest remains, however, in improving explosives detection technology – whether for screening passenger baggage or the contents of containers moving by rail. Nanoscience may contribute to the development of better ways to detect explosives and to search closed containers, but these investigations will be driven by concerns far wider than railroad R&D.

4.2.3.2. Flame Retardants

The possibility of applying nanoscience to the development of passenger seat fabrics that are less combustible and less toxic if ignited than coverings used today was mentioned earlier. Again the impetus for research in this area is likely to come from outside the rail arena.

4.2.3.3. Passenger Business / Entertainment Systems

As airlines move into at-seat entertainment and Internet access, Amtrak and even some commuter lines may try to do the same. It would be useful to know if nanoscience developments will somehow allow RF bandwidth constraints so evident today to become a thing of the past. Our nanotechnology experts do not see this as very likely, and again, opportunities / solutions will not be driven by rail requirements.

4.2.4. Braking Systems

4.2.4.1. Wireless Electronically Controlled Pneumatic Brakes (ECPB)

Wireless control of the application and release of train brakes has great promise. As background, application of railroad brakes have been both <u>powered</u> and <u>signaled</u> by air pressure since the days of George Westinghouse (as early as the 1870s). Air brakes are arranged in a fail-safe manner by placing an air pressure vessel (the auxiliary reservoir) on each car, pressurizing it from the locomotive through the train line / brake pipe, and then using reductions of air pressure in the train line to signal application of the brakes. The difficulties with this design are three: (1)
Brakes in the rear of the train are slow to apply, because in the best case the reduction of pressure signal propagates only at the speed of sound, worse case, much slower. (2) The auxiliary reservoirs can run out of air pressure if improperly operated by the engineer. (3) Air reservoirs cannot be re-charged during a brake application.

Electronically controlled brakes solve all three problems. The signal to apply brakes moves at the speed of light, so braking can be simultaneous throughout the train or propagated from the rear to stretch the train and avoid "running in" of slack in the train (rear cars pushing forward cars), which can cause derailments. The train line is used for only one purpose, recharging reservoirs, and this action can be continued throughout any braking operation. (Pneumatic pressure would still be used to power the brake cylinders, but the control system would be electrical.) Note, however, that there would be great difficulty in mixing and matching conventional pneumatic brakes and ECPB systems in the same train. Also, <u>wired</u> ECPB systems would have to be integral throughout the train. <u>Wireless</u> ECPB systems could hop over an unequipped or nonfunctioning car in the consist, but at the loss of braking power on the skipped cars.

Now comes the question of how nanoscience might help in the development of the ECPB systems. In the case of wired signaling, there is little opportunity. The electric line running through the train would be used for powering control valves as well as passing the control signal. A wireless system, on the other hand, requires an electrical power source on each car to operate the RF network and brake valve controls. Early designs for wireless ECPB systems have used axel rotation as a power source. Our expectation is that nano-materials research may provide better solutions, perhaps in the generation or storage of small amounts of electricity, and perhaps also in improving the efficiency of small RF transmitters for the system.

4.2.4.2. End of Train Device (EOTD) Power Systems

End of train devices have replaced the venerable caboose. Their function is to confirm and report air pressure at the end of the train line. This information is radioed back to the locomotive. In recent years, two-way EOTDs have been deployed; these devices can receive a command from the locomotive or an off-train source to engage the emergency brakes in the event of a run-away. EOTDs operate on standard battery power, but battery charging has been a problem. As with ECPBs, nanoscience contributions to small mobile power sources and RF transmitters would be beneficial.

Another functionality that might be served by EOTDs in the future is precise determination of end of train position. To accomplish this, the EOTD might incorporate a GPS receiver that could report the train end position over the same transmitter used for passing brake pipe pressure readings to the locomotive. Precise knowledge of the location of the end of a train is useful to the train crew in knowing that the train is intact, or that a crossing has been cleared, etc. A problem today, in addition to unreliable power supply on the end of a train, is that the GPS signal may be blocked by the mass of the last car in the train. Improvements in the GPS system and local antenna may help make end-of-train position determination feasible in the near future.

4.2.4.3. Brake Shoes

One of the early applications of nanotechnology in transportation is likely to be the incorporation of nano-fibers in brake shoes and linings. This is an area in which unavailability of asbestos has caused problems. Automotive companies are pushing the nano-tech research envelope in a number of areas, including braking systems. Targeting rail brake linings as an early nano opportunity makes sense.

4.2.5. Containers

Highway-rail intermodal transportation has increased at a rapid pace in the last two decades. Container shipments now more than double trailer loads handled by railroads, and half of all rail intermodal traffic involves movement to or from international points. Challenges to further growth of intermodal transportation are the difficulty of maintaining standards, and investment needs at congested transfer hubs and ports.

4.2.5.1. RF I.D. Transponders

Since there are reportedly some 8 million containers in worldwide service at any one time, keeping track of the fleet is a huge problem. One company (American President Lines) attempted to tag its fleet with RF transponders about a decade ago, but ultimately had to give up the project as too costly both in tagging containers and building the needed network of readers. Visionaries say that if we could get the per unit cost of transponders down to a few dollars, and flesh out the reader network (perhaps as a public utility), benefits would be enormous. The system would enable tracking and tracing of container movements (a commercial and national security benefit), more efficient repositioning of empties, and better compliance with cargo shipment rules.

4.2.5.2. Smart Seals

An electronic seal on a cargo container allows immediate reporting of a security breach. Shipping interests support the idea in concept but think it would be hugely expensive and would not guarantee that the cargo in the container is what it is supposed to be. Advances in nano-scale sensors may help in efforts to confirm that a container has not been opened along its journey. Certain types of tracers used inside a container may also help locate the point of a security breach or even the miscreant involved.

4.2.5.3. Biometric Employee I.D. Verification

A *Transportation Worker Identification Card* (TWIC) has been officially proposed as a security/anti-terrorism precaution and is in the early stages of deployment. High security transportation facilities, such as airports, ports, container yards, and control centers may soon adopt biometric I.D. verification devices. Over time, TWICs may incorporate improvements or refinements built on nanoscience applications.

4.3. Track and Facilities

Railroads gain their inherent efficiency from the low rolling resistance of steel wheels on steel rails, but the fixed location of tracks and terminals is a competitive disadvantage when the market demands, and highway transportation can deliver, flexible transportation.

4.3.1. Premium Trackwork

Pounding forces at critical points in the railroad track structure can misalign track, cause derailments, damage lading, reduce passenger comfort, and increase both track and rolling stock maintenance expense. Our nanotechnology experts believe an early commercial application taking advantage of the radically changed properties of materials at the nano-scale is in the development of ingredients that would be added to specialty steels to make them more durable and resistant to stresses in the rail environment. Likely applications of the new premium steels would be in rail-rail crossing diamonds, or at the switch point or the frog of turnouts (track switches).

4.3.2. Broken Rail Detection

American railroads that are signaled to add safety and capacity typically work by using a current of electricity in the track (a circuit) to determine the presence of a train. When a train passes over the track segment, it "shunts" – short circuits – the electrical track loop, and causes a signal to drop to red. The basic track circuit was invented in 1872 by William Robinson and it has served the industry well ever since. But there is more, as railroads gain a second kind of benefit from use of the electrical circuit in the rail. It is also used to determine if the continuity of a segment of track is intact – i.e. that the rail metal carrying the circuit is not broken. This feature is so valuable that alternative signal systems designed to move away from track circuits (such as radio-based positive train control) may not be adopted if it means no broken rail protection. Railroads would have to find another means of checking for broken rail, or they might have to leave track circuits in place for this second purpose long after the signal system has any need of them.

The question thus arises, can nano-scale applications contribute in any way to solving the broken rail detection problem? Some experimentation has been carried out with standard fiber optic filaments laid under the cross-ties to detect train presence (by pressure distorting the light wave). More to the point, attempts have been made to check for rail continuity by annealing the fiber to the steel rail; presumably the glass fiber will break when the steel rail does! This has not been very successful, in part because the use of epoxy resin for annealing the fiber to the rail has not worked well. It would seem that nano-properties of materials will allow for development of super-adhesives that could be used with the optic fiber. Better yet, nanotechnology advances might yield an integral rail web coating that passes the continuity message long distances and is capable of reporting the exact location of not only a complete rail break, but also even tiny fissures that could grow into major problems.

Another approach to broken rail detection would use ultra-sound to scan ahead of a train and report abnormalities with sufficient lead time to slow or stop the train. We do not know if this will prove feasible, but it is another of those situations where breakthroughs in nanoscience in one area may have entirely unexpected benefits elsewhere. Linked study of acoustic waves, light waves, magnetism, and materials research at the nano scale may have outcomes that we cannot now foresee.

4.3.3. Track Misalignment, "Sun-Kinks," & Subsurface Failure Detection

Current broken rail detection systems are of no use if electrical continuity is not broken even when track perturbation is fully capable of derailing the train. This in fact occurred in the Bayou Canot (Mobile Bay) derailment of an Amtrak train that cost 47 lives in 1993. The barge hit the rail trestle hard enough to misalign the rails and wreck the train, but apparently did not break the track circuit. Another fairly common problem is heat kinking of the rail when a warm spell leaves no room for expansion of the rail within its intended alignment. As with broken rail detection, some experimentation with optic fiber has been tried to see if misalignment sufficient to derail a train can be detected by abnormal bending of the light wave.

Detection of a track subsurface failure, such as due to a washout or earthquake damage, would be useful. Several major derailments in recent years were attributed to subsurface softening or washouts. One inventor has come up with a detector the size and shape of a piece of ballast rock; if it washes out of the roadbed to a detectable distance away, an alarm would be sent and trains slowed or stopped. Perhaps a tiny battery-transmitter device would be useful in such an assembly.

4.3.4. Track Lubrication

Rail life (measured by millions of gross tons carried over a track segment of given length before the rail must be relayed) has about doubled over the last fifteen years. This is due to use of better steels in rail, improved track-train dynamics, better ongoing track maintenance practices, and track lubrication. If nanoscience leads to improvements in specialty lubricants (as discussed earlier) there would be corresponding benefits in track lubrication.

4.3.5. Rail Property Perimeter Protection

September 11 has focused much attention on better means of protecting the perimeter of military installations, power plants, airports, ports, etc. There is a great deal of current interest in over the horizon radar as a tool in border protection. Nanoscience should have many applications in designing better perimeter protection systems. While these developments will be driven by needs in other areas, railroad property surveillance and protection will ultimately benefit.

4.4. Telecommunications, Signals, and Highway-Rail Intersections

The "Communications Revolution" is upon the railroads. Railroads use telecommunications and related computerized systems to manage their networks remotely, to send dispatching and work-order instructions to trains, to manage field maintenance, to receive customer orders and report car location, and on and on. Companies in the industry operate some of the largest private telecom networks in the world. Bandwidth is extremely scarce, and railroads are under mandate from the Federal Communications Commission to "refarm" the voice channels currently used to double their number. Technology breakthroughs that make communications bandwidth more productive, that speed and ease understanding of remote circumstances, and that report information now hidden from view will be a large part of what will keep railroads in business for another century.

4.4.1. Railroad RF Bandwidth Efficiency

FCC rules require micro-channelization (re-farming) of the RF spectrum most used by railroads (160 mHz). New radios will have to operate on the narrowband frequencies in coming years. Meanwhile, the shift to digital from analog for both voice and data, and the vastly increased use of data-radio applications means that re-farming is not so much the issue as is simply bandwidth scarcity. Railroads are concerned about co-channel interference in their narrow spectrum and the integrity of communications in their operations. And they need better, cheaper, easier ways to select an available communication channel. These issues are very expensive to address.

What impact will nanoscience have on telecommunications? Is there anything about the new science that might fundamentally change the rather dismal outlook for new bandwidth available to railroads and other transportation enterprises, including Intelligent Transportation Systems and supply chain management industries? We have not been able to put a finger on the Rosetta Stone that will enable understanding of this issue. We will keep trying.

4.4.2. Cyber-Terrorism Countermeasures

One promising area in developing countermeasures to cyber-terrorism appears to be expansion of the idea of verifying "known and trusted" sources of information. This approach goes all the way back to Medieval days and the use of the wax seal and the king's ring to authenticate messages. If, as we expect, nanotechnology will increase the computing power of very small devices, it may be possible to increase the level of encryption associated with very small messages or packets of information. This might enable new approaches to authentication of correspondents (and disqualification of cyber traffic from unknown and unverified sources). While by no means unique to railroads, considering the fact that rail networks operate out in the great outdoors and over the length and width of the land, protection of their *supervisory control and data acquisition* (SCADA) networks from unauthorized use is an important public security objective.

4.4.3. Signal System Enhancements

Signal systems using microprocessor logic have come into their own in the railroad industry. Remote sensors, perhaps making use of breakthroughs in nanoscience, will increasingly be integrated into the protections and capacity increases made possible with enhanced signal systems. Various coatings making use of materials properties at the nano-scale will help railroads preserve the investment, and new illumination devices may lead to better signaling ideas.

4.4.4. Enhanced Positive Train Control (PTC) System Capabilities

Several areas mentioned above might feed breakthroughs in positive train control. These include better batteries, RF communications, and coatings. Other PTC-related issues include: the value of knowing end of train location precisely, the positive determination of which of two tracks a train is on, positive train integrity checking, expanded access to data-radio bandwidth without concern for co-channel interference, greater accuracy and absolute dependability of GPS location determinations, ability to sense rogue (unauthorized) trains in PTC territory, and more.

4.4.5. Train Approach Detection for Crossing Warning Systems

As part of a proposal to NCHRP for the study of low cost active grade crossing warning systems (NCHRP 3-76B), TC has been thinking about new ways to determine with complete reliability the approach and speed of a train – in order to activate a warning device. To give one example, suppose a coating could be put on the nose of every locomotive or cab control unit – a coating that would be particularly and unmistakably noticeable to a microwave or radar gun. Then suppose that these devices and the related crossing warning gear were less expensive to install and maintain than conventional track circuits with constant warning time capability, and that over a period of extensive testing the system proved more reliable than current systems by a considerable factor. What is the most innovative part of this scenario? It might be that nano-based coating on the nose of the locomotive with the peculiar properties; the radar can't miss it and it won't ever get dirty!

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A caveat must be registered with respect to the preceding discussion. NUTC can engage in technology forecasting and broadly suggest promising commercial applications of new science. We are not, however, the regulators nor the investors! To suggest the possibility of an application is not to determine its feasibility, its compliance with regulatory standards, nor its cost-effectiveness compared with alternatives. It would be a disservice to the sponsor of this research and the railroad industry if the reader were to ignore this caveat.

5. Implications for FRA 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 FRA, given its role in promoting safety and efficiency in the railroad industry. 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 FRA to set priorities on its interests in nano-scale R&D outcomes. Those efforts that result in improvements in 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.

5.2. Developing and Strengthening Partnerships

The FRA should consider establishing or strengthening partnerships with other government agencies, as well as academia, to leverage financial and other resources, and thereby support nano-scale R&D efforts in areas of common interest. For example, NASA initiatives in nano-scale R&D are likely to hold great interest and applicability for FRA. NASA's strengths in materials science and development at the nano-scale is particularly relevant to FRA interests in advanced materials that could improve the safety and performance of railcar structures and components, as well as infrastructure. The FRA should ensure awareness 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 FRA to monitor. 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 nano-scale R&D is occurring in the nation's academic institutions, the FRA should monitor the results of research from this sector. (The catalog entries attached as Appendix B to this report represent a beginning in this respect.) The FRA should then consider establishing or strengthening partnerships with those institutions that are performing research relevant to the railroad industry. Perhaps a valuable role the FRA 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, FRA should continually monitor research efforts in other countries. Nanoscience and nanotechnology are global phenomena; many foreign countries have established significant nano-scale R&D efforts, some of which have very focused programs, such as Taiwan's in nano-scale electronics. Other countries and regions to watch include Japan, Western Europe and Hong Kong.

5.3. Recognizing and Avoiding Barriers to Innovation

5.3.1. Regulation

FRA should make every attempt to avoid those processes that will unnecessarily hinder the development and adoption of nanotechnology applications.

5.3.2. 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 nano-scale inspection of macro-scale parts because the proper tools have yet to be developed. This area is likely very new to FRA and the railroad 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 FRA should work collaboratively with NIST.

5.3.3. Economics

At present, it is very expensive to produce certain types of nano-particles, particularly carbon nano-tubes. For nano-materials to find their way into railroad-related applications, the cost will have to come down dramatically. It is likely that nano-scale developments will find their way into other industries first, such as aviation, where there may be greater value placed on improved strength and weight characteristics of nano-materials, or various electronics industries, where scale and volume manufacturing make the cost of nanotechnology applications more justifiable. FRA should take every opportunity to piggyback on and benefit from developments and innovations in other industries. FRA will also need to leverage the resources of other government agencies in order to introduce nanotechnology to the rail sector.

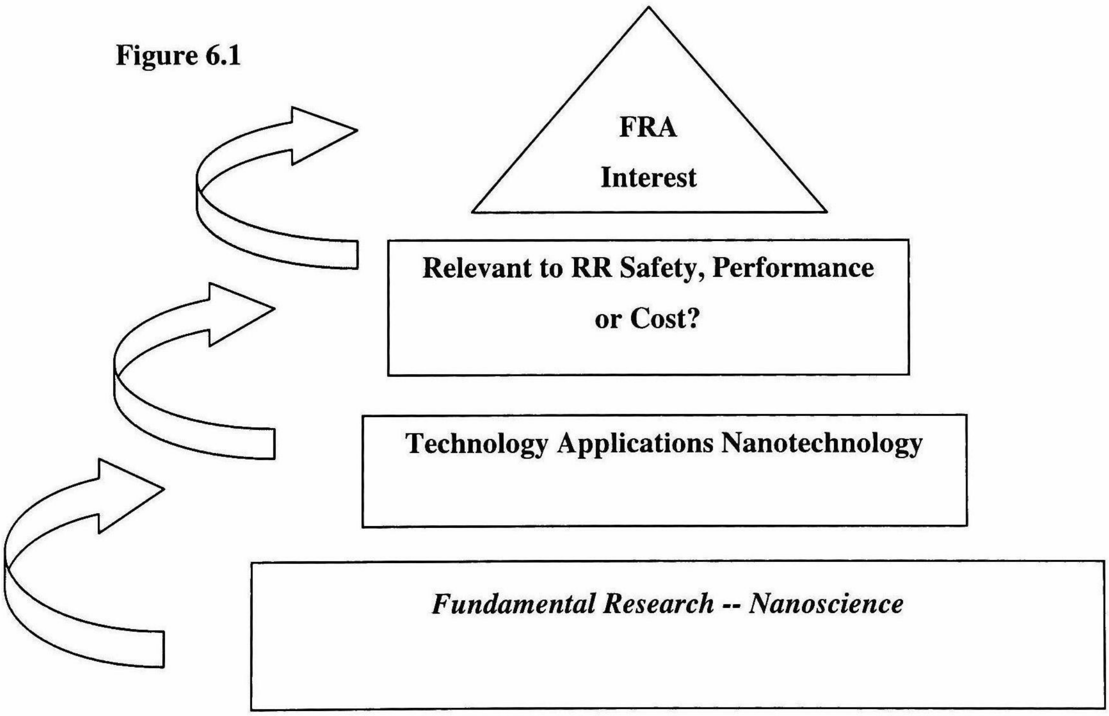
5.3.4. Lack of Human Capital

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 allocated to workforce training and graduate education programs.

6. Summary and Conclusions

Given the substantial investment in nano-scale R&D on the part the federal government and others in the public and private sectors, it is highly likely that new and innovative nano-technologies will be developed with applications in a wide variety of industries, including the railroad industry. The goal of this study has been to identify and describe a representative set of nanoscience and nanotechnology efforts having prospective relevance to the railroad industry. Figure 6.1 below provides an overview of 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 railroad safety, performance or cost, or a combination thereof. These categories are *structural materials, coatings, lubricants, sensors*, and *electronic devices*. Highlights of potential safety-related applications include:

- Novel nano-scale-sized materials such as carbon nano-tubes and "buckyballs," nano-scale metals and nano-clays that can be used in composites to improve a wide range of materials properties including greater strength and reduced weight.
- Nano-scale-sized materials that can be incorporated into coatings for wear-, erosion-, corrosion-, and abrasion-resistance and for protection of rail structures, systems and infrastructure.
- Lubricants incorporating nano-scale particles for reduced-friction between parts and improved performance and reliability of railcar and infrastructure parts.
- Highly intelligent and sensitive sensors at very small scale for health- and condition- monitoring of railroad 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 FRA, given its role in promoting rail safety and efficiency.

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Appendix B – A Catalog of Nanotechnology Resources for Transportation Researchers