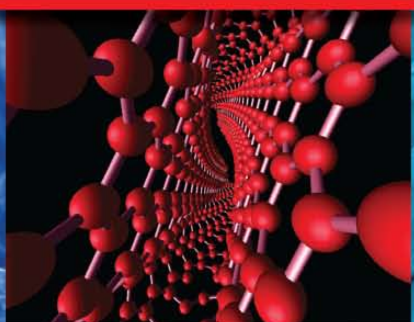
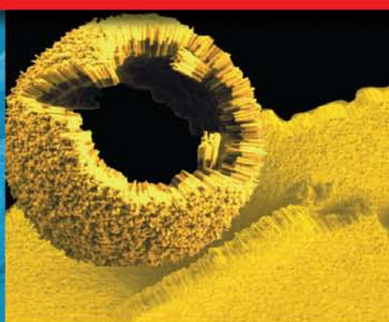
Nanomanufacturing for Energy Efficiency

Workshop



REPORT

December 2007

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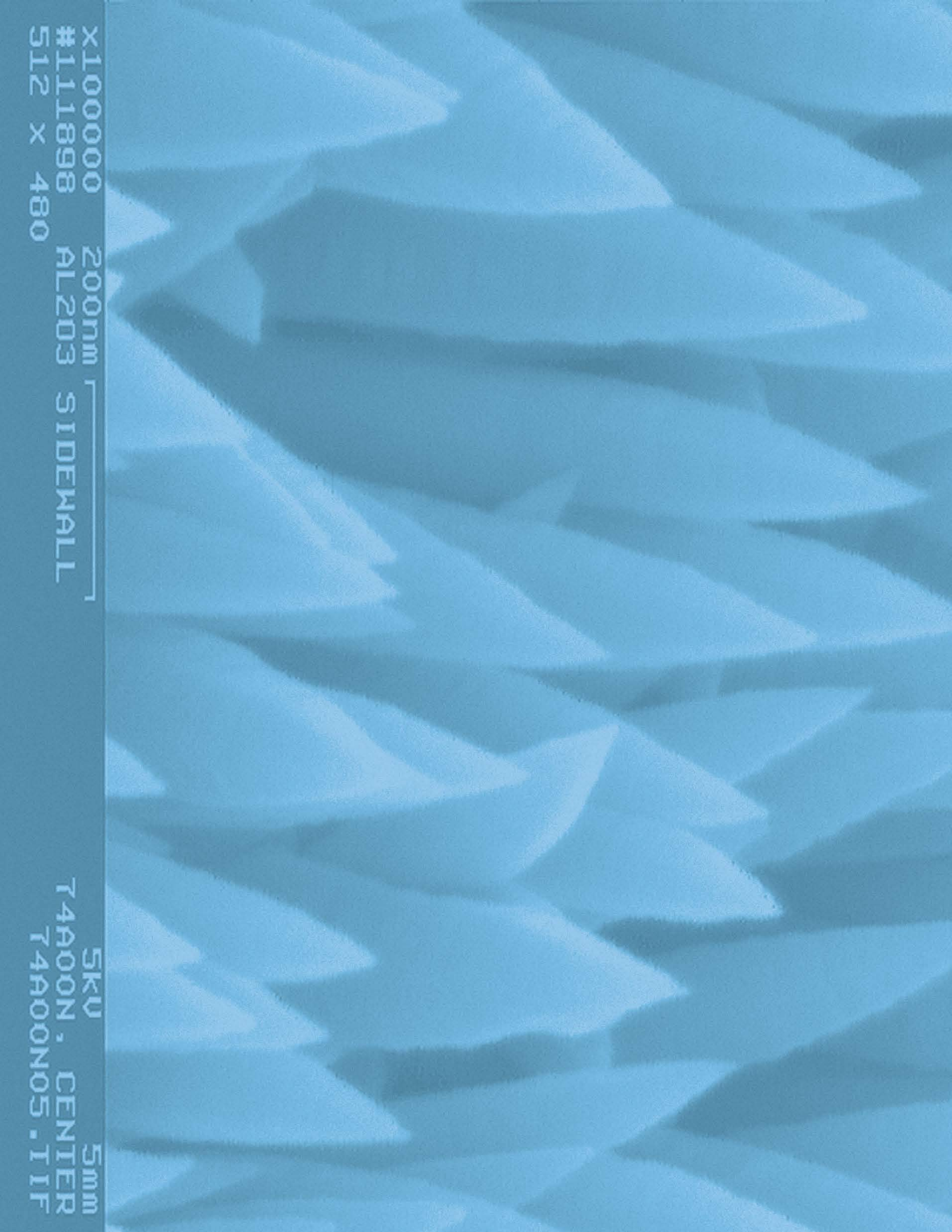
Industrial Technologies Program

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable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Preface

What is Nanotechnology and Nanomanufacturing?

Nanotechnology is typically defined as the understanding and control of matter at dimensions of approximately between 1 and 100 nanometers. Nanotechnology is not just the miniaturization of technologies—materials at the nanoscale differ significantly from bulk materials in terms of surface area and quantum effects. These differences result in nanomaterials exhibiting mechanical, chemical, electrical, thermal, and biological properties that are unique compared to those of bulk materials. These exceptional properties have the potential to be integrated into innovative products and processes that can dramatically change the way things work.

Nanomanufacturing is the use of nanotechnology to develop processes and products, whether it is the production of nanomaterials, the fabrication of products that integrate nanomaterials or nanoscale features, or the use of nano-enabled processes to create other products. Projected by many visionary leaders as the "industrial revolution of the 21st century," nanomanufacturing is primed to change markets, industries, and business models worldwide. If pursued rapidly, the U.S. industrial manufacturing sector can spearhead this transformation with new, more precise, and better performing methods of cost-effectively making thousands of innovative products for consumers.

Energy and Environmental Contribution

Nanomanufacturing is expected to contribute to the success of the nation's major energy and environmental initiatives. Many of the envisioned nanomanufactured goods will use energy more efficiently, produce other goods with far lesser energy consumption, or convert, store, and deliver energy more effectively. It is anticipated that nanotechnology

will enable solar cells that are produced at reduced costs and provide higher efficiency; light-weight transportation components that improve fuel economy in automobiles and trucks; more efficient lighting (i.e., LEDs) at homes and offices; and better performing catalysts/separations/materials technologies that enhance the energy efficiency of manufacturing. The impact from these products and processes will translate directly into large-scale energy savings and reductions in CO_2 emissions. The potential for nano-related energy developments has led Morgan Stanley to describe nanotechnology as the most promising technology for driving "game changing" advances in renewable energy and energy-use technologies.*

* Morgan Stanley Equity Research, August 2005, Report on Specialty Chemicals

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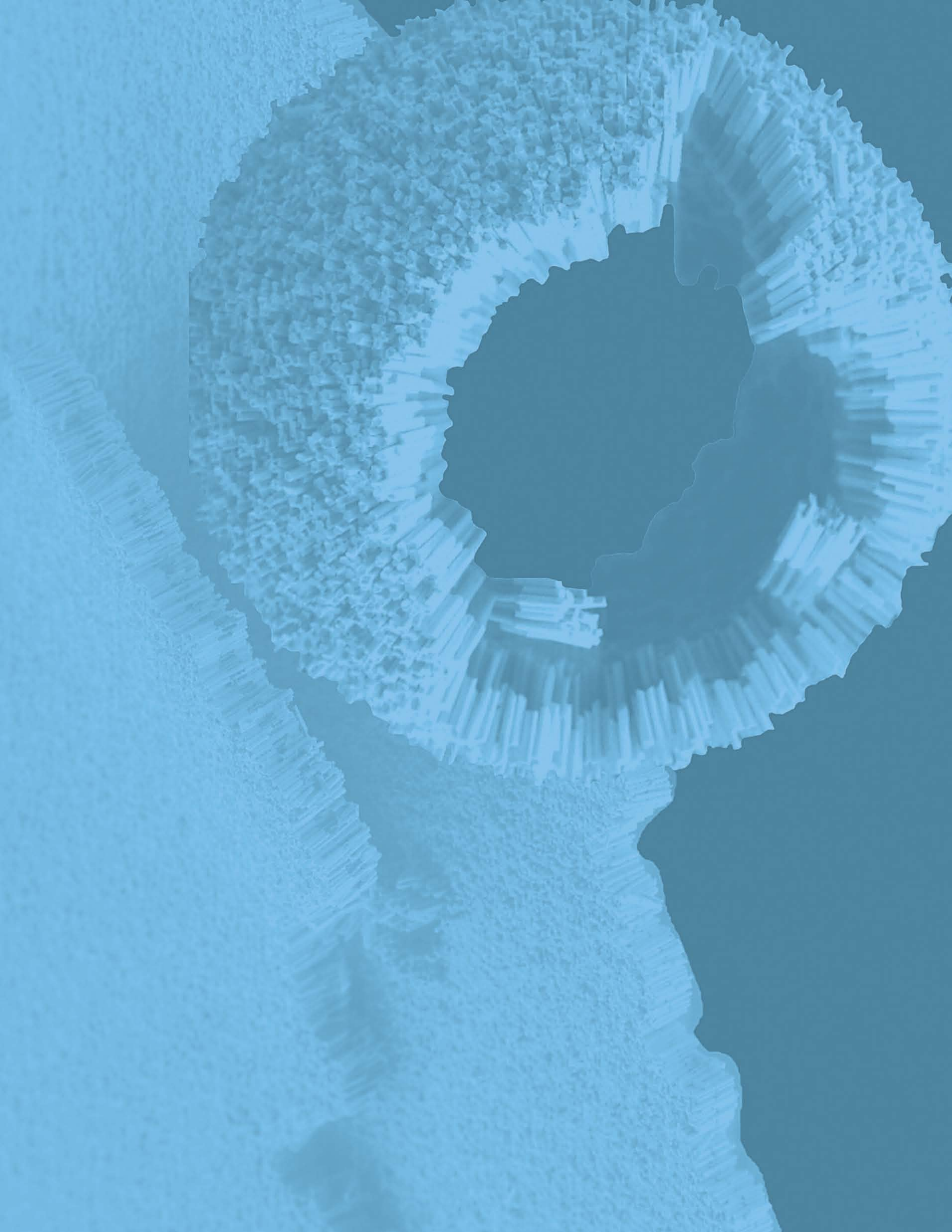
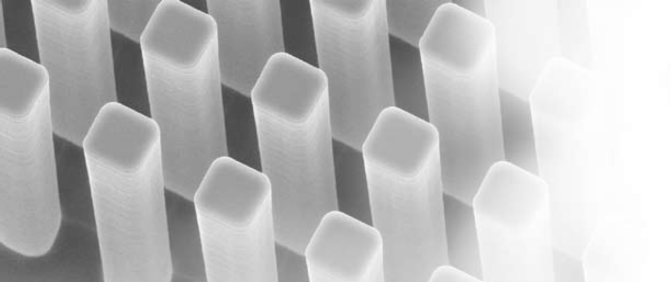




Executive Summary

Industrial stakeholders recognize that significant energy savings are possible from the use of nanotechnologies in industrial manufacturing settings. Estimates of 0.5 to 1.1 quadrillion Btu/year* of energy savings and over 60 million metric tons of CO_2e/yr† reduction have been predicted as benefits from a limited set of nanotechnology applications in the chemicals, refining, and maritime industries alone. Given this potential, accelerating the development of nanomanufacturing technologies is critical in reducing industrial energy consumption and strengthening the global competitiveness of the U.S. manufacturing sector. However, substantial technical challenges must be overcome to enable a commercially viable nanomanufacturing industry.

More then 100 industry experts, scientists, and engineers met on June 5-6, 2007 at the Nanomanufacturing for Energy Efficiency Workshop to identify nanomanufacturing research, development and demonstration (RD&D) needs and business initiatives that, if implemented, will lead to sizeable energy reductions and increased productivity in the industrial sector in the next 5 to 10 years. The following crosscutting manufacturing areas were identified as target applications:

- Catalysis – lower temperature reactions and reduction of byproducts
- Coatings – low-friction, low-drag, and self-lubricating surfaces
- Light-weighting – reduced rotating, sliding, and conveying weights
- Material modification – ultra-hard, wear-resistant, and enhanced properties
- Separations – alternative to distillation and evaporative processes
- Thermal management – superior heat transfer fluids, low conductivity barriers
- Thin films – thermoelectric heat recovery, energy storage

The Workshop sessions identified two applied research and engineering challenges in developing a reliable industrial nanomanufacturing base:

- the ability to produce nanomaterials with the requisite qualities and in quantities useful for industry manufacturing applications, and
- the ability to integrate these nanomaterials at an industrial scale into useful products without losing the nanomaterial's unique properties that produce the desired result.

Overcoming the technological challenges would require concentrating resources on a set of materials and focusing applied RD&D on nanotechnology scale-up to achieve the capability to manufacture large quantities of nanomaterials. The production capacity and the ability to deliver consistent material properties are the metrics that will gauge final success in this area.

The Workshop participants identified the following key technology development and support activities for government and industry funding and collaborations to accelerate the development and use of nanotechnologies within the industrial sector.

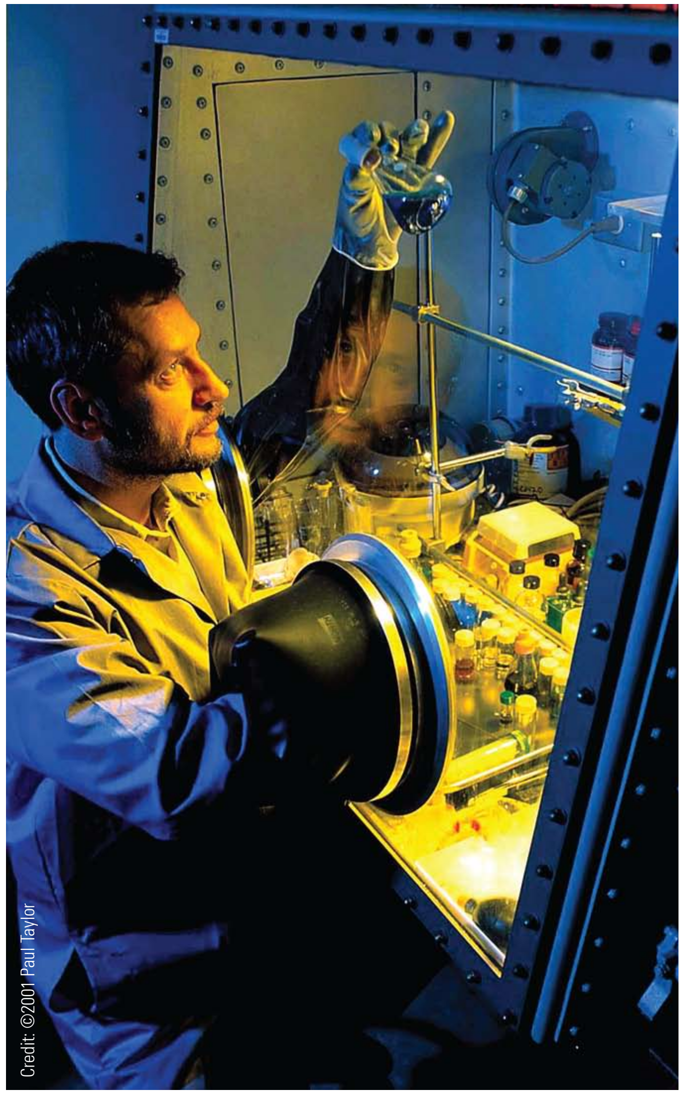
* One quadrillion Btu or a "quad" equals 10^{15} Btu.
† Carbon dioxide equivalents per year

Technology Development

- Examine industrial scale-up technologies for nanomaterials and integration technologies
- Establish infrastructure centers focused on nanomaterials scalability in areas of synthesis, separations, purification, stabilization, and integration
- Develop and enhance characterization and process control tools
- Implement demonstration and validation activities as proof-of-progress to aid in rapid commercialization
- Develop better modeling tools for nanoscale research
- Create and support data sharing and training activities in support of the research being conducted
- Initiate scoping studies to identify which applications would produce the greatest energy reductions across industries and to develop performance targets and metrics

RD&D Support Structures

- Promote nanotechnology transfer by establishing best practices, encouraging education of technology transfer practices, and building relationships with industry and trade associations
- Establish an industrial advisory board(s)
- Support and foster industry collaboration in the above technical areas
- Review contract mechanisms to best implement intellectual property (IP) rights in a manner that simplifies transfer of IP
- Support development of standards for nanomaterials

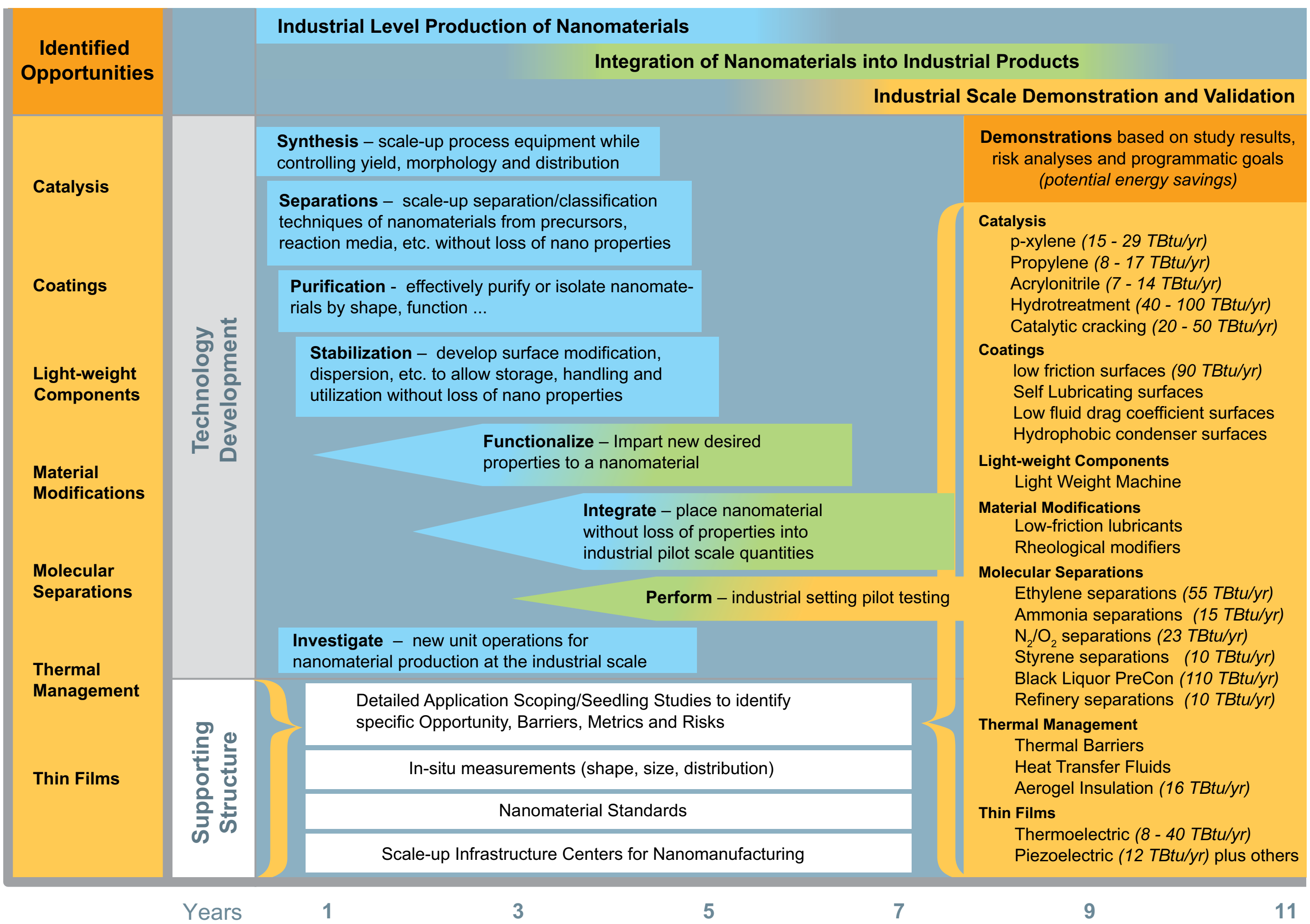


Dr. Vladimir Kolesnichenko, a University of New Orleans research specialist, preparing a precursor material for use in the synthesis of novel inorganic nanomaterials.

Exhibit A summarizes the recommended framework of RD&D pathways and activities over the next 10 years that will lead to the development of nanotechnologies for reducing energy intensity in their respective industry applications.

Although the United States has accomplished significant progress in nanoscience over the past five years, realizing the energy and economical benefits of nanotechnology requires translating the scientific discoveries into commercial manufacturing processes and products. Applied RD&D to enable mass production of nanomaterials and scale-up processes will bridge this gap between the basic sciences and industrial applications, thus contributing to energy reductions in the manufacturing sector.

Exhibit A: RD&D Pathway for Industrial Applications



Nanotree, Credit: ©Ghim Wei Ho and Prof. Mark Welland, Nanostructure Center, University of Cambridge.

How thin is a nanometer?

A nanometer is one-billionth of a meter; a sheet of paper is about 100,000 nanometers thick.

Introduction

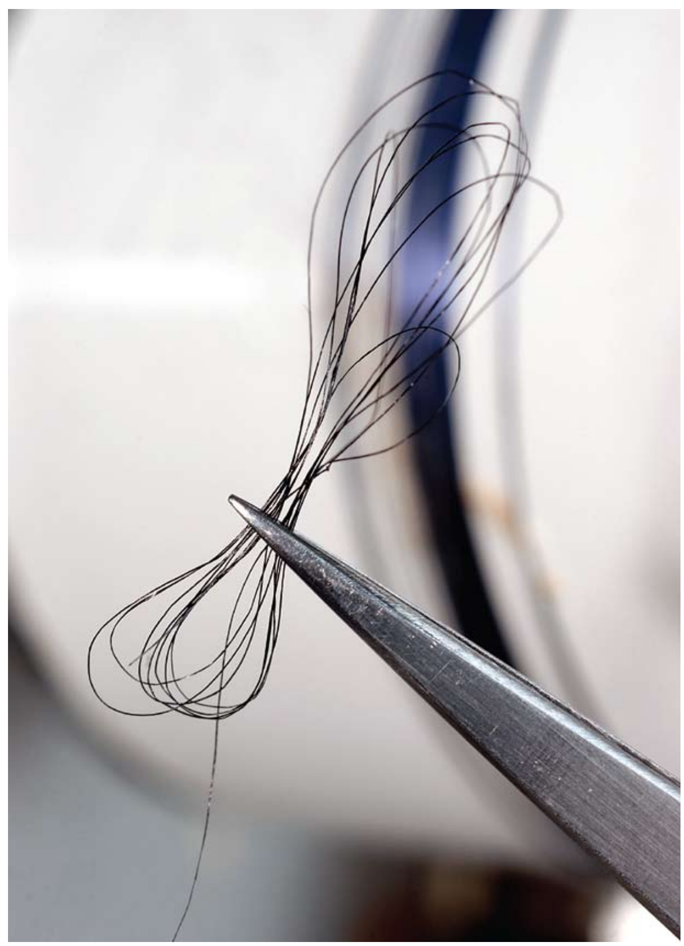
The Nanomanufacturing for Energy Efficiency Workshop, June 5-6, 2007, identified technical and business roadblocks and charted pathways for enabling viable nanotechnologies that will markedly reduce industrial energy consumption.

Attended by over 100 experts, the Workshop discussions were primarily guided by industry representatives but also included participation from government and academia. This report summarizes the outcome of the Workshop, laying out a framework of recommended research, development and deployment (RD&D) pathways and associated activities for the next 10 years.

Need for Prioritizing Nanomanufacturing

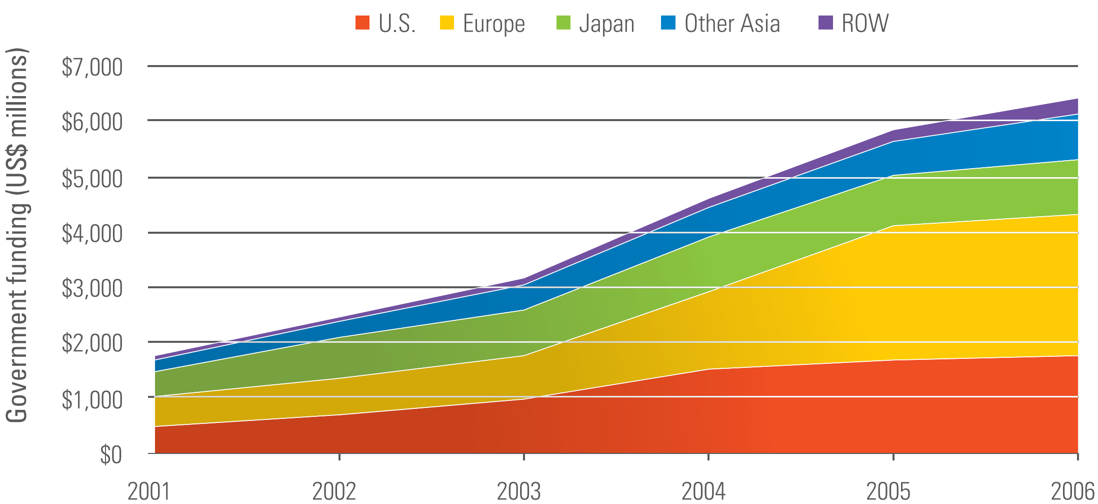
The U.S. government recognizes the great value in nanotechnology and has invested $8.3 billion in research over seven (including the FY'08 reqeust*) years. The President established the National Nanotechnology Initiative (NNI) in 2001, leading to the creation of nanotechnology research centers at several universities; five Department of Energy (DOE) Nanoscale Science Research Centers and other user facilties funded by NNI agencies. The resulting scientific breakthroughs have quickly established the United States as the world leader in nanoscience. However, to realize the economic and social benefits of nanotechnology, these scientific discoveries must be translated into commercial manufacturing processes and products, which will require significant investment in applied research and engineering.

Currently, the U.S. lags behind funding of other countries in the percentage of total nanotechnology R&D funding allocated for applied R&D—the component critical for product commercialization (Exhibit 1). Additionally, other countries have realized the importance of nanotechnology investment and they are currently approaching the United States in their overall spending on nanotechnology research. In order to maintain U.S. leadership and global competitiveness in nanotechnology, the United States must have a greater focus on applied RD&D to transform basic research into useable products and processes. The larger investment is especially required to develop the necessary infrastructure to commercialize nanotechnology—a need that currently deters the U.S. manufacturers from conducting the necessary applied research and application



New Class of Nano-Fibers
Credit: Photo by Gary Meek; courtesy Georgia Tech

Exhibit 1: Global Spending on Nanotechnology and Allocation toward Applied R&D[1]



Source: Lux Research, The Nanotech Report, 5th edition

Applied R&D Funding as a Percentage of Total Nanotechnology Spending	
US NNI	10%
Germany	30%
Japan	30%
China (Beijing)	50%
China (Taiwan)	60%
Korea	60%

Source: National Science Foundation

development on their own. High infrastructure costs with long payback periods and technical/market uncertainties make energy-related nanomanufacturing investments a less attractive area for private sector investment in the near term when compared with proven technology to produce high-value electronics, pharmaceuticals, or other consumer goods.[2]

Recognizing the critical need for applied research to realize the full benefits of nanotechnology, the National Nanotechnology Advisory Panel recently recommended that the government mission agencies develop applied nanotechnology programs. The Department of Defense, National Science Foundation, Department of Commerce, and National Institute of Standards and Technology (NIST) have implemented nanomanufacturing programs. The potential benefits of nanotechnology coupled with industrial stakeholder interests have manifested into a nanomanufacturing for energy efficiency effort.

Nanomanufacturing Efforts

The nanomanufacturing efforts will focus on research, development, and demonstration (RD&D) of nanotechnologies for energy applications. Energy reduction goals will be achieved through research and development, as well as market-specific demonstrations, supporting entrepreneurial commercialization partners, loan guarantees, and other resources of the Federal Government.

Nanomanufacturing is expected to contribute toward achieving the goal of a 25 percent reduction in U.S. industrial energy intensity by 2017 in support of the Energy Policy Act of 2005, and of affecting an 18 percent reduction in U.S. carbon emission intensity by 2012 as established by the Administration's "National Goal to Reduce Emissions Intensity." Moreover, efforts in nanomanufacturing directly support the 21st Century Nanotechnology Research and Development Act of 2003, which calls for scientific and engineering research to accelerate the deployment of nanotechnology in the private sector.

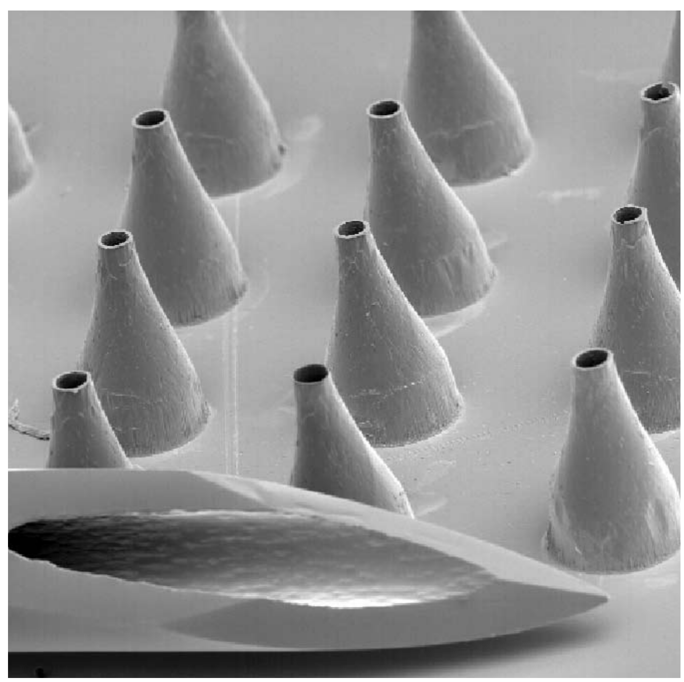
Partnering with industry from the onset in new technology arenas is a proven practice that helps industry and government understand the opportunities, the key challenges, and the strategies needed for successful market penetration of new technologies.

Accordingly, the Nanomanufacturing for Energy Efficiency Workshop was organized to seek industry input in planning RD&D and business strategies to accomplish its goal. The Workshop was guided by an industrial steering committee comprised of:

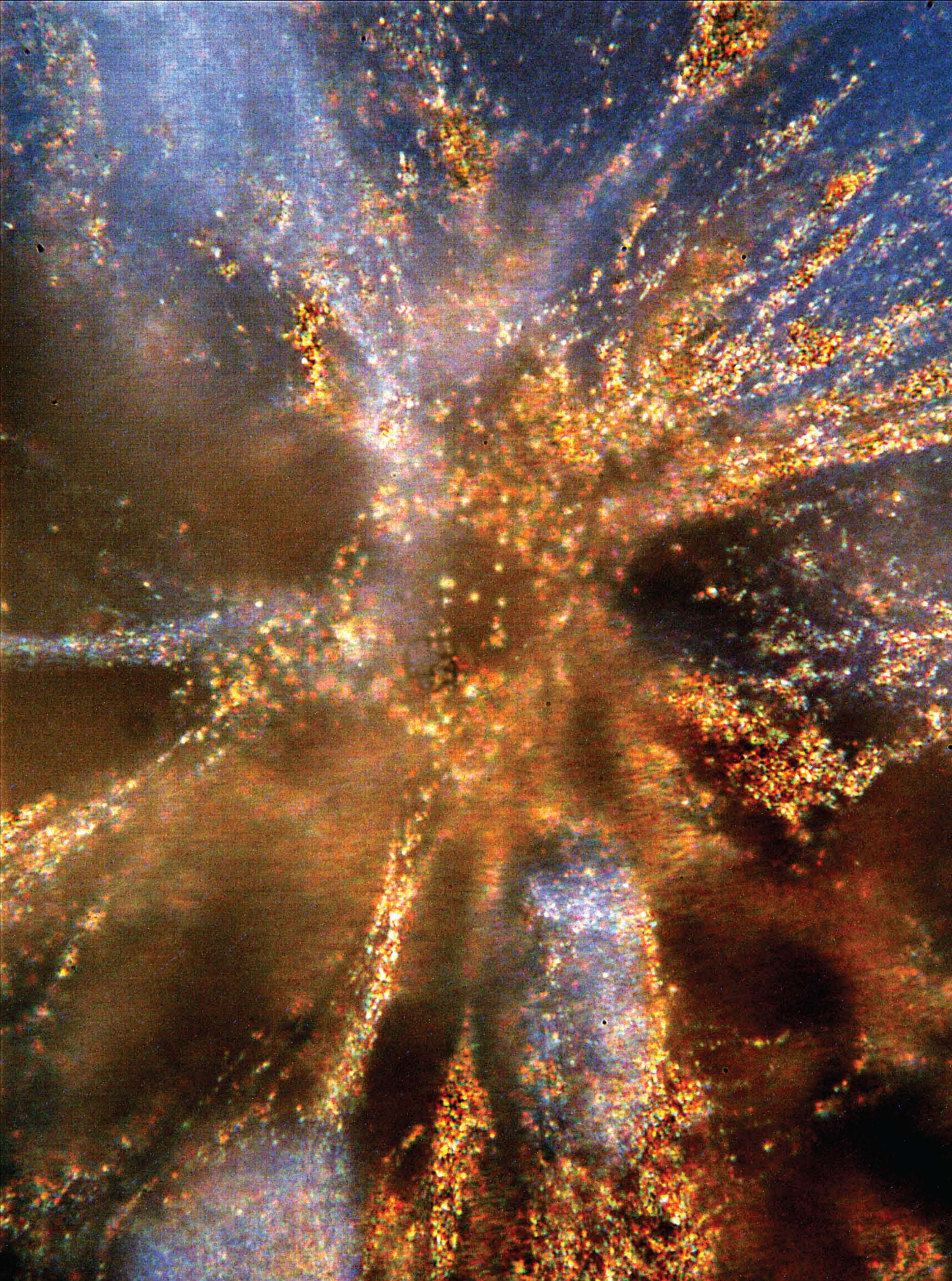
- Bob Doering, Senior Fellow and Silicon Technology-Development Manager (Texas Instruments)
- Jack Kruper, Research Fellow (Dow Chemical)
- George Maracas, Director Nanotechnology (Motorola)
- Mohan Manoharan, Manager Coatings and Surface Technologies Laboratory (General Electric)
- Darlene Solomon, Chief Technology Officer and Vice President Agilent Laboratories (Agilent Technologies)
- Tom Theis, Director Physical Sciences (IBM)
- Larry Thomas, Business Director, Advanced Materials (Air Products and Chemicals)
- Tim Weber, Director of the Advanced Materials and Process Lab (Hewlett Packard)

The Workshop Steering Committee was supported by Oak Ridge National Laboratory and BCS, Incorporated. Teaming together, the group designed the workshop with the purpose of identifying strategies or focus areas for pre-competitive research that would lead to accelerated use of nanotechnologies.

The Workshop was comprised of individual presentations, panel discussions, and strategy sessions (see Appendix A for Agenda and Appendix B for a complete list of participants). The Workshop proceedings identified opportunities presented by nanotechnology use in industry, the technical and business barriers, and the strategies that will overcome them. Further, the participants prioritized research and development focus areas for the coming years. It is anticipated that meeting the high priority needs and strategies stated herein will accelerate the development of nanotechnologies that will substantially reduce energy intensity in the industrial sector. A comprehensive list of nanotechnology priority needs identified at the Workshop is presented in Appendix C.



Hollow Metal Microneedles
Credit: Courtesy S. P. Davis, M. R. Prausnitz, M. G. Allen, Georgia Institute of Technology



"Light Scattered by Gold Nanorods", Credit: The USC Nanocenter

RD&D Opportunities and Pathways for Energy Savings

The industry representatives and market analysts participating at the Nanomanufacturing Workshop identified several opportunities for energy savings from nanotechnology products.[3] Nanomanufacturing techniques will eventually be used by all types of industries, developing products for everyday use and enabling innovative products in the future. The industry representatives agreed that over the next few decades, advances in nanotechnology will touch nearly every aspect of life, from everyday items like lightweight, high-strength materials for automobiles to new medical technologies and solutions for problems posed by the emerging global energy crisis.[4]

Nanomanufacturing will enhance industry efficiency, process flexibility, and product value. The chemicals industry performed a benefits analysis on a set of nanomaterials–catalysts, coatings, and membranes–and for a limited set of applications–chemicals production, petroleum refining, and maritime–to evaluate the impact of nanotechnology. This limited set of nano-enabled product applications was estimated to result in value creation of $10-20 billion/yr, GNP increase of $30-63 billion, employment increase of 455,000-975,000, and energy savings of 0.5-1.1 quadrillion Btu/yr.[5] These applications represent only a small portion of the industrial manufacturing sector that could be impacted by nanotechnology and provide an indication of the of benefits that could be realized.

The energy savings opportunities identified at the Workshop were grouped into three categories based on their mode of impact:

- **Industrial Manufacturing Energy Efficiency:** Nanotechnology allows developing catalysts, coatings, and other materials and structures that will reduce the energy consumed in industrial manufacturing operations.
- **Product End-Use Energy Efficiency:** Nanotechnology can be integrated into products that, when used, consume less energy than conventional products. Products like LED lighting, lightweight vehicle components, thin film displays, and other consumer products provide end-use energy efficiencies that will save energy everyday while being used.
- **Energy Production and Storage:** Nanotechnology offers new techniques to produce, transport, and store energy, enabling more efficient alternative energy technologies.

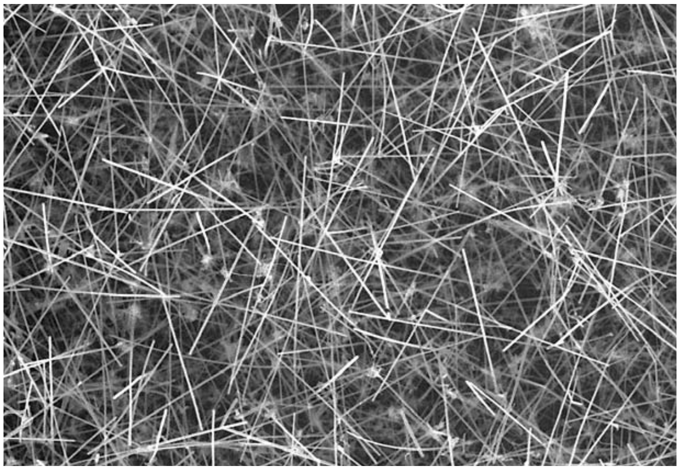
Industrial Manufacturing Energy Efficiency

The Nanomanufacturing Workshop participants identified the following applications of nanotechnology in industrial manufacturing that will significantly improve energy efficiency:

- Catalysis
- Coatings
- Super Strong, Lightweight, Long-Lasting Materials
- Material Modification
- Separations
- Thermal Management
- Thin Films

Catalysts

Nanoparticles, nanowires and other nanostructured materials have very high surface areas to provide greater catalytic activity. The ability to control the production of these shapes and the support structure on which they will reside offers new opportunities in catalyst performance. Other nanomanufacturing techniques such as atomic layer deposition used



to create a very specific structure offer further opportunities in the catalysis field. Energy savings related to improved catalysts are substantial, primarily due to their potential for decreasing byproduct formation and enabling lower reaction temperatures. Los Alamos National Laboratory estimated the energy impacts of nanoscale catalysts in the chemical production and refining industries at 0.28 to 0.60 quadrillion Btu/yr.[6] It was estimated at the Nanomanufacturing Workshop that Dow Chemical Company alone will save between $30-50 million this year by using nanoparticle catalysts. Although there are significant energy savings opportunities associated with catalysis, there are technological barriers that need to be addressed before these savings can be realized.

Workshop participants identified high-temperature stability of materials, lack of nanoscale modeling abilities, and the very limited availability of raw nanomaterials for catalytic product development as significant barriers to developing nanocatalysts for energy savings applications. Overcoming these barriers will require significant RD&D efforts, followed by demonstration and validation of the technology to accelerate its market deployment. The RD&D pathways for developing nano-enabled catalysts are shown in Exhibit 2.

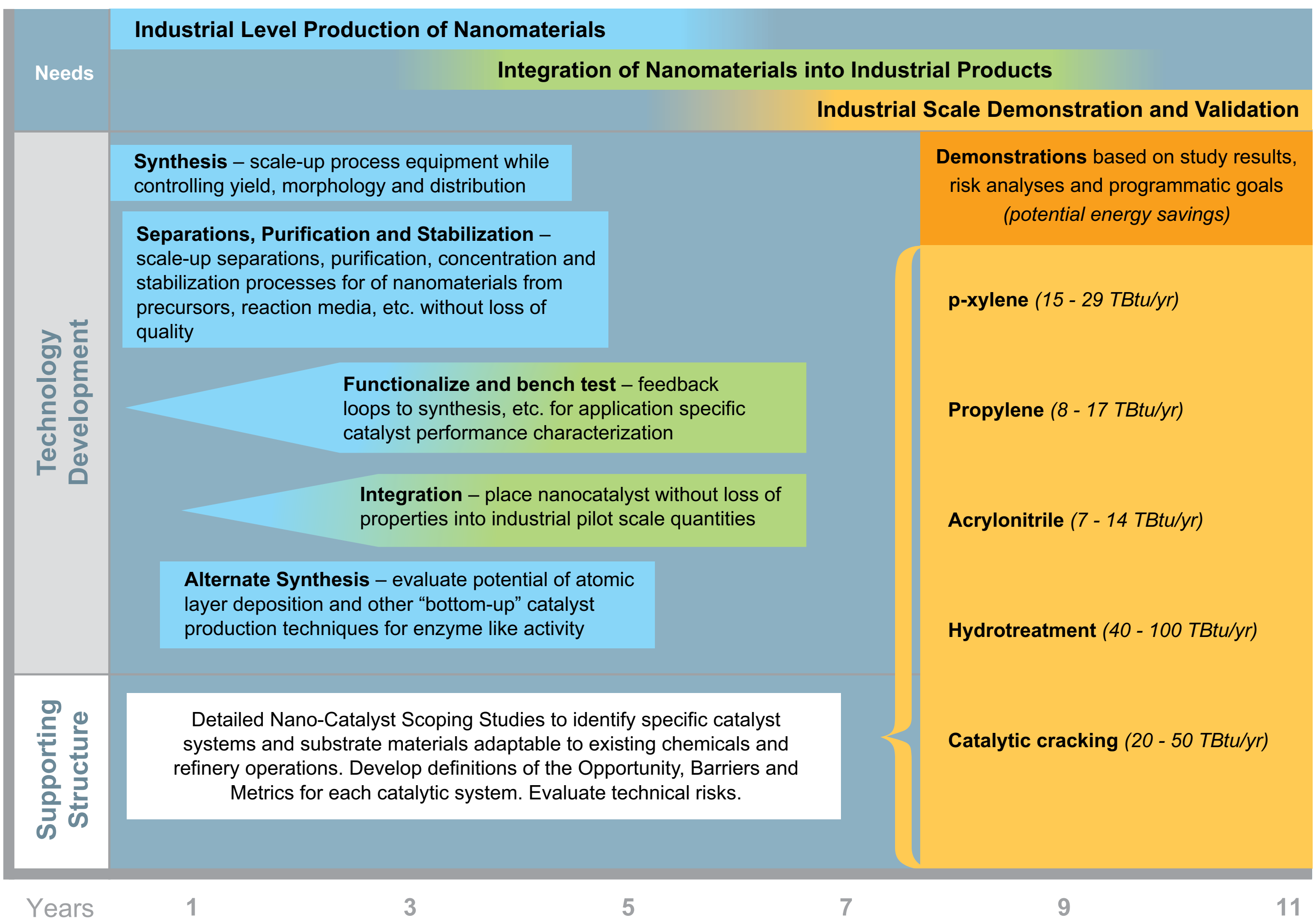
Coatings, Surface Modifications & Treatment

The capability to tailor surfaces with nanoscale coatings of functional materials provides the possibility to create corrosion-resistant, anti-fouling, low-friction, durable, and/or super hydrophobic surfaces. Corrosion costs across all industries represent approximately 4.2 percent of GNP.[7] The potential energy impact of anti-fouling coatings in the shipping industry could exceed 0.15 quadrillion Btu/year.[8]

Low friction and low drag coatings find applications in every industry, especially those industries that rely heavily on the use of rotating machinery. Coatings with these properties have the ability to save enormous amounts of energy in pumps, compressors, and turbines alone. The development of low-wear, erosion-resistant coatings also have many industrial applications such as die making and drilling and mining equipment. Processes that make and use industrial tooling are energy intensive and the ability to develop longer lasting tooling would yield energy savings.

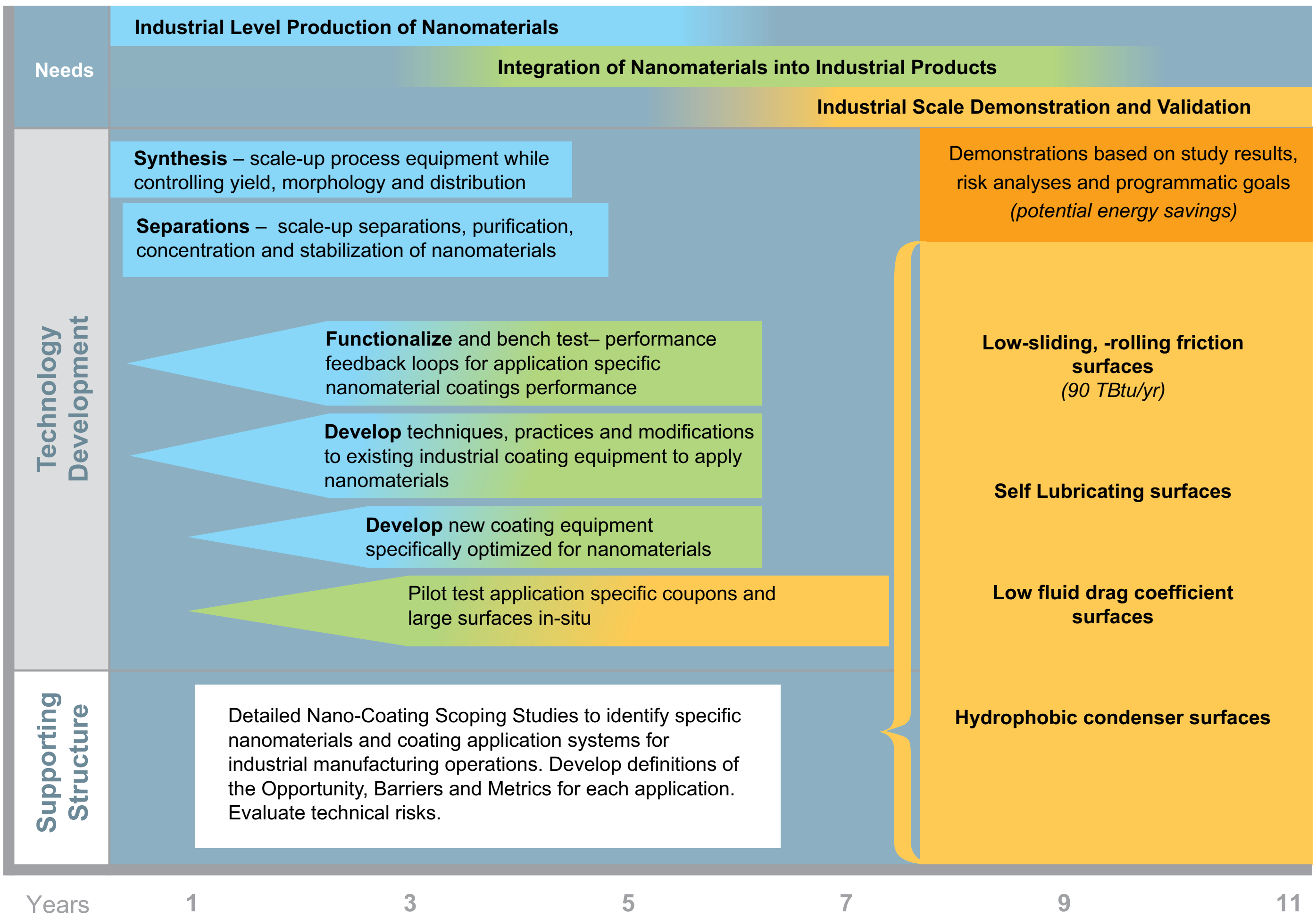
Although nano-enabled coatings show much promise, industry leaders identified the lack of understanding of structural and interface properties of nanomaterials and the impact of defects attributed to the coatings, as major barriers impeding the development of nano-enabled coatings for energy efficiency. Coatings technologies will benefit from continued applied RD&D that addresses these specific barriers. In addition to RD&D efforts needed to develop advanced coatings, significant funding needs to be allocated to develop processes that will enable these coatings to be

Exhibit 2: RD&D Pathway for Industrial Catalysis Applications



incorporated into products. The long-term results of continued commitment to developing nanotechnology-based coatings will result in new everyday-use products throughout industry. The RD&D pathways to energy savings from nano-coatings are shown in Exhibit 3.

Exhibit 3: RD&D Pathway for Industrial Coatings, Surface Modifications & Treatment

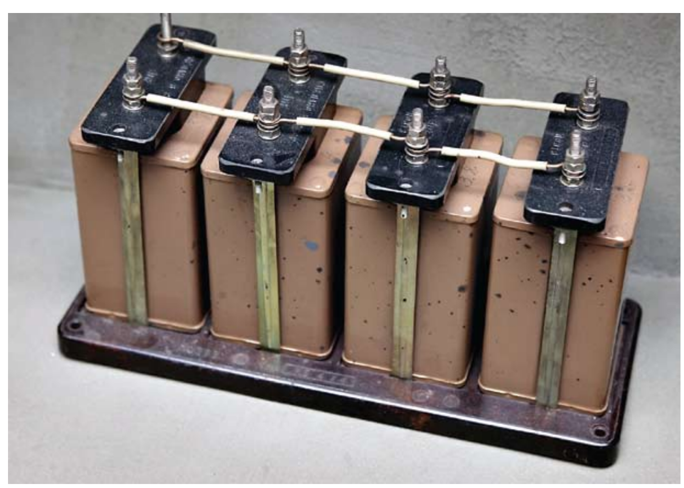


Super Strong, Lightweight, Long-Lasting Materials

Significant energy savings can be achieved by using nanomaterials to create new lighter, stronger, and longer-lasting components. These energy savings can accrue all along the value chain from basic industries producing materials such as steel and aluminum to the manufacturing and production of consumer goods.

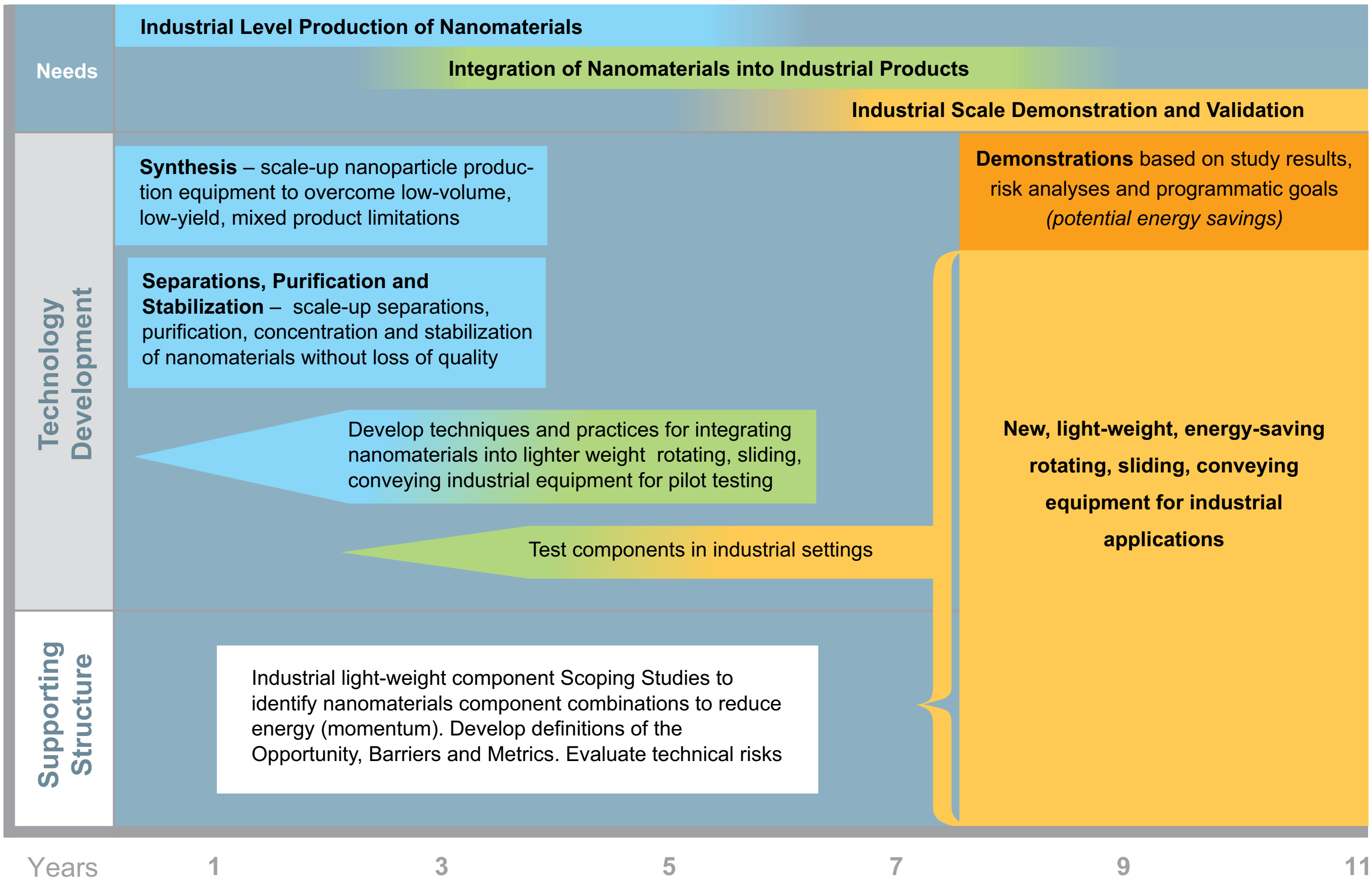
Lightweight materials will result in significant energy savings in industrial applications that involve sliding, conveying, and rotating process equipment. Industries consume large amounts of energy to move their raw materials through manufacturing processes to produce end-use products. In some conveyor belt applications, the belts can often weigh more than the product they are transporting. Lightweight materials will reduce the power required in these and similar applications, resulting in energy savings.

Potential product development challenges such as nanophase metallic composites and processes such as rapid annealing and low-temperature consolidation, need to be pursued. Low-temperature, nondestructive joining methods for nanomaterials are needed, as are techniques, such as powder metallurgy of nanomaterials, for improving machining efficiencies, which often require removal of up to 50 percent of precursor material.



In order to apply nanotechnology to develop lightweight technology, an understanding of the interactions between the nanomaterials and their surrounding matrix and methods to manipulate these interactions must be developed. The technology development needed to enable lightweight materials for use across multiple industrial applications is shown in Exhibit 4.

Exhibit 4: RD&D Pathway for Super Strong, Lightweight, Long-Lasting Materials



Material Modification

Rheological Modifiers

The use of nanoparticles as rheological modifiers in processing and pumping high viscosity fluids offers a potential near-term application. Such nanoparticles make fluids less viscous and are currently in use in some injection molding applications. This ability lowers the cost of extruding and transporting fluids, while increasing the longevity of pumping equipment. Although this energy savings opportunity is application specific, its potential is large and can be realized in the near term as it could be rapidly applied to existing industrial processes.

Enhanced Lubrication

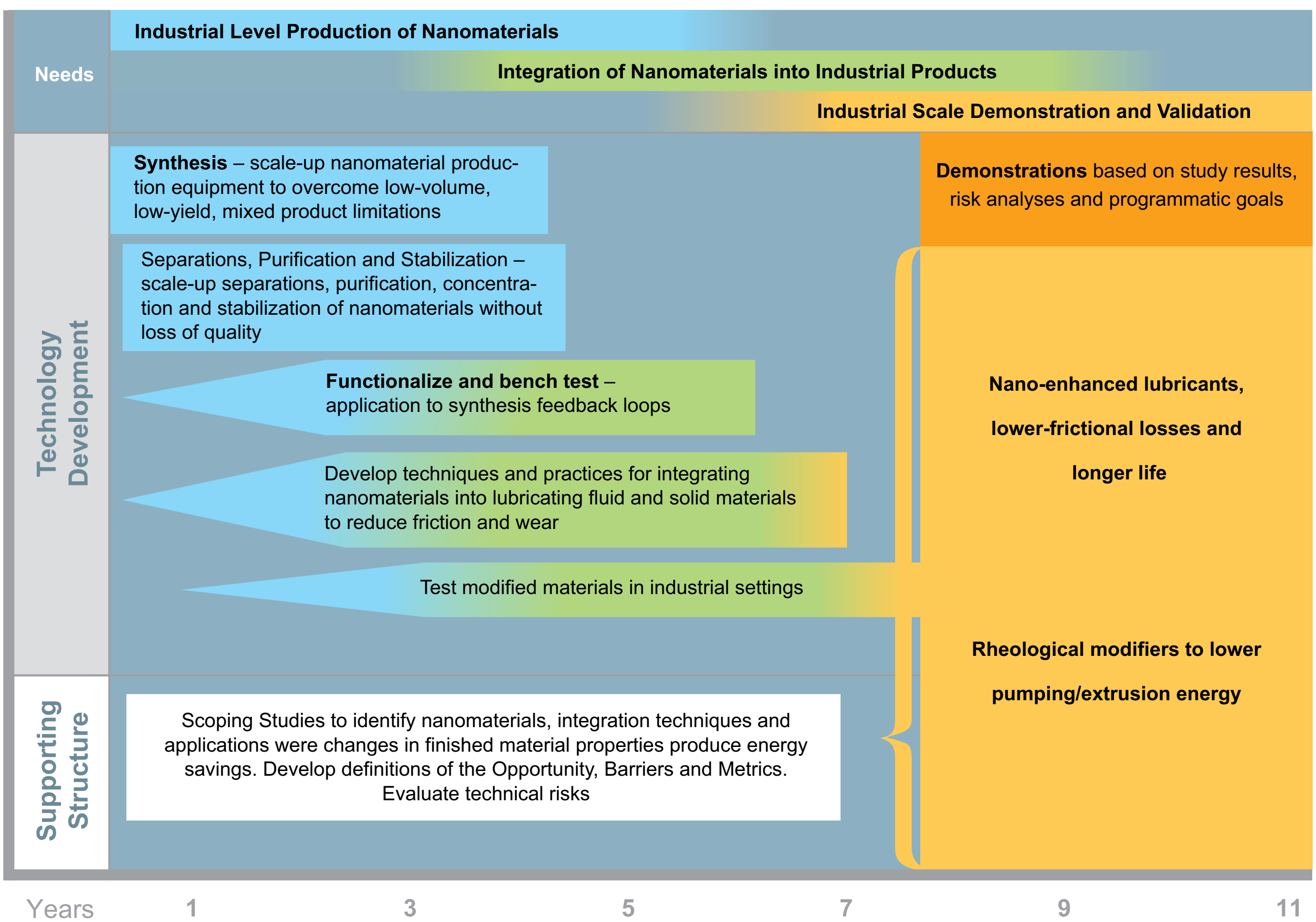
Lubricants containing nano-sized spheres ("ball bearings") will lower frictional losses and last longer in pumps and equipment drivers. Currently, these modified lubricants are costly and unproven, limiting their applicability. Further, concerns regarding their disposal, recycling, handling and lifecycle remain unresolved.

Nano-Enabled Materials for Forest Products

Currently, research efforts are in place to develop materials with enhanced properties such as greater strength, water resistance, and fire-retardance and to improve packaging using nano-enabled forest products.[9] The forest products industry is focusing on other promising areas for nanotechnology applications related to manufacturing including using nanoscale materials to develop composite materials and using nanoscale sensors for monitoring and control during processing. These new materials are lighter, more durable, and conserve natural resources.

Although there are significant efforts underway, there still needs to be continued development in the area of materials modification. These efforts need to expand on the results of basic research and focus on retaining the benefits of the nanomaterials in the final products. The RD&D pathways to enable these technologies are shown in Exhibit 5.

Exhibit 5: RD&D Pathway for Industrial Material Modification Applications

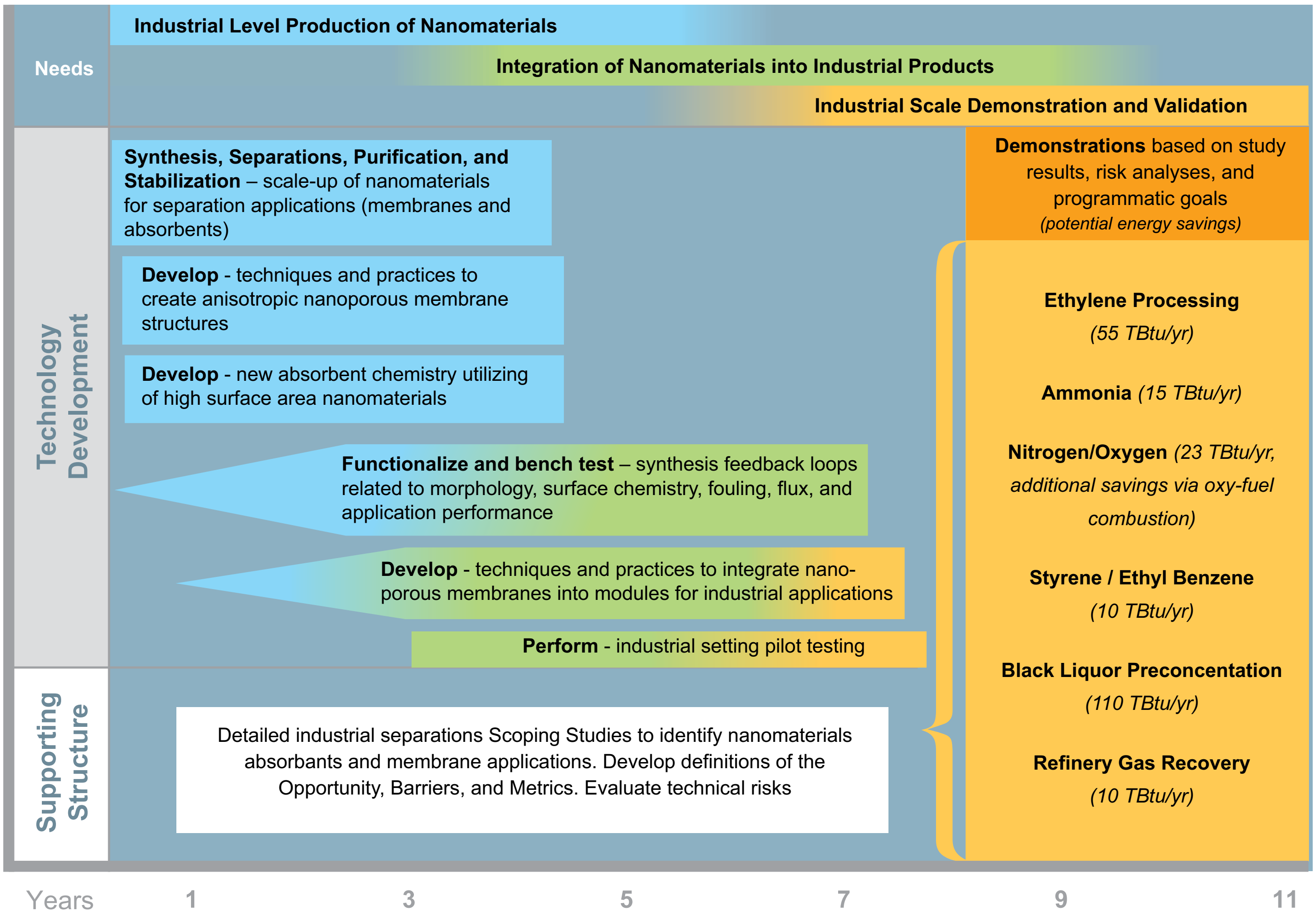


Separations

Nanoporous materials such as membranes and sorbents can enable more energy-efficient industrial separations. A total of more than 6 quadrillion Btu is now consumed annually for separations in the chemicals, petrochemicals, and forest products industries. Applications utilizing nanostructured materials for separations could save more than 0.24 quadrillion Btu/ year in these industries.[10] Industrial separations systems also provide an excellent opportunity for heat recovery. Recoverable useful energy (exergy) losses in distillation processes alone amount to 0.17 quadrillion Btu/yr.[11] More permeable nanotube membranes could reduce the energy costs of desalination by up to 75 percent compared to conventional membranes used in reverse osmosis.[12] Advances in nanotech-application in separations will be achieved through improved understanding of the complex transport mechanisms and fouling tendencies at the nanoscale and by developing the nanomanufacturing infrastructure to fabricate media with engineered pore sizes and desired functionality.

Since separations are highly energy intensive throughout manufacturing industry, with especially large potential for energy savings in the chemicals and petroleum industries, it was a major focus of discussions at the Nanomanufacturing Workshop. Identified barriers to the development of separations included the need for membranes with high selectivity and improved fouling and defect-free characteristics. Other major barriers to applicability of nanotechnology in separations are the ability to tailor the membrane pore size and the ability to extend the membranes developed in the laboratory to the sizes needed for industrial applications. Solutions

Exhibit 6: RD&D Pathway for Industrial Separations Applications



to overcoming these barriers will require aggressive technology development. The suggested RD&D pathways for pursuing energy savings in separations to their fullest extent are shown in Exhibit 6.

Thermal Management

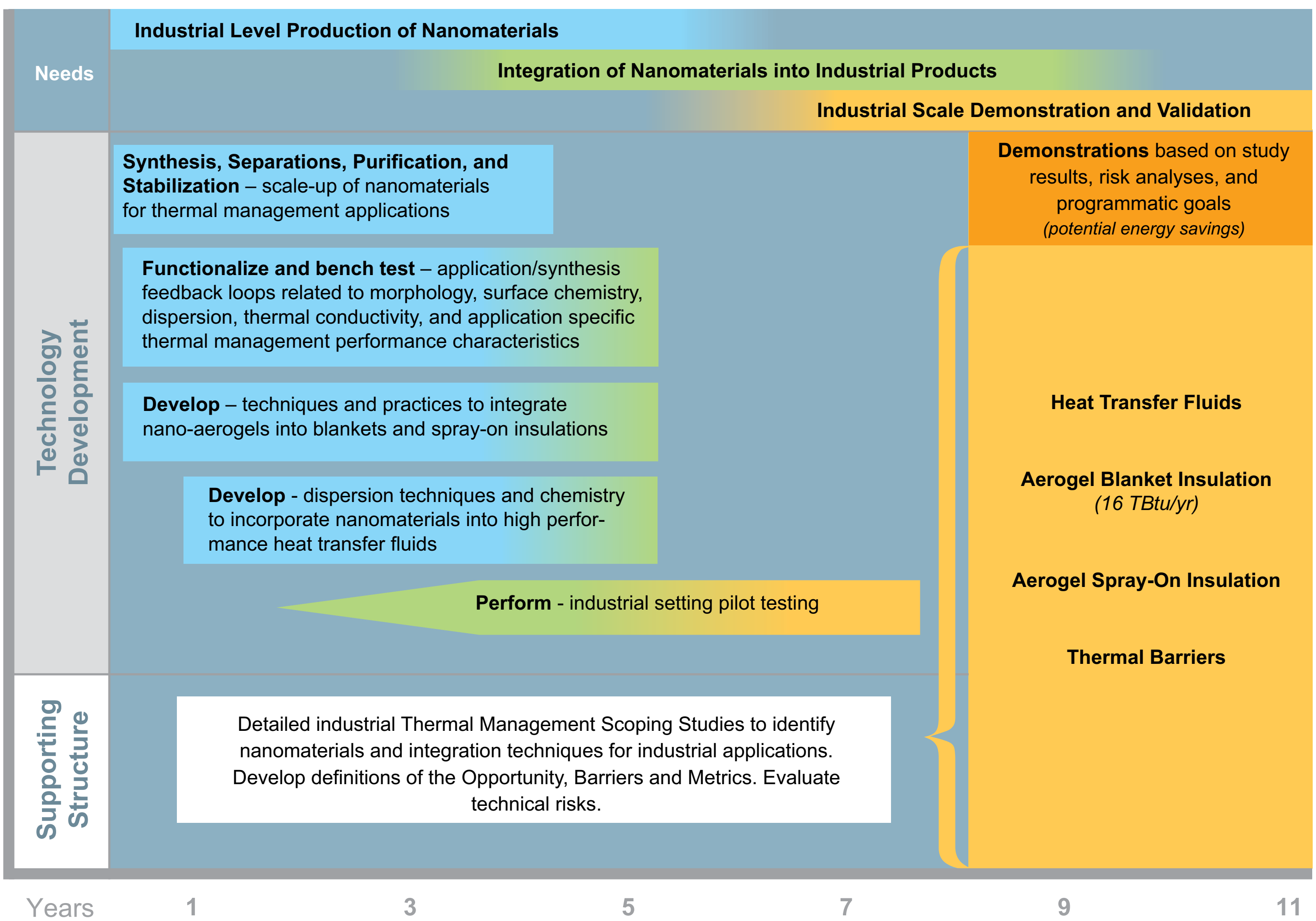
Heat Transfer Fluids

Heat transfer fluids enhanced with nanomaterials (nanofluids) can improve thermal and economic performance in industrial waste heat recovery and heat transfer applications. Enabling higher energy efficiency of existing industrial heat recovery systems, "nanofluids" will find applications in large industrial operations such as refineries, chemical plants, and paper mills. One commercial producer of high-performance heat transfer fluids cites heat transfer improvements of up to 30 percent from using nanofluids.[13] The major market inhibitor is the lack of understanding of heat transfer process and corrosion properties, as well as of the fluid dynamics of nanofluids.

High Performance Insulation

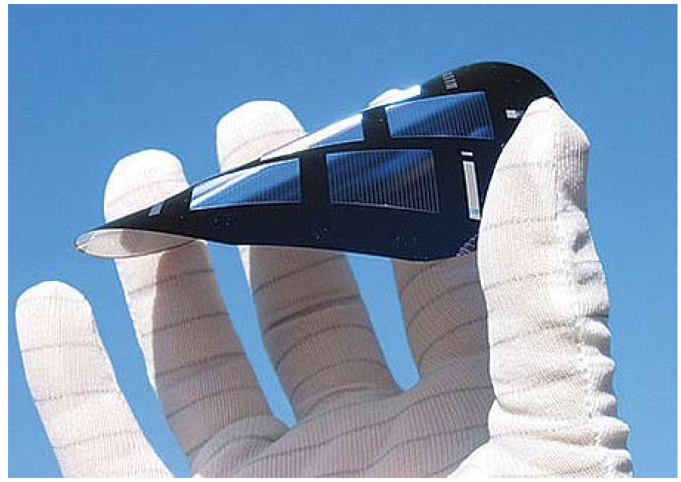
Thermal losses from industrial energy systems and buildings account for a large part of U.S. energy consumption. Conventional insulation materials like fiberglass, calcium silicate, and mineral wool provide only limited insulation, allowing significant heat loss to occur. Nanostructured aerogels have the lowest thermal conductivity of any known material and offer new opportunities in insulation design and application that will improve energy conservation. However, concerns pertaining to durability and property degradation with time impede market acceptance of this technology. Overcoming these concerns and bringing these technologies to the market require focused RD&D effort (Exhibit 7).

Exhibit 7: RD&D Pathway for Industrial Thermal Management Applications



Thin Films

Thin film deposition will crosscut several energy production applications, including photovoltaics for solar energy. Thin film batteries are more fuel-efficient, charge within minutes, and hold a charge 40 times longer than existing batteries.[14] Thin films are also important in a variety of chemical and materials applications. Brief descriptions of these technologies' relevant impacts follow.



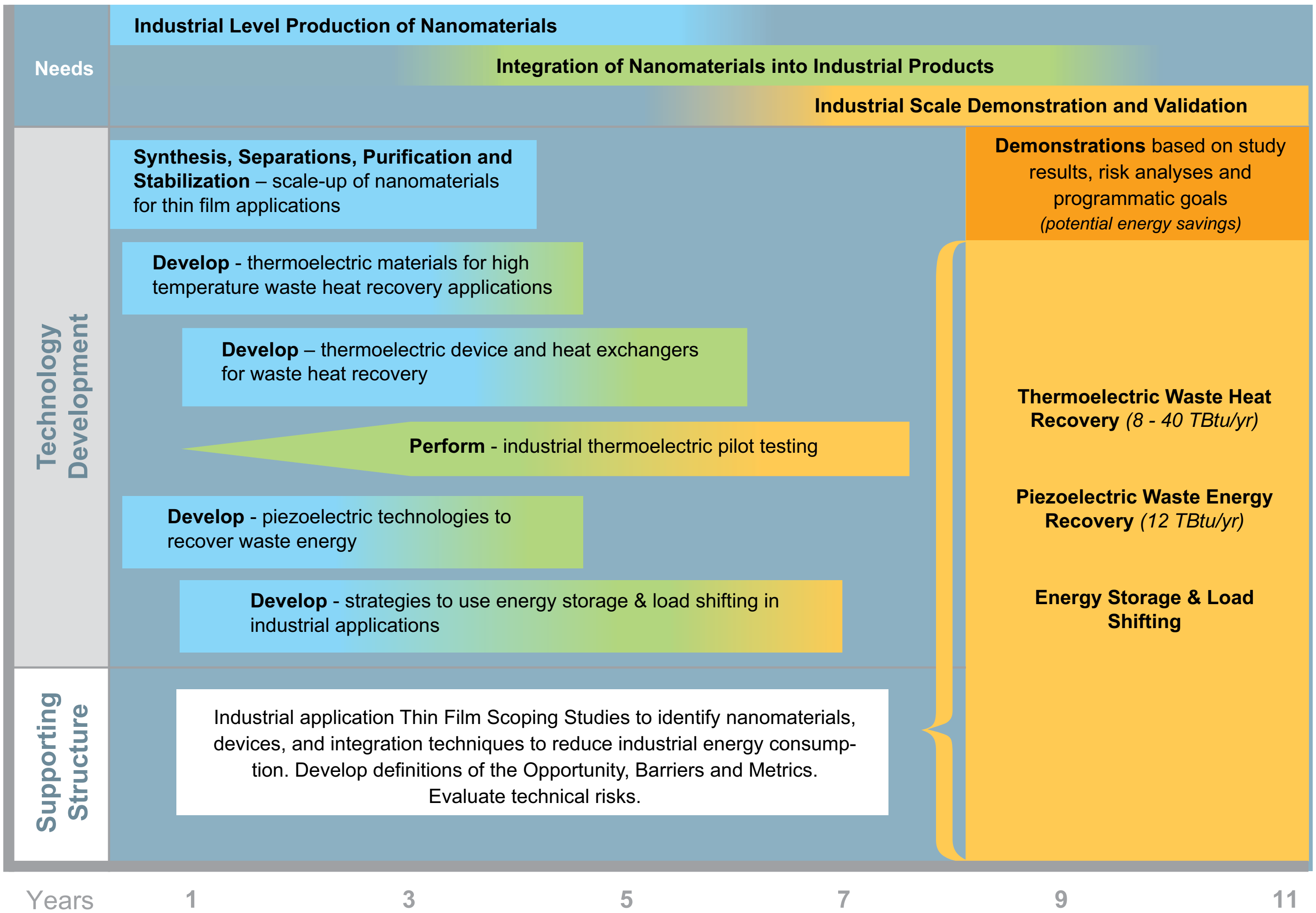
Thermoelectric

Nanostructured materials offer the potential to greatly reduce the total energy used and lost during process heating. Approximately 15 quadrillion Btu of energy is used in the U.S. for process heating. Utilizing nanostructured thermoelectric devices for waste heat recovery may significantly reduce total industrial energy consumption. Other sources of wasted energy such as vibration or pressure changes could ultimately be captured by nanomaterials. As much as 1.8 quadrillion Btu of waste heat may be recoverable annually using thermoelectric materials.[15] Several kinds of nanostructured materials show great promise for producing thermoelectric devices with efficiencies 3 to 5 times higher than any conventional technology. This would make feasible the direct conversion of waste heat from industrial processes and motor vehicles to electricity. Such materials include quantum well films, quantum dots, and quantum wires. The ability to control thermoelectric structures to precisely constrain the movement of electron holes is a major barrier to developing quantum dots and quantum wells. Also, there remains a need for precise manufacturing processes and highly sensitive characterization devices to accelerate progress in this area.

Energy Storage

Potential industrial applications include uninterruptible power supplies and auxiliary power systems. Improved industrial battery systems could increase energy efficiency and reduce losses resulting from electrical grid interruptions. Thin film technology has the potential to lower the energy losses in batteries by reducing losses exhibited at the electrodes. The RD&D efforts needed to improve thin film technologies are shown in Exhibit 8.

Exhibit 8: RD&D Pathway for Industrial Thin Film Applications



Product End-Use Efficiency

The Workshop participants identified the following nanotechnology applications that will markedly increase product end-use energy efficiency:

- Solid-State Lighting
- Data Storage and Processing
- Transportation (light-weighting)
- Electronics

Solid-State Lighting

Incandescent and fluorescent lights are only about 5 and 25 percent efficient, respectively. Light emitting diodes (LEDs) have the ability to improve energy conversion efficiency, reduce heat load, increase brightness, and reduce the dimensions and cost of solid state lighting applications. LEDs are already in use for colored lighting, while LEDs that emit white light are available for niche applications. The cost and efficiency of LEDs for commercial and residential lighting applications, however, needs improvement. Inexpensive nanofabrication can help in expanding LEDs lighting applications.[16] Integrating high efficiency quantum dots into LEDs could help make LEDs a viable lighting option.

Data Storage and Electronics

Nanomanufacturing will continue to impact data storage and processing beyond its traditional role in semiconductor manufacture. Applications such as thin film transistors for flat panel displays will reduce energy consumption. Nanotechnology-enabled computer chips may lead to processing power far beyond our current technology's capability. Nanostrctured-coatings will provide improved electrostatic protection and better thermal management.

Thin film transistors (TFTs) for computers and flat panel displays manufactured using nanomaterials consume less energy and generate less heat. According to the United States Display Consortium, a nano-structured material that reduces energy cosumption by 44 percent, could result in saving trillions of BTU of energy.[19] These savings can only be realized by the introduction of energy-efficient nanostructured materials.

Transportation

The U.S. transportation sector consumes 28 quadrillion Btu annually. Nanomanufacturing offers great potential to reduce both transportation energy intensity and its dependence on fossil fuels. Lighter and stronger body panels, engine, frame and suspension components, truck beds, and shipping containers possible from the use of nanotech-enabled materials, particularly novel composite materials, will benefit all transportation sectors. The use of catalysts to enable fuel switching from gasoline to diesel will reduce emissions and lower energy demand. Composite materials already contribute to a 12 percent fuel efficiency gain in new airliners, and many companies are looking to nanocomposites to extend these gains further.[17]

Energy Production and Storage

The following potential nanotechnology applications for energy production and storage equipment, and processes were identified at the Nanomanufacturing Workshop:

- Photovoltaic Power Systems
- Fuel Cells
- Batteries and Ultracapacitors for Electrical Energy Storage
- Power Transmission
- Biofuels Production

Photovoltaic Systems

The use of nanostructured materials in photovoltaic (PV) derives offers the potential for more economical manufacture, as well as more efficient capture of solar energy. Research is leading to device efficiencies greater than 14-15 percent at costs less than $100/m^2, which will allow manufacturers to reach the goal of $1/W.[21] Current barriers to PV nanofacturing include a lack of understanding of the correlation between nanostructured material properties and device performance. This ability is needed to manufacture both composites and quantum dot devices cost effectively.

Fuel Cells

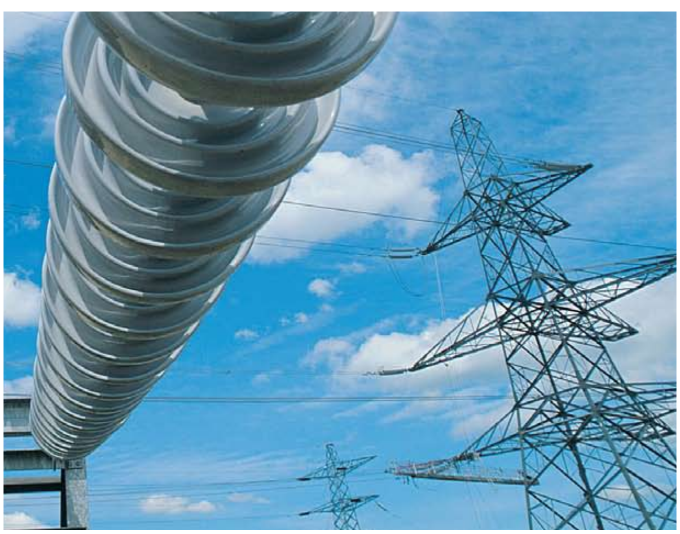
There is an enormous potential for fuel cell technologies, however, obstacles like catalyst cost and performance and electrolyte conductivity and durability prevent their widespread market adoption. Nanotechnology could play an important role in the commercialization of fuel cells. Nanoparticle-based catalysts for fuel cells are able to operate 50 times longer while using less material than traditional fuel cell catalysts. Nanostructured materials can also greatly enhance conductivity performance for fuel cell electrolytes.

Batteries and Ultracapacitors for Electrical Energy Storage

Nanostructured electrodes for lithium-ion batteries have demonstrated power densities 10 times greater than conventional batteries. Likewise, tailoring of the nanoscale pores of carbon electrodes has improved the energy density and frequency response of ultracapacitors. Improved energy storage devices will help make alternative energy technologies like biomass and solar commercially viable. Additionally, improved batteries and ultracapacitors could help alleviate incurred losses caused by short-term interruptions to the electric grid. Improving the energy density of these technologies without raising manufacturing costs requires development of scalable, economical nanomanufacturing processes.

Power Transmission

Some carbon nanotubes have electrical conductivity similar to that of copper, but at one-sixth the weight, and could have 100 times the current carrying capacity of the best low-temperature superconductors. Reducing current losses in power transmission lines from 7 percent to 6 percent would result in a national annual energy savings of 0.2 quadrillion Btu.[22] The latest generation of high-temperature superconducting wires is enabled via 3-D self-assembly of insulating nanodots, and meets the performance requirements for most large-scale applications. Also, superconducting motors and generators enabled by nanotechnology can cut current losses, weight, and volume by a factor of two, and are also much more tolerant of voltage sag, frequency instabilities, and reactive power fluctuations than their conventional counterparts.[23]



Biofuels Production

The use of biofuels for transportation and as chemical feedstocks can supplement the use of fossil fuels, the current lifeline of these industries. Nanomanufacturing and nanomaterials will play a widespread role in biomass conversion. Cost-effective biofuel production requires catalysts to efficiently extract fuel from biomass feedstock. Nanomaterials used as catalysts are being developed for the chemicals industry and are also expected to play a significant role in the production of biofuels.

Technology Barriers to Nanomanufacturing for Energy Efficiency

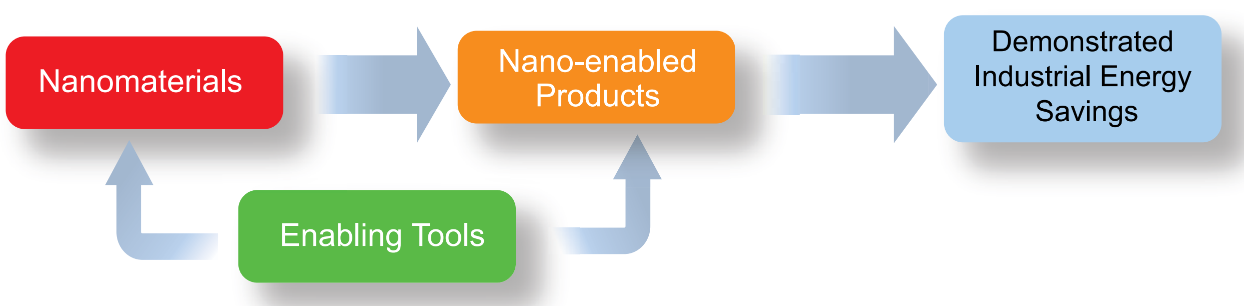
Nanomanufacturing for industrial energy efficiency begins with the large-scale production of nanomaterials with desired properties that will be integrated into products and processes. These products and processes allow industry to produce, with lower energy intensity, the materials and products its customers expect. These nanotech-enabled products and processes can significantly reduce energy consumption in U.S. industrial manufacturing, by over 1.0×10^{15} Btu/yr (1.0 quad), and lower carbon related emissions by over 60 million tonnes CO_{2e}/yr. Achieving this level of energy savings, valued at over $5 billion/yr, within the next ten years will require focused RD&D efforts to develop and demonstrate technologies, along with resources and enactment of policy initiatives to encourage future investment.

The industry experts at the Nanomanufacturing Workshop identified four primary nanomanufacturing RD&D focus areas:

- Developing the knowledge, skills and equipment to produce nanomaterials with the properties, quality, economy, and in the quantity required
- Developing the knowledge, skills and equipment to integrate nanomaterials into nanotech-enabled products that can be produced with the properties, quality, economy, and in the quantity required
- Developing the crosscutting tools for analysis, process control and modeling of nanomaterials and nanotech-enabled products
- Demonstrating and validating nanotech-enabled product energy efficiency performance in industrial manufacturing applications

These areas form the pathways to overcoming nanomanufacturing barriers (Exhibit 9).

Exhibit 9: Pathway to Nanomanufacturing for Energy Efficiency



Additionally, the need to address environmental, health, and safety (EHS) issues specifically related to the manufacture of nanomaterials, nano-enabled products, and end-use activities has been a primary focus of research for the NNI and DOE, and the resulting knowledge will help in promoting practices that minimize resulting EHS impacts.

Producing Nanomaterials

Nanomanufacturing for industrial energy efficiency will require the production of nanomaterials in large quantities in order to be integrated into the scale of products and processes that will allow industry to significantly lower its energy use. Today many potentially important nanomaterials are produced in small batches that yield micrograms to a few kilograms. Industrial products and processes may require many tons of nanomaterials. For example, a 40,000 bbl/day FCC refinery unit requires 70 tons of catalyst per year. Further, the large industrial quantities will need to cost significantly less than experimental batches, yet must be of the same quality. Meeting the cost, quality, and quantity requirements is a major technical challenge and it will require the development of new nanomaterial production scale-up techniques and equipment.

Credit: Photo by University Photocommunications, Southern Illinois University, Carbondale

Integrating Nanomaterials into Nanotech-Enabled Products and Processes

Industrial nanomaterials can be single elements (e.g., carbon, cobalt, iron, and nickel, etc.) or multi-component compounds (e.g., alumina, metal alloys, molybdenum sulfide, silica, and zeolites, etc.). These are formed into nanoscale dots, wells, wires, tubes, combs, cones, films, saws, diamonds, spheres, or other shapes. Their functional use can be based on one or more of their unique mechanical, chemical, electrical, thermal, morphological, and or biological properties. Once produced, nanomaterials may be integrated directly into products or may require further processing to give them additional properties before being integrated into a nanotech-enabled product. The specific material composition, shape, and integration techniques will be dependent on the industrial application in which the nanotech-enabled product will save energy. Material integration techniques and processes need to be developed to rapidly build the large volumes of nanotechnology-enabled products without diminishing the unique properties of the nanomaterial.

Process Control and Predictive Modeling

Nanomaterial production and integration into nanotech-enabled products presents new measurement (metrology) and production control challenges. Laboratory analytical tools do not satisfy the real-time in-situ demands of producing industrial quantities of nanomaterials or nanoenabled products. In addition, knowledge and databases for modeling nanomaterials and nanoproducts are currently lacking, and this is impeding development. The requirements for analytical, process control, and predictive modeling tools crosscut both nanomaterial and nanotech-enabled product production.

Demonstration and Validation

Applied nanotechnology is too new to clearly identify the industrial applications that will yield the largest energy savings. Therefore, demonstrating and validating nano-enabled product energy efficiency performance in industrial manufacturing applications is essential to obtaining market acceptance of these nanotechnologies as capable of contributing toward the estimated energy savings of over 1.0 quadrillion Btu of energy. Projected industrial energy savings are primarily based on assumptions that extrapolate nanomaterial properties to the industrial-scale applications. Detailed scoping studies are needed to identify the best and most achievable opportunities. Directing RD&D toward large energy-saving opportunities will require frequent assessments of progress and a willingness to reassign and escalate efforts.

Workshop participants pointed out that nanotech-enabled products will enter and succeed in the marketplace faster if RD&D are application-based (i.e., focused on customer needs) rather than discovery based (Exhibit 10). Likewise, accelerating nanotechnology development for industrial energy efficiency RD&D should be directed to applications where nano-enabled products satisfy industrial needs or enhance productivity while saving energy.

Exhibit 10: Change in Traditional RD&D from Council for Chemicals Research presentation at the Nanomanufacturing Workshop

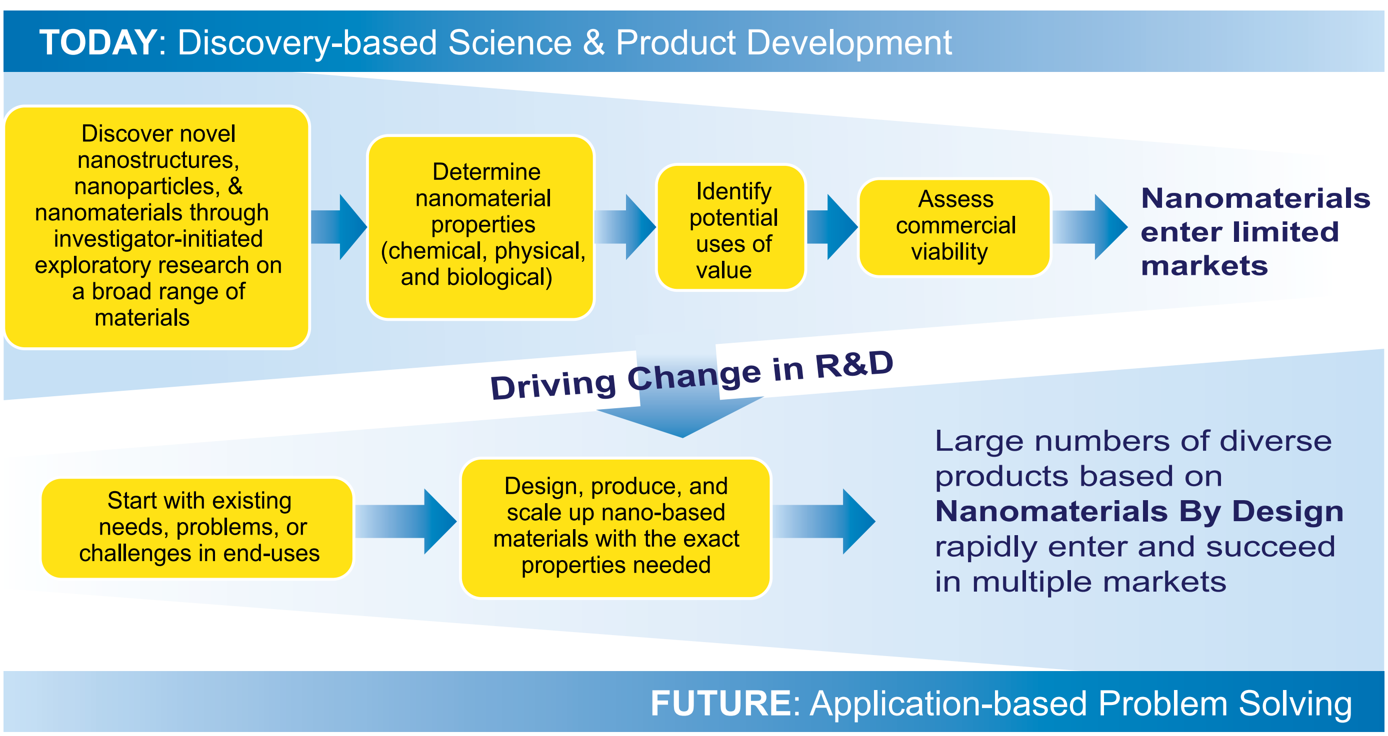
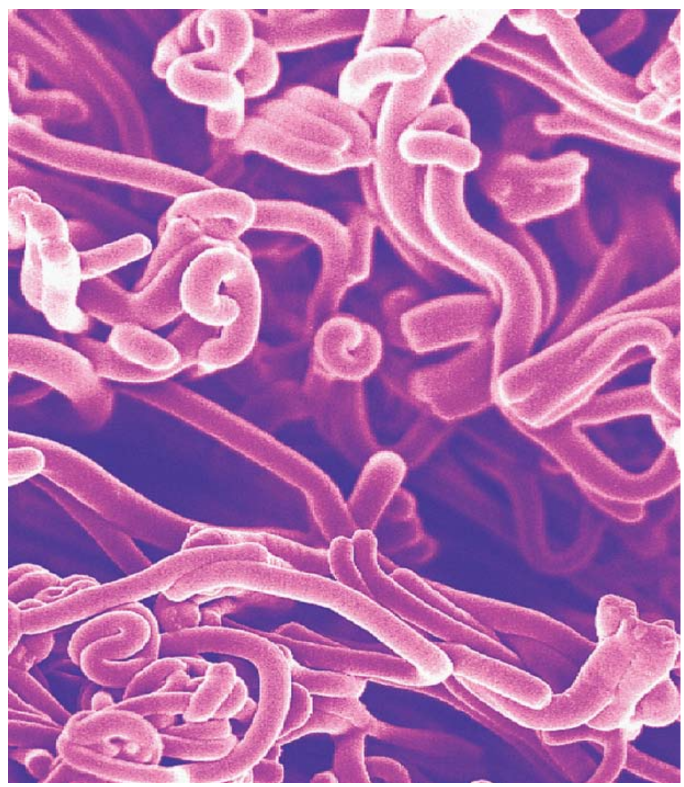


Exhibit 11: Summary of Major Technical Barriers to Nanomanufacturing

Nanomaterials Production	Nanotech-enabled Product Production	Crosscutting Enabling Tools	Demonstration & Validation
Quantities are limited	Retaining nanoscale properties while incorporating into products	Inadequate metrology for in-situ, real-time analysis of materials and products	Rate of market acceptance will be accelerated by demonstration and validation
Properties are inconsistent	Developing high-rate product incorporation techniques for the scale-up of industrial applications	Predictive models for nano-structure, property, and use relationships	Lack of definitional studies to determine optimal applications to improve industrial energy use

Importantly, it should be recognized that the knowledge, skills, and equipment used to develop nanotech-enabled products for industrial energy efficiency gains will also be needed to accelerate the development of nanotechnology-enabled products in many other areas.

Exhibit 11 provides a summary of the major technical barriers to nanomanufacturing for energy efficiency.



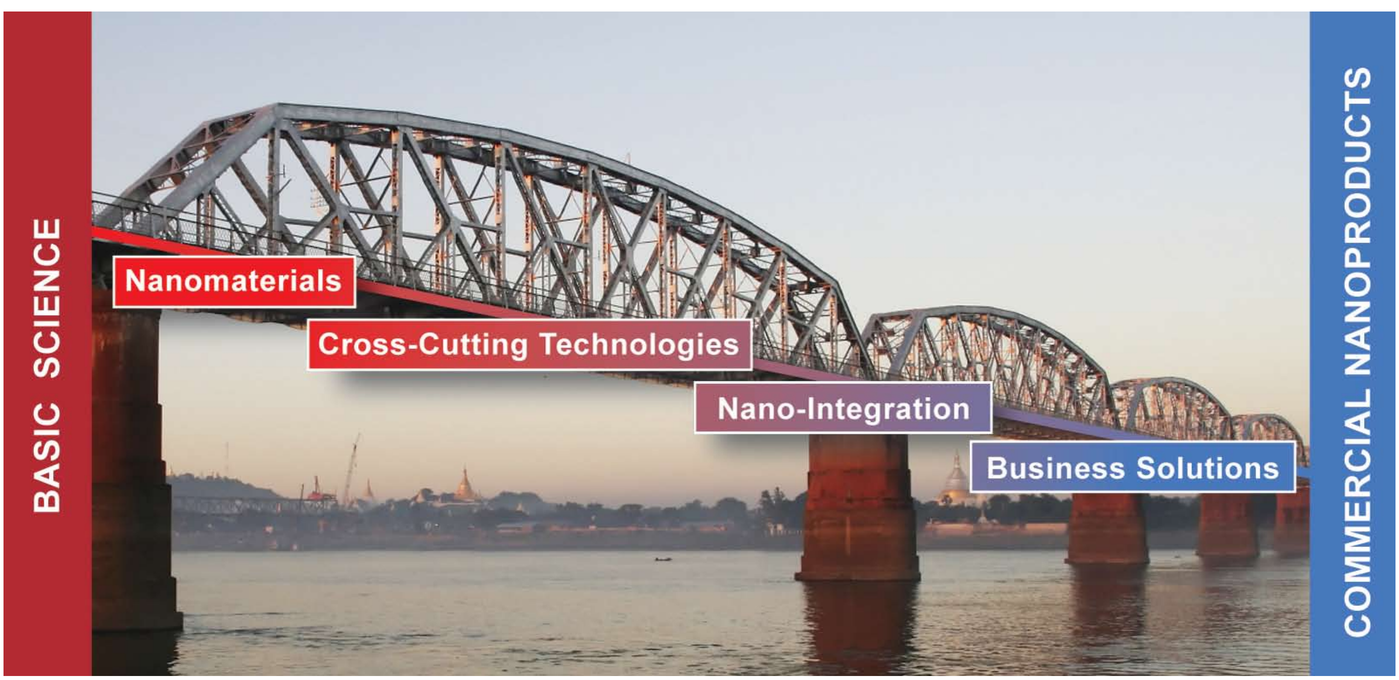
"Angelo Hair Pasta", Credit: ©VISUAL, Materials Research Science and Engineering Center, University of Massachusetts, Amherst

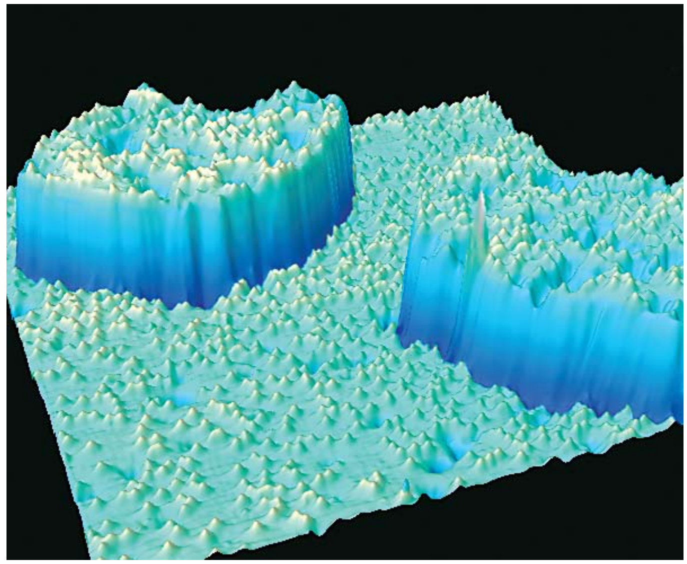
Priority Technology RD&D Needs

Government agencies, academia, and industry are engaged in nanoscience basic research. Their efforts have contributed greatly to the understanding of phenomena at the nanoscale. However, basic research only begins to address the requirements for industrial-scale, cost-effective, and reliable production of nanomaterials or the methods for integrating these materials into nanotech-enabled products for use in industrial applications. Applied RD&D is needed to transition nanotechnology from bench-top science to mainstream industrial use. Pursuing nanoscale applied R&D dictates the need to simultaneously integrate nanomaterials synthesis, product integration, characterization, and modeling with end-use applications. One of the key conclusions resulting from the Workshop is the need to bridge the gap (Exhibit 12) from basic science to commercialization by focusing on applied RD&D projects to provide industry with the tools and knowledge to apply nanoproducts to industrial processes that reduce energy use and unit production costs.

Credit: Photo by Gary Meek; courtesy Georgia Tech

Exhibit 12: Bridging the Gap from Basic Research to Commercialization





Atomic Scale Alloying of Chromium Atoms
Credit: J. A. Stroscio, A. Davies, D. T. Pierce, and R. J. Celotta, National Institute of Standards and Technology (NIST)

The need for a "nanomaterial to end-use application" RD&D approach for more rapid commercialization of nanomanufacturing was identified in all five breakout sessions of the Nanomanufacturing Workshop. Attendees noted trials and failures to integrate currently available multi-walled carbon nanotubes into high-end structural composite resins. These failures were attributed to a lack of intellectual knowledge exchange between nanomaterial developers, who focused on production and properties at the nanoparticle scale, and industry end-users focused on functionality of the nanomaterial in the bulk phase of complex resin systems. Attendees noted other end-use applications of nanomaterials such as thin films and catalysis that suffer delays in commercialization because of the difficulty and lack of knowledge in integrating nanomaterials into final products. Many anecdotal experiences highlighted the need for multidisciplinary teams that have varied expertise and a willingness to share each others' experiences in order to successfully integrate nanomaterials into products that retain their nanoscale-properties. (A complete list of technical barriers and RD&D needs identified at the Nanomanufacturing Workshop is provided in Appendix C.)

Nanomaterials Production for Use in Industry

Nanomaterial production is a combination of art and science, and the selective and uniform production of nanomaterials with specific dimensions and properties is not a common achievement. Current methods used to produce and isolate nanoparticles from synthesis reactions media result in low yields, relatively large amounts of precursor waste, compromised performance, and finished materials that cannot easily be reproduced. The inability to extend the desired manufacturing of nanostructures to larger sizes via controlled growth, self-growth, self-assembly, or patterning combinations also hinders large-scale production. The current inefficient processes and practices add significant manufacturing costs to nanomaterials, whether they are used directly or as building blocks integrated into nanotech-enabled products for use in industry.

Many of the production systems and operating techniques currently used to produce nanomaterials (e.g., chemical vapor deposition, physical vapor deposition, reactive sputtering, laser pyrolysis, plasma spray conversion, mechanical alloying, grinding, high gravity reactive precipitation, solgel, and others) are relatively capital-intensive, and involve sophisticated equipment that requires highly skilled, labor-intensive operation and maintenance. Today nanomaterials scale-up is mainly accomplished by installing additional units of these bench-top production systems. This scale-up practice does not provide economies of scale and is not adequate for the magnitude of production required for nanomanufacturing to significantly reduce energy use in industrial manufacturing processes. The nanoparticle synthesis and behavior in some cases defies the use of classical manufacturing unit operations and requires new paradigms in large-scale manufacturing approaches and equipment in order to commercialize.

In a typical nanomaterial production operation there are four processing stages: synthesis, separation, purification, and stabilization. Each step is followed by a quality assurance procedure. The nanomaterial production is further complicated by the fact that each stage presents new technical challenges from the previous stage, and the tools used for quality assurance at each stage may be different. The unique challenges at each of the different stages of nanomaterial production are as follows:

Synthesis – This stage refers to producing nanomaterials that possess the material properties, chemical composition, morphology, and quality required for the application. Synthesis can often depend on the specific reactor used to produce the materials. A common problem for nanomaterial synthesis is the lack of understanding of the fundamental mechanisms that form the nanomaterials during synthesis. Another problem is that much of the nanomaterial synthesis occurs in the gas phase, where impurities are easily carried through the process unaltered and in some cases even concentrated.

Separation – Results of the synthesis stage usually include a combination of the desired end-product, unreacted precursors, and unwanted byproducts. The separation stage involves removing the unwanted media, leaving the desired end-product. This media must be removed without affecting the quality, structure, and properties of the end-product—a challenging requirement, especially when working with materials at the nanoscale. One of the most common required separations is the de-aggregation of the nanomaterial particles.

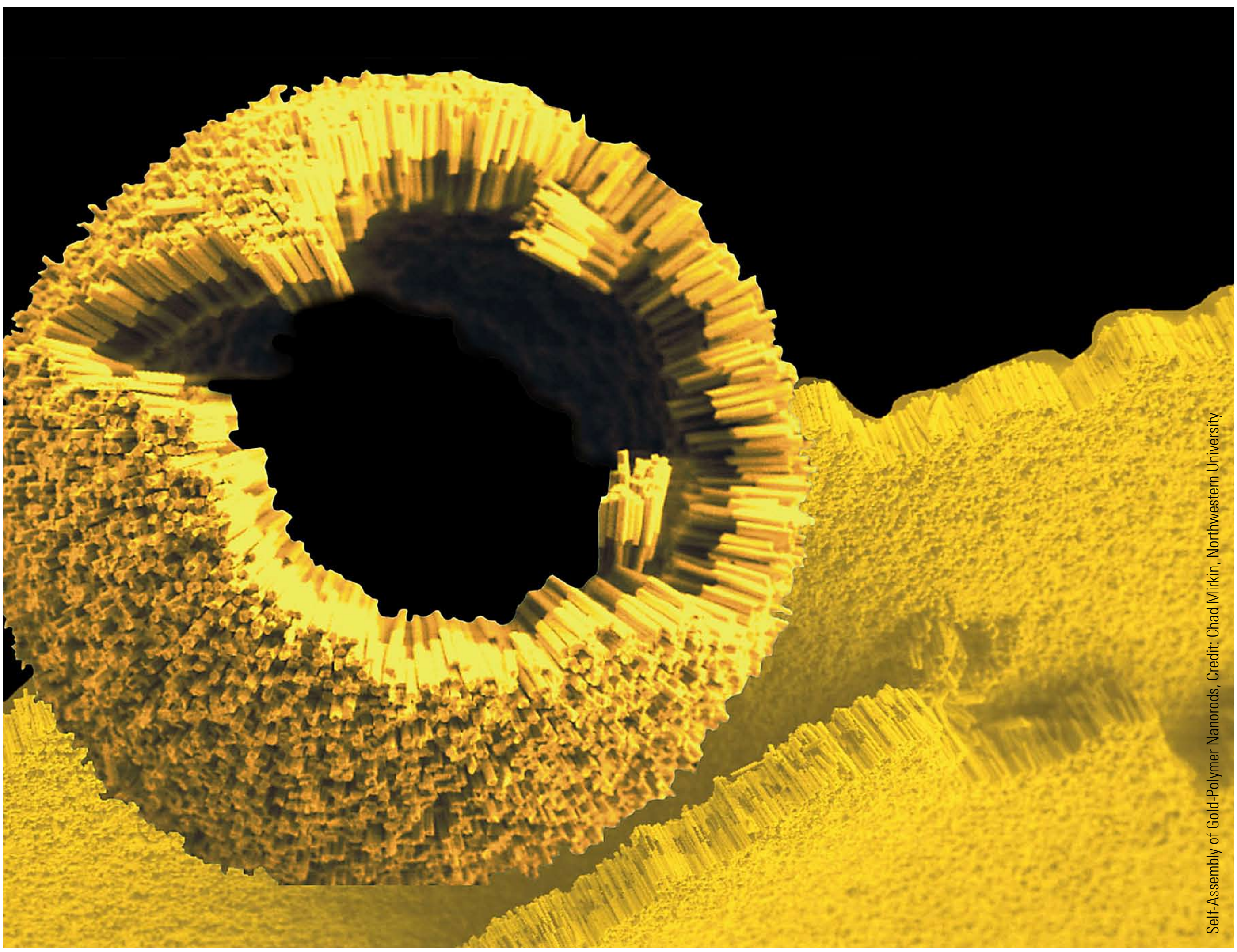
Purification – Many times the end-product needs to be further purified or isolated for utilization of nanomaterials by function. For example, nanomaterials with slightly different sizes, compositions, or properties may have different applications. The ability to segregate these materials by size, composition, and property (mechanical, electrical, optical, etc.) is necessary to exploit the wide applicability of nanomaterials. This ability will first require understanding the correlation between the material and the application uses. The precision requirements to accomplish the needed purification will be at tolerance levels well beyond the current capabilities.

Stabilization – Once produced, a nanomaterial often needs to be modified for storage and handling or for end use in a specific application. Retention of the unique magnetic, electronic, mechanical, surface, morphology, or other properties is critical. Thermal stability of the nanomaterials is of particular concern for high-temperature applications. Processes such as surface modification, dispersion, etc. that allow nanomaterials to be stored, handled and utilized while retaining desired functionality are needed.

In addition to these production stages, surface modification methods are sometimes needed to functionalize the nanomaterials, enable dispersion, and/or to impart specific surface properties. An example of this involves the use of silane coupling agents to provide reaction with an epoxy composite matrix or the addition of catalysts for reaction processes. The development of scalable nanomaterial surface-modification techniques are needed to enable functionalized materials that can be reproduced.

The four stages of nanomaterial production and modification methods present unique and costly challenges for starting material specifications, scale-up, purity, and quality control not typically encountered with manufacturing materials of larger dimensions. RD&D to develop robust and reliable production methods for a wide range of materials is needed to expand the commercial use of nanomaterials. Additional RD&D is required to better understand the properties that lead to specific application functionality. Defining application needs clearly upfront will augment research efforts in these areas. This will require raw material suppliers, nanomaterial producers, and users to establish strong customer-supplier partnerships to work through the process and establish raw material inputs, preferred synthesis routes, and quality requirements.

Exhibit 13 shows priority RD&D needs to establish large-volume, reliable, and functional nanomaterials.



Self-Assembly of Gold-Polymer Nanorods, Credit: Chad Mirkin, Northwestern University

Exhibit 13: RD&D Needs to Enable Reliable Supply of Functional Nanomaterials

Barriers	Strategies	Priority
Lack of reliability of nanomaterials supplies	Develop new, standard, high-yield, low-cost, scaleable processes to manufacture nanomaterials in the volumes required for industrial applications	High
	Develop cost-effective separation, functionalization, and dispersion techniques for nanomaterials	High
	Develop better understanding of synthesis fundamentals in order to perfect synthesis unit operations	Medium
	Determine the impact of aging and storage on nanomaterials	Medium
	Develop novel manufacturing techniques for hierarchical assembly	Medium
	Research life cycle issues	Medium
Lack of technologies to improve materials properties and performance	Investigate novel/new process technology to improve materials properties and performance and demonstrate their repeatability	High
Lack of ability to disperse stable nanomaterials through final production	Develop technologies for application-specific dispersions for final production	Medium
Lack of processing capabilities for high-temperature processes	Address thermal stability and retain nanotech benefits for high thermal environments	Medium
Materials issues	Develop materials by design, rational design across regional scales	Medium
	Develop durable coatings using scalable processes	Medium
	Develop structure/function relationships of self-assembling nanomaterials	Medium
	Couple/integrate (process development with sensors & controls)	Medium
	Develop chemical/physical surface functionalization	Medium
	Develop cost-effective separation, functionalization, and dispersion of nanomaterials for coatings	Medium
	Develop self-correcting materials	Medium

Manufacture of Nanotechnology-Enabled Products

The science of integrating nanomaterials into the macro-product world is in its infancy. Today, various integration processes have been demonstrated in isolation for relatively simple products (e.g., architectural coatings, batteries, etc). However, little research has focused on utilizing new or combinations of approaches to meet the criteria needed for new, large scale, more complex and demanding industrial applications. The phenomena that make nanoscience so exciting also cause great difficulties in integrating nanomaterials into products that retain the nanomaterials' unique properties. Manufacturing of nanotech-enabled products is challenging because nanomaterials have a high propensity to agglomerate, highly reactive surfaces, and a tendency to change properties with time, temperature, and handling conditions. Equally challenging is the fact that once nanomaterials are successfully embedded into fibers, sheets, thin films, tubes, bars, or other forms, there is limited technology to join these into useful products without altering the properties. Likewise, when morphology is important to product performance (e.g., in catalysts, membranes), it is challenging to manufacture uniform quality throughout the module or body. Overcoming barriers relating to the manufacture of nanoenabled products from nanomaterials requires a shift from R&D's traditional focus on nanoscale properties to functionality in larger forms.

Currently, manufacturing of nanotechnology-enabled products attempts to adapt many traditional manufacturing techniques and unit operations. These may not be optimal in terms of their ability to integrate nanomaterials and retain functionality. New product manufacturing techniques and equipment need to be developed, since the inability to integrate nanoparticle functionality into products is a major inhibitor to commercialization and a focal point for workshop attendees.

Technologies used to incorporated nanomaterials into products that are of near-term high priority interest to industry include joining of structural composites, surface engineering, coatings, nanostructured bulk materials, and new functional materials. For example, nanomaterials have a significant potential for use in lightweight structural components, but traditional joining processes typically involve high-temperature annealing that alters nanomaterials. New rapid low-temperature annealing techniques are required that will not destroy the nanostructure properties. Multidisciplinary teams will be needed at the laboratory and pilot scale to accomplish these objectives. Exhibit 14 shows priority RD&D needs for manufacturing products containing nanomaterials.

Exhibit 14: RD&D Strategy for Manufacture of Nanotechnology-Enabled Products

Barriers	Strategies	Priority
Lack of scalable unit operations for reliable, cost-effective incorporation of nanomaterials into intermediates and products	Develop new, standard, high-yield, low-cost, scaleable processes that can manufacture products incorporating nanomaterials	High
	Provide access to pilot-scale manufacturing equipment for process validation and demonstration	High
Lack of ability to preserve the functionality of nanomaterials when incorporating them into intermediates and products	Understand nanoscale interfaces and develop methods for preserving the functionality of nanomaterials	High

Crosscutting Analytical Tools

Tools that enable characterization, process control, and nanomaterial and product modeling will boost innovation, growth, and commercialization in nanomanufacturing process development and end-use applications. New in-situ, "real-time" process control and characterization tools must be developed to establish methods for producing nanomaterials in large commercial-scale volumes. Many of the current analytical tools provide only a small snapshot of the desired measurement. This limitation has been described as akin to using a digital camera shot from 10 inches above the sand when the question was to determine the condition of all the sand on Daytona Beach.

Industry participants at the workshop expressed strong "quality control/quality assurance (QC/QA)" concerns with the currently available nanomaterials, especially related to "batch to batch" variations. Tools used in research settings generally have not been adapted successfully for industrial QC/QA for nanomaterials—industry sees a strong need for new tools that ensure adequate precision for industrial-scale QC/QA. Tools that rapidly and accurately report the size, shape, and distribution of nanomaterials are needed. The fine measurement and property control of porous nanomaterials is a roadblock in the development of many promising energy-efficient products, e.g., thin films, membranes, and catalysts. Developing robust modeling and simulation tools that can establish correlations between nanoparticle, bulk nanomaterial, and nanoproduct properties is required to rapidly and effectively develop nanomanufacturing processes.

Currently, there is a significant lack of property data or algorithms for predictive modeling of nanotechnology. These shortcomings impede the simulation of multifunctional combinations of nanomaterials and macro systems. These inadequacies limit performance validation for designers and the ability to answer what-if questions concerning performance of nanotechnology-enabled products under industrial, commercial, and consumer use conditions.

Characterization and Process Control Tools

Integrating the sensors, models, and process control components for rapid data assessment and control response at the nanoscale will require a long-term commitment to RD&D in diverse science and technology fields.

The real-time characterization techniques for process monitoring and process control are similar to those needed for metrology and include optical and spectroscopic analyses, mass spectroscopy, small angle X-ray scattering, and magnetic resonance imaging (MRI).[30] Pathways for extension of these techniques to the industrial-scale unit operations of synthesis, separation, purification, stabilization/functionalization, and assembly are needed. Nanomaterial characterization capabilities require both in-situ and ex-situ characterization methods, ways to examine surface chemistry at the nanoscale (like fractional coverage and thickness of coatings on nano-particles), and methods to control and monitor particle dispersion in a solid phase.

The Nanomanufacturing Workshop attendees identified large-volume electronic property characterization of one-dimensional nanomaterials and in-situ nanoparticle (sub-50 nm) monitoring as the primary research need areas. Efforts should be focused on finding techniques for characterizing band gap distribution and determining particle size and particle surface roughness. Instrumentation is needed to rapidly determine nanoparticle size distribution capabilities for manufacturing controls and as ES&H monitors.

Priority RD&D needs for characterization and process control and their projected timeframes are summarized in Exhibit 15.

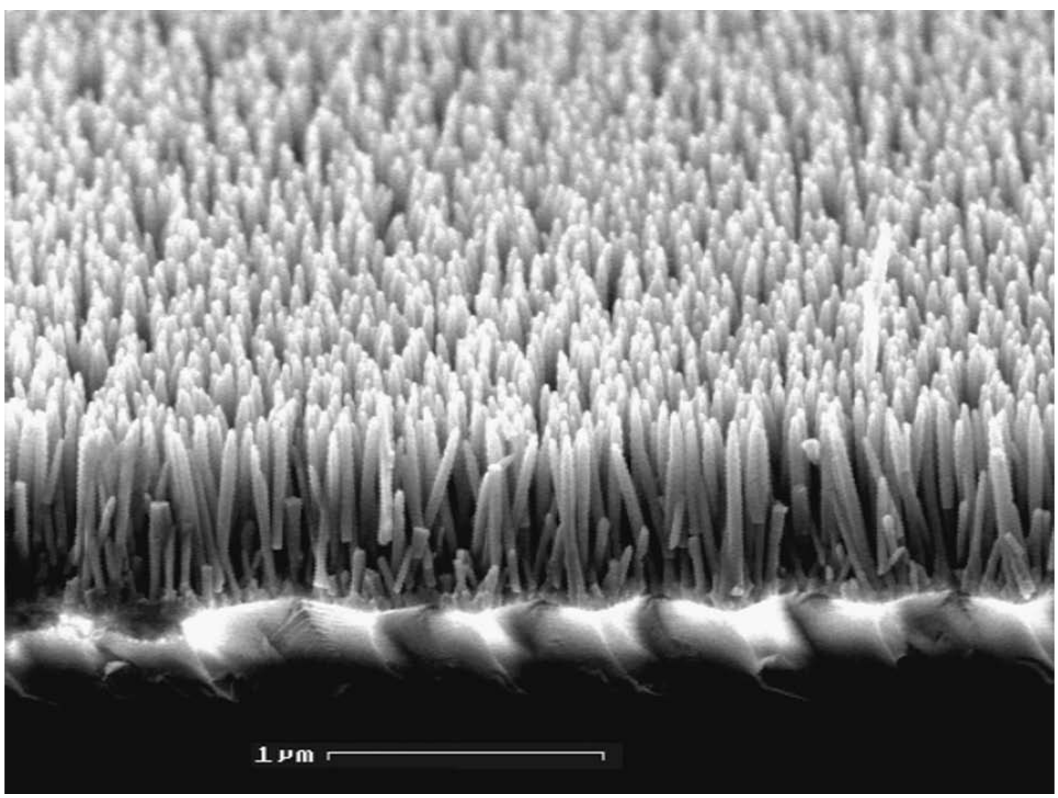
Exhibit 15: Recommended RD&D Strategy for Process Control

Barriers	Strategy	Priority
Lack of characterization/monitoring tools for production processes that utilize nanomaterials	Develop robust, on-line, real-time, in-situ characterization/monitoring tools	High
Lack of standard testing methods for quality of intermediates containing nanomaterials	Develop non-destructive quality control testing methods for intermediates containing nanomaterials for producers and users	High
Lack of process control methods for nanomanufacturing processes	Develop process control technologies for nanomanufacturing processes	Medium
	Develop accelerated test procedures for nanoscale coatings and nanostructured surfaces	Medium
	Investigate/understand macro effects	Medium
	Develop nanotech-based sensor technology to sense power stand-by mode and automatically step-down power-pull requirements	Medium
Characterization Needs	Develop nanotechnology-based sensors to enable real-time on-line measurement of process variants	Medium

Modeling Tools

The ease and speed of the transition from laboratory to commercial introduction will depend on the availability of robust modeling and simulation tools that can predict experimental outcomes. Laboratory experimentation can be cumbersome, time consuming, costly, and often does not completely represent the final manufacturing conditions. Computer-aided modeling and simulation can supplement physical experiments, accelerate future research, and expedite market entry. Knowledge of cause and effect relationships based on lab observations can be used to simulate and predict the effects of environmental conditions (temperature, humidity, etc.), subtle process variances, batch-to-batch variations, and equipment scale-up. Modeling can be used to mitigate the impacts of these effects successfully and economically.

Robust, high-confidence models and simulations are needed to predict the properties and behaviors of new nanomaterials and assembled systems across scales– from synthesis of particles to their integration into devices, and, finally, to their performance in industrial applications. Models and simulations will aid the development of synthesis and assembly protocols that impart and preserve required functional properties across scales. At the application level, they will define the functional needs and probable designs of nanostructures.



Modeling procedures are needed to combine lessons learned from experiments across the field of nanomanufacturing. It will be used to extrapolate properties (such as electronic, chemical, structural, toxicological, and environmental properties) from known conditions and apply them to novel cases. These models will be able to help in the design of experiments, increase the efficiency of research, recognize and assess emergent properties, accurately predict performance, reduce the required number of design iterations and experiments, and reduce the number of tools required for design. Ultimately, a library of validated protocols will couple modeling and experimental results and will help researchers find customized material solutions for specific needs. Priority modeling RD&D needs and their timeframe are shown in Exhibit 16.

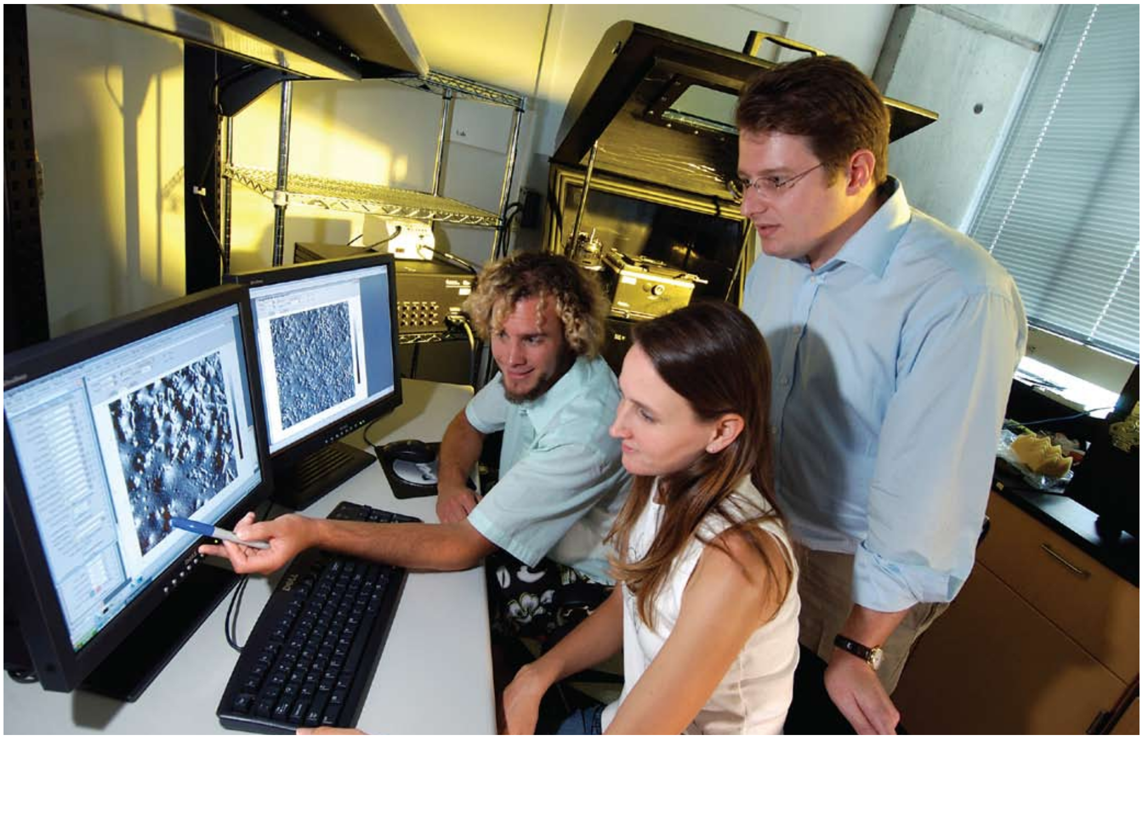
Exhibit 16: Recommended Predictive Modeling Tools

Barriers	Strategies	Priority
Lack of algorithms and codes for nanotechnology models	Develop mathematical algorithms and codes needed to create nanotechnology models	High
Lack of ability to model across scales	Develop multi-level, multi-scale integrated models that work together across different nanotech fields	High
Lack of predictive modeling for structure/property relationships for industrial materials	Develop models that allow the prediction of the properties of products incorporating nanomaterials so that "Nanomaterials by Design" works. (Joint Semiconductor/ Chemicals effort working with NIST)	High
Lack of data on nanomaterial properties	Develop a database of nanomaterial properties	Medium
Modeling issues	Fund modeling projects	Medium
	Develop process simulation via parametric studies	Medium
	Develop reliable ground state structure/energy prediction in vacuum solution	Medium
	Rational modeling for discovery of heterogeneous catalysts	Medium
	Model kinetic control and processes	Medium
	Develop computationally designed coatings/surface modifications for wear and tribology, and other applications	Medium
	Develop reaction transition state barrier modeling via DFT methods	Medium

Demonstration and Validation

The key to accelerating nanomanufacturing for energy efficiency is to lower the technical and business risks. Highly public and successful demonstration and validation projects are needed. Choice of nanomaterial composition and function, the method of integration into a nanotech-enabled product, and the expected performance are application-dependent. The foundation of a successful demonstration and validation project is a comprehensive examination of the nanomanufacturing opportunities from a technical and business perspective before the project is initiated.

Exhibit 17 shows some of the many identified opportunities for industrial energy efficiency improvements using nanotechnology and the wide variety of nanomaterial functions and integration procedures for the different end uses. These opportunities have been identified in the published literature and various estimates of their potential to reduce industrial energy consumption have been reported (See conclusions section of the report). These opportunities and energy savings are based on wide-ranging reports using varying assumptions and projection methodologies. A rigorous determination of opportunities and projected benefits would provide better targeting for RD&D activities that can lead to successful demonstration and validation projects. This determination could be accomplished by conducting multiple in-depth seedling/scoping studies that each examine a specific application. These studies would scrutinize the role of nanotechnology in terms of potential energy savings and would describe the technical risks and probability of success, and detail the barriers to producing the specific nanomaterials and integration technologies required to manufacture the product for that application. Each study would include the development of detailed metrics and performance targets related to properties, quality, and quantities of both nanomaterials and material integration. These studies would support project planning by providing preliminary estimates and targets of manufacturing economics concerning the commercial viability of the product. These multiple application-specific studies would form the basis for



pursuing specific RD&D projects and for determining the range of equipment and instrumentation that would be basic to a nanomanufacturing user's center.

Exhibit 17: Variations in Nanomanufacturing Opportunities

NANOMATERIAL	PRODUCT	INDUSTRIAL APPLICATION	
Property	**Integration Technique**		***Potential Energy Savings***
surface activity	placement on support	CATALYSIS	~280 to ~600 TBtu/yr
material composition	fuel suspension		
lubricious	deposition techniques	COATINGS	~90 TBtu/yr
hydrophobic	deposition techniques		
hardness	deposition techniques		
structure & surface properties	dispersion, bonding, casting	LIGHT WEIGHT	
shape & lubricious	dispersion & suspension	MATERIALS MODIFICATION	
thermal conductivity	solgel	THERMAL MANAGEMENT	~16 TBtu/yr
thermal conductivity & capacity	fluid suspensions		
morphology & surface properties	membrane module	SEPARATIONS	~120 to ~330 TBtu/yr
morphology & surface properties	absorbent body		
semiconductor	modular device	THIN FILMS	~8 to ~80 TBtu/yr
piezoelectric	modular device		

Combinations of a nanomaterial morphology or special mechanical, chemical, electrical, thermal, and biological properties provide enhanced functions that, when integrated properly into a product or process, can yield improvements in energy efficiency. Each industrial application of a nanomaterial (e.g., catalysis, coatings...) will rely on different nanoscale-properties and product integration techniques to achieve energy efficient manufacturing. A sampling of these combinations are shown above with estimates of their potential energy savings. The foundation of a successful RD&D demonstration is a comprehensive examination of the nanomanufacturing opportunities from a technical properties, product integration, application performance, and business perspective before a project is initiated.

Business Needs for Commercial Nanomanufacturing

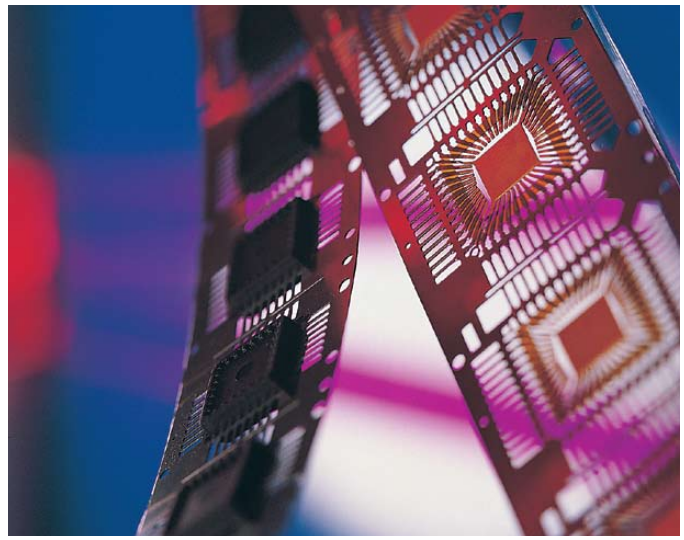
Science and engineering are not the only challenges to commercializing nanotechnology. Areas such as finance; environmental, safety, and health, market acceptance; regulation; and other business-related issues will impact the rate of commercial deployment and the ultimate industrial energy savings realized from nanotechnology. Business strategies to encourage innovation and mitigate risks are top enablers for industries seeking to deliver novel products to the marketplace.

The most pressing commercialization barriers identified by Workshop participants relate to the need for strategic partnerships, industrial infrastructure, streamlined intellectual property rights process, and favorable policy and regulations.

Strategic Partnerships

The fostering of strategic partnerships between industry and government through cost-, equipment- and information-sharing activities needs to be a priority in order to leverage resources, build diverse, skilled teams, and reduce business risks.

Risk Mitigation and Leveraging Resources
Many of the innovations in nanomaterials production and product integration reside in start-up companies that may be small, "capital-strapped" entities vulnerable to a variety of market forces. Companies that rely on these small ventures for their nanomaterials supply face significant risks. Industry participants at the Workshop expressed the need for strategic partnerships to mitigate this risk, and encouraged DOE to play a strong role in fostering these partnerships.



Further, the Workshop participants indicated that it is of paramount importance to ease the risks associated with investing in new technologies through government-sponsored applied research programs and technology transfer. Although there are no ideal models for risk mitigation activities in these areas, there are practices that have proven successful. Publishing of government-sponsored research should be encouraged, terms of successful partnerships and technology transfer should be publicized, and research programs should assist in establishing clear boundaries of intellectual property rights.

Government-funded applied RD&D to encourage multi-partner technology demonstrations is critical for innovative technologies to penetrate the mainstream market. Industrial-scale demonstrations will aid in attracting additional investments that will help these emerging technologies to bridge the gap from research labs to commercial use.

Another important step to accelerating the adoption of new nanomanufacturing technologies is information exchange and demonstration of technologies. Technology progress and success stories need to be publicized to encourage collaborative research and motivate developers. Priority needs for mitigating risks and leveraging resources via strategic partnerships are shown in Exhibit 18.

Exhibit 18: Priority Business Needs for Mitigating Risks, Leveraging Resources, and Developing Strategic Partnerships

Barriers	Strategies	Priority
Lack of funding for applied RD&D for commercialization ("valley of death")	Fund start-up corporate collaborations	High
	Fund government-sponsored incubation parks	High
	Fund applied R&D to cover gap between presently funded pure research and demonstrations	High
	Use Advanced Technology Program (ATP) "key factors" and/or funding model	Medium
	Collaborate internationally and with other NNI agencies to assure broad support and understanding	Medium
	Help identify lead users of technology	Medium
Lack of commercial influence on basic research funding	Establish industry advisory boards	High
	Establish industry participation in proposal review process	High
	Establish integration/collaboration between DOE nanoscience program and applied programs	High
	Feedback to ensure funding matches priorities	High
	Input requirements into NNI reauthorization	Medium
	Recommend new hires have industry experience	Medium
Need to improve information exchange	Share cross-cutting technologies across industries	High
	Summarize/coordinate roadmaps	Medium
	Publish a document that highlights successes (catalysis, separation science, nanoelectronics, etc.)	Medium
	Centers of Excellence	Medium

Industrial Infrastructure
Currently, there exists limited industrial infrastructure for manufacturing nanomaterials and nanotechnology-enabled products. In today's competitive economic environment, incentives do not exist for either the end-users or the nanomaterials producers to take on the high excessive costs associated with establishing the new infrastructure needed to develop energy-efficient nanotechnologies, or to demonstrate or validate them.

Industry leaders at the Workshop recommended establishing collaborative research "nanomanufacturing centers" that focus on applied RD&D to augment the existing centers allocated for basic research. These centers would enable pilot studies and investigation of scale-up processes, while focusing on retention of nanomaterial functionality in products. The vision is that the centers would be driven by the goal of commercialization. These facilities would provide industry with easy access to specialized equipment and processes, enabling the refinement of current nanomanufacturing processes and the establishment of new nanoscale manufacturing concepts.

Further, since the cost of developing research centers is high and requires significant time to organize and execute the construction effort, Workshop participants agreed on a virtual nanomanufacturing center to be established in the near term so as to expedite nanomanufacturing development. This type of center will be virtually accessible across the nation and can be used conveniently for networking with universities, national laboratories, and industry facilities to leverage knowledge and expertise in development areas such as scale-up equipment and instrumentation.

Priority needs for establishing an infrastructure conducive to building a reliable and lasting nanomanufacturing industry are shown in Exhibit 19.

The recommended "nanomanufacturing centers" should allow industry to take advantage of the facilities, specialized equipment, and expertise that reside at DOE and other national laboratories through EERE facilities and technology research programs. These centers must also ensure equitable and affordable access to all industrial parties. The cutting-edge tools at these centers must be made available to external parties via pay-as-you-go or collaborative arrangements.

Lastly, these nanomanufacturing centers must focus on creating tools and methods to develop materials and processes and to measure properties that are of commercial interest. Such properties include mechanical, electrical, magnetic, optical, transport (heat, mass, and momentum), diffusion, thermodynamic, surface-surface, and absorption/adsorption.

Intellectual Property (IP) Rights

The wide range of entities holding patent and patent applications for nanotech-related developments yields complications that are coupled with a vast number of untested patent and license issues, creating significant business risks for product development. These shortcomings limit the ability of companies to license technology from universities and national laboratories. Licensing mechanisms are inconsistent across these organizations, and there are often disconnects between the value placed on IP, particularly future value, by research organizations and industrial companies. Participants at the Workshop had concerns regarding the lack of clarity in IP rights between industry, universities, and national laboratories.

Workshop participants encouraged government-sponsored workshops on technology transfer to overcome these issues and suggested creating

Exhibit 19: Priority Business Needs for Establishing Infrastructure for Nanomanufacturing

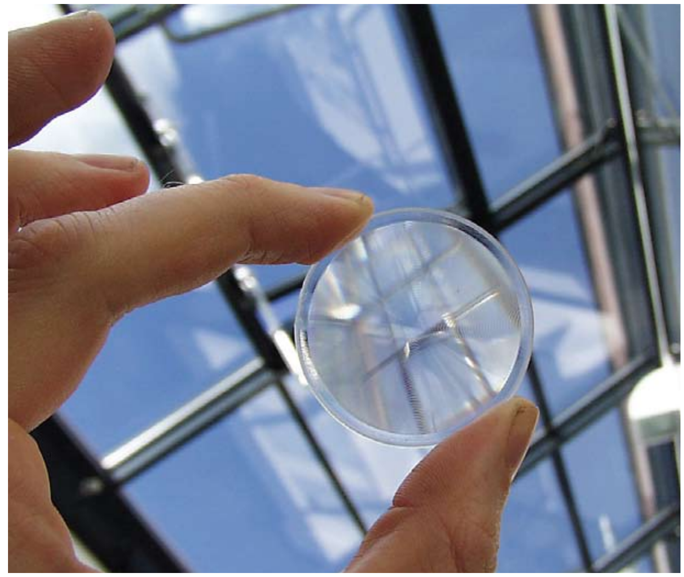
Barriers	Strategies	Priority
Lack of reliability of nanomaterial supply	Develop a "virtual nanomanufacturing center"	High
	Fund a manufacturing center to assist with scalability	High
	Focus grant renewal on reproducibility	Medium
	Qualification and certification of nanomaterials suppliers	Medium
	Develop standards	Medium
	Establish "manufacturer of last resort"	Medium
Lack of reliability of production/ scale-up of products containing nanomaterials	Establish pilot facilities for testing/ process development/demonstration of nanomanufacturing	Medium
	Establish "scale up" benchmarks to reduce risk	Medium
Economic uncertainties (lack of established infrastructure)	Provide process development and nanomaterials production centers to assist suppliers in improving their processes and reduce risk	Medium
	Use market pull instead of technology push in nanotechnology adaptation, e.g., cost of raw material	Medium
	Investigate recycling costs	Medium
	Perform Life Cycle Analysis of nanoproducts including energy analysis	Medium

incentives to standardize research-industry partnerships that create IP rights. Emphasis was placed on the need to speed up the patent process and resolve patent and license disputes.

Workshop participants recommended some mechanisms, as shown in Exhibit 20, to ensure that intellectual property issues do not inhibit the commercialization of nanomanufacturing.

Policy and Regulation

Federal policy and regulation can play a "make or break" role in the success of nanotechnology. An uncertain or changing regulatory environment will inhibit industry investment in nanomanufacturing. Participants indicated that industry is reluctant to risk investing money and resources into a technology where regulatory uncertainty or lack of policy commitment exists with regard to environmental policy. Collection and distribution of enviromental, health, and safety (EHS) data for nanomaterials, as well as development of guidelines for safe handling naomaterials, will assist in technology development and application. Although it is not DOE's place to regulate EHS, its role in disseminating information of this nature could be helpful. Additionally, DOE should consider supporting RD&D process technologies that minimize EHS impacts. The establishment of internationally accepted standards for nanomaterials should be seriously considered.



Deep Aspheric Fresnel Lens
Credit: Developed under the U.S.-Germany Transregional Collaborative Research Center SFB-TR4, funded by the National Science Foundation and the German Science Foundation.

Further, the Workshop participants recommended that the U.S. Government should enact policies, legislation, and incentives to reduce commercialization risk and encourage broad markets and large-scale nanomanufacturing development. The establishment of a Federal priority within this area will demonstrate to industry that the country is committed beyond nanoscience to its ultimate application in reducing energy use and meeting our national goals.

The flexibility of companies to submit their nanomaterials to other agencies or programs for testing is another business practice desired by industry. Support to develop manufacturing processes and monitoring and control systems that will reduce nanomaterial losses during production, product losses, environmental discharges, and worker exposure is also needed to promote industrial investment.

Exhibit 20: Priority Intellectual Property Needs

Barriers	Strategies	Priority
Sharing and valuing intellectual property	Provide incentives for academic-industry partnerships	High
	Find and promote best practices for TTOs	Medium
	Work with USPTO to speed patent process	Medium
	Facilitate resolution of patent thickets	Medium
	Reduce government's IP rights	Medium

As the nanomanufacturing business matures, each manufacturing company will be mandated to develop techniques for validating its claims to the customer. The government's role in this process should be to establish accepted standards and measurements that are useful in verifying nanoparticle properties. Again, this would be akin to the testing standards developed by ISO, etc. and other internationally recognize organizations, except with a focus on properties at the nano-scale. Interaction with industry would be required to determine which properties are important to success in various applications. The active role of industry and government in establishing standards pertaining to nanotechnology will accelerate and encourage business investment and technology development.

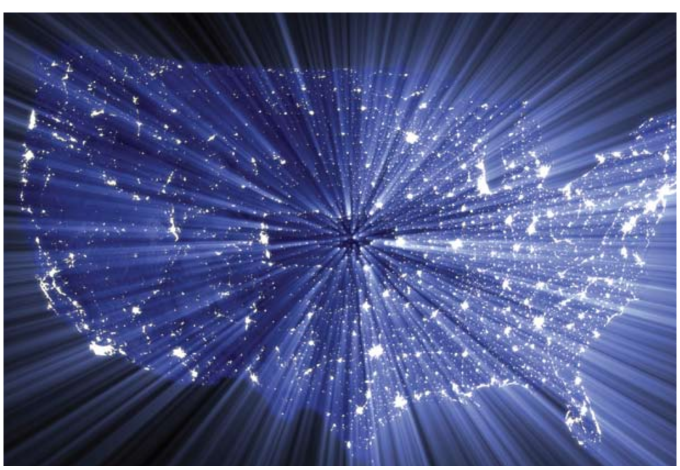
A significant long-term Federal RD&D investment combined with supportive policy will demonstrate a solid Federal commitment and will likely encourage industry investment. Priority needs for establishing productive policy and regulatory practices are shown in Exhibit 21.

Exhibit 21: Priority Policy and Regulator Needs

Barriers	Strategies	Priorities
Lack of policy drivers for innovation	Commitment from DOE and other NNI agencies to fund R&D and infrastructure (20 years from conception to commercialization)	High
	Develop incentives for companies and consumers to change from traditional technologies/products to energy-efficient ones through communications and policy (such as Energy Star)	High
Regulatory uncertainty	Provide data and handling guidelines to industry	High
	Establish nanotechnology standards	High
	Identify lead agency	Medium
	Evaluate standardization efforts	Medium
	Offer EHS testing to grant recipients	Medium

Conclusions

The industry participants at the Nanomanufacturing for Energy Efficiency Workshop agreed on the energy-saving potential of nanotechnology, estimated to be over 1.0 quadrillion Btu annually from its application in the chemicals, refining, and forest products industries alone. Evaluations of government-wide initiatives in nanotechnology indicate that several agencies are currently engaged in nanoscience, modeling, and characterization research. However, there exists a large gap between the advances in nanotechnology basic science and its application to develop products. The industry experts at the Workshop identified major barriers impeding the commercialization of energy-efficient nanotechnologies. They developed and prioritized a list of time-specific RD&D and business strategies that will help overcome these barriers and bridge the necessary gaps to contribute to the goal of improving industrial energy efficiency. The strategies recommended to overcome the barriers and research gaps encompass a wide range of areas including mass production of nanomaterials; scale-up processes; establishing energy-efficient industry production, end-use products, and crosscutting enabling technologies; as well as addressing business and policy issues.



They indicated that the success of nanomanufacturing for industrial energy efficiency will require close collaboration among virtually every stakeholder, including the following types of organizations:

- Companies of all sizes
- Suppliers of specialty, bulk, and reference materials
- Equipment and software manufacturers, including suppliers of analytical tools
- Companies with specialized expertise, experience, and/or research facilities
- Universities, especially those with nanomanufacturing centers
- National laboratories, especially those with nanotechnology centers
- Government research organizations and facilities across Federal and state agencies
- Independent, non-profit research organizations
- Industrial end users and consumers of nanotechnology and related information

Applied RD&D and business solutions outlined in this document are summarized in Exhibit 22. Participants recommended that these solutions, implemented in partnership with stakeholders, will accelerate commercialization of innovative nanotechnology solutions. The results of this synergy will help the nation achieve its energy security goals and establish U.S. industry as the world leader in nanomanufacturing technology.

Exhibit 22: Applied RD&D and Business Solutions (estimated/reported range of energy savings)

TBtu/yr	System/Application Specific Nanomanufacturing RD&D		Ref
	Catalyst *Nanoparticles have a high surface area providing higher catalytic activity*		
	Chemicals Manufacturing		
42 - 84	*application specific - "Top 50" commodity chemicals savings range 25% to 50% based on closure of gap between today's practice and theoretical selectivity*		1
158 - 316	*All other chemical industry catalysis applications*		1
80 - 200	Petroleum Refining	*application specific*	1
	Forest Products	*liberate nanofibrils*	
	Electric Power	*flue gas clean-up*	
	Fuel Cell Catalyst…		
	Nanostructured Catalyst "Enzyme lite"	*highly tailored nanoscale chemical specific catalysis, using technologies like atomic layer deposition, self assembly.... will consume significantly less energy and produce less byproduct*	
	Coatings (all industries)		
90	Low-friction	*assume 80% of industrial electric use goes to applications where friction (bearings, gear boxes, seals,...) is 1% of electric consumption and nano-coatings are frictionless*	
	Low-lubrication	*low of self-lubricating surfaces, lower friction, and use of lubricating oils*	
	Heat transfer	*reduce fouling & corrosion improving heat exchange performance-heat exchanger thermal barriers and material protection*	
	Hydrophobicity	*use on condensing surfaces can increase heat transfer coefficient by 30%, applicable to vertical & rotary surface dryer applications, i.e., plastics, food, paper industries*	
	Low-drag coefficient	*Ship hull coatings-150 TBtu/yr-Coating will be an industrial product, however energy savings come from use phase. Possible product extensions in pipe and fittings*	1
	Material Modifications (all industries)		
	Composite wood	*lighter, stronger, longer-lasting saves raw materials*	
	Composite materials	*replaces metal/alloy production*	
	Rheological modification	*saves pumping/transport energy*	
	Lubricants	*Nanosphere or nanoscale ball bearings*	
	Separations		
	Chemicals Manufacturing		
6 - 10	Adsorbants	*application-specific; assume 5% of total is adsorbants*	5
117 - 192	Membranes	*application specific-study looked at 61% (1837 of 3019 TBtu) of the energy used by the chemicals inPdustry; identified potential savings of 123 TBtu/yr*	5

Exhibit 22: Applied RD&D and Business Solutions (estimated/reported range of energy savings) (Cont.)

TBtu/yr	System/Application Specific Nanomanufacturing RD&D		Ref
	Separations		
20	Petroleum Refining	*application specific- e.g., membrane flare gas recovery*	5
	Forest Products	*lignins, hemicelluloses selective removal*	
110	Membranes	*black liquor preconcentration, 30% reduction in evaporator demand*	5
	Thermal Management (all industries)		
16	Aerogel blanket insulations	*Energy savings estimate for improved durability, not thermal conductivity, 40% market share, 160,000 miles of steam pipe (1-5 psig)*	4
	Aerogel spray-on insulations	*provide corrosion under insulation (CUI) and thin thermal barrier with very low thermal conductivity (k)*	
	Thermal barriers	*new opportunities in terms of equipment design*	
	Heat transfer fluids	*higher transfer coefficients and low fouling fluids provide better performance*	
	Heat storage	*high heat capacity fluids*	
	Thin Films (all industries)		
31	Ultrahard/durable surfaces	*Energy savings from: pump components 5 TBtu/yr, die & molds 5 TBtu/yr, mining equipment 0.1 TBtu/yr... totals 31 TBtu/yr in 2030*	3
	Energy storage & batteries	*Significant energy efficiency improvements in the use-phase*	
	Thermoelectric (waste heat recovery)	*(low range ZT =1; high range ZT=4)*	
3 - 16	Application specific	*high temperature furnace flue gases*	2
5 - 24	*Cross industry estimate approx - 2.5 x (3143/1265) - applications*		2
12	Piezoelectric (vibration)	*capture vibration energy for reuse*	2
	Combustion additives (all industries)		
	Temperature/rate control	*e.g., piston diesel shows an 11% improvement during use phase - control of industrial combustion has possible benefits*	
	Sensors (all industries)		
25	Combustion optimization	*new sensors for harsh environment*	
1,146	**TOTALS**		

1 Estimated Energy Savings and Financial Impacts of nanomaterials by Design on Selected Applications in the Chemicals Industry, March 2006, Vision2020, LANL.

2 Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery, Nov 2006, PNNL & BCS.

3 Advanced Wear Resistant Nanocomposites for Increased Energy Efficiency, Fact Sheet Ames

4 Fact sheet - Aspen Aerogel.

5 Materials for Separation Technologies: Energy and Emission Reduction Opportunities, 2005, ORNL & BCS.

"Flower Bouquet," a 3-D nanostructure grown by controlled nucleation of silicon carbide nanowires on Gallium catalyst particles. As the growth proceeds, individual nanowires 'knit' together to form 3-D structures.

Credit: ©Ghim Wei Ho and Prof. Mark Welland, Nanostructure Center, University of Cambridge

Appendix A: Nanomanufacturing Workshop Agenda

DAY 1: 6/5/2007 – DEVOTED TO PRESENTATIONS BY NANOMANUFACTURING EXPERTS AND PANEL DISCUSSIONS AND WILL SET THE STAGE FOR THE NEXT DAY'S BREAKOUT SESSIONS.		
Registration	12:00 PM	1:30 PM
Welcome Douglas Kaempf, DOE Program Manager,Industrial Technologies Program	1:30 PM	1:45 PM
DOE and the Nanotechnology Revolution John Mizroch, Principle Deputy Assistant Secretary for Energy Efficiency and Renewable Energy, DOE	1:45 PM	2:10 PM
National Nanotechnology Initiative: The Next 5 Years Altaf Carim, Department of Energy Office of Science, National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering and Technology Subcommittee Agency Co-Chair, DOE/Office of Science	2:10 PM	2:25 PM
Nanomanufacturing Challenges Facing Industry Don Anthony, President, Council for Chemical Research	2:25 PM	2:40 PM
Nanotechnology Commercialization: Past, Present, Future Matthew Nordan, President, Lux Research Inc.	2:40 PM	2:55 PM
Break 2:55 PM 3:10 PM		
Nanomaterial Manufacturing Panel This panel will address nanomanufacturing issues associated with the industrial production and scale-up of nanomaterials for energy-efficient processes or products. Panelists: • Donald R. Young, Aspen Aerogels, Inc. • Daniel Rardon, PPG Industries, Inc. • Larry Thomas, Air Products & Chemicals, Inc. • Michele L. Ostraat, DuPont Engineering Research and Technology	3:10 PM	4:00 PM

MANUFACTURING OF NANO INTERMEDIATES, SYSTEMS, AND PRODUCTS PANEL This panel will address design and production issues related to incorporating nanomaterials into products that will dramatically improve industrial energy efficiency or energy systems within the next 5 to 10 years. Panelists: • Brian Sager, Nanosolar, Inc. • John H. Belk, Boeing • Greg Lemming, Intel • Michele L. Ostraat, DuPont Engineering Research and Technology	4:00 PM	4:50 PM
Break	4:50 PM	5:05 PM
NANO COMMERCIALIZATION PANEL This panel will address broad commercialization issues specific to nanotechnology (e.g., financing novel products, Environmental Health Safety (EHS), and nanomaterials characterization) Panelists: • Robert Smith, Nantero, Inc. • Margaret Blohm, General Electric • Craig Prater, Veeco Instruments • Thomas Rogers, Technology2020	5:05 PM	6:00 PM
NETWORKING RECEPTION (Roman Strada Room)	6:00 PM	7:30 PM
Dinner on your own – Baltimore Inner Harbor		
DAY 2: 6/6/2007 – DEVOTED TO FIVE CONCURRENT FACILITATED BREAKOUT SESSIONS.		
Continental Breakfast/Registration	7:00 AM	8:00 AM
Breakout Sessions Facilitation Rules	8:00 AM	8:15 AM
FIVE CONCURRENT FACILITATED SESSIONS • Nanomanufacturing Materials and Nanointermediates • Manufacturing Phase Energy Savings (Efficiency) • Use Phase Energy Savings (Efficiency) • Power Production Energy Savings (Efficiency) • Business Challenges	8:15 AM	2:30 PM
Sessions Reporting	2:45 PM	3:45 PM
CLOSE OUT AND THANK YOU	3:45 PM	4:00 PM

Appendix B: Workshop Attendees

Sajjad Ahmed
PPG Industries, Inc.

Fred Allen
RADii Solutions

George Andrews
General Motors Research & Development

Nikoi Annan
Owens Corning

Don Anthony
Council for Chemical Research

Frank Armatis
3M

Sam Baldwin
Department of Energy

Kevin Ball
BP, Plc

Leandro Balzano
Shell

Lionel Batty
GrafTech International

Brad Beardsley
Caterpillar Inc.

Shawn Beckman
SDC Materials

Dave Belak
Engineering Systems Solutions, Inc.

John Belk
Boeing

Robert Bianco
Goodrich Corporation

Margaret Blohm
General Electric

Craig Blue
Oak Ridge National Laboratory

Steven Buntin
NIST

Rob Burns
Lux Research

Paul Burrows
Pacific Northwest National Laboratory

Ahmed Busnaina
Northeastern University

Altaf Carim
Department of Energy/ Office of Science and Technology Council

Robert Carr
Rubbermaid

Isaac Chan
Department of Energy

Hongda Chen
USDA

Joe Clark
Day Pitney

Claus Daniel
Oak Ridge National Laboratory

Edward Daniels
Argonne National Laboratory

Biswajit Das
University of Nevada

Diane Devaul
Northeast Midwest Institute

Sara Dillich
Department of Energy

Michael Dowell
Powdermet, Inc.

Brian D'Urso
Oak Ridge National Laboratory

James Eberhardt
DOE Transportation

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Greg Farrell
Kinghorn, Hilbert & Associates

P. Ferreir
University of Illinois at Urbana-Champagne

Gary Fischman
National Academies of Sciences / National Materials Advisory Board

Paul Fishing
Employer not provided

Douglas Freitag
Dow Corning Company

Lisa Prokurat Franks
U.S. Army Tank Automotive RDE Center

Srinivas Garimella
Alcoa

Charles Gause
Luna Nanoworks

Jerry Gibbs
Department of Energy

Patti Glaza
Small Times Magazine

Marcos Gomez
BASF Future Business

Daniel Gruneberg
Lux Research Inc.

Karl Haider
Bayer MaterialScience - New Technologies Group

David Hamman
Nano-CEMMS, University of Illinois at Urbana-Champaign

Michael Holman
Lux Research

Joseph Holmes
Acuity Edge, Inc.

Ehr-Ping Huangfu
Department of Energy

Karen Hunter
USDA

Venkatarayaloo Janarthanan
Praxair

Mahesh Jha
DOE Golden Field Office

Phil Jones
Imerys Corp.

Haresh Kamath
EPRI Solutions

Douglas Kaempf
Department of Energy

Ganesh S kandan
NEI Corporation

Nety Krishna
AMAT

Thomas Krotine
Ecology Coatings Inc.

Jack Kruper
Dow Corporation

Tom Lamb
Solutia Inc.

Albert Lee
National Inst. of Biomedical Imaging & Bioengineering

Dominic Lee
Oak Ridge National Laboratory

Gregory Leeming
Intel Corp.

Stephen Lehrman
Office of Senator Mark Pryor

Jianyu Liang
Worcester Polytechnic Institute

Alan Liby
Oak Ridge National Laboratory

Frank Liotta
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Appendix C: Technical and Business Needs Identified at Nanomanufacturing Workshop

Technical RD&D Barriers and Needs Identified to Accelerate Commercial Nanomanufacturing

Barriers	Strategies	
Production of Nanomaterials		
Lack of reliability of nanomaterials supplies	Develop new, standard, high-yield, low-cost, scaleable processes that can manufacture nanomaterials	High Priority
	Develop cost effective separation, functionalization, and dispersion of nanomaterials	High Priority
	Develop better understanding of synthesis fundamentals in order to perfect synthesis unit operations	Medium Priority
	Determine the impact of aging and storage on nanomaterials	Medium Priority
	Medium Priority: Develop novel manufacturing techniques for hierarchical assembly	Medium Priority
	Medium Priority: Research life cycle issues	Medium Priority
Lack of technologies to improve materials properties and performance	Investigate novel/ new process technology to improve materials properties and performance and demonstrate their repeatability	High Priority
Lack of ability to disperse stable nanomaterials through final production	Develop technologies for application specific dispersions for final production	Medium Priority
Lack of processing capabilities for high temperature processes	Address thermal stability and retain nano benefits for high thermal environments	Medium Priority
Materials issues	Develop materials by design, rational design across regional scales	Medium Priority
	Develop durable coatings using scalable processes	Medium Priority
	Develop structure/ function relationships of self assembling nanomaterials	Medium Priority
	Couple/ integrate (process development with sensors & controls)	Medium Priority
	Develop chemical/physical surface functionalization	Medium Priority
	Develop cost effective separation, functionalization, and dispersion of nanomaterials for coatings	Medium Priority
	Develop self correcting materials	Medium Priority
Production of Nano Intermediates and Products		
Lack of scalable unit operations for reliable, cost-effective incorporation of nanomaterials into nanointermediates and products	Develop new, standard, high-yield, low-cost, scaleable processes that can manufacture products incorporating nanomaterials	High Priority
	Provide access to pilot scale manufacturing equipment for process validation and demonstration	High Priority

Technical RD&D Barriers and Needs Identified to Accelerate Commercial Nanomanufacturing (Cont.)

Barriers	Strategies	
Characterization & Process Control for production of nanomaterials		
Lack of characterization/monitoring tools for production processes that utilize nanomaterials	Develop robust, on-line, real-time, in-situ characterization/monitoring tools	High Priority
Lack of standard testing methods for quality of intermediates containing nanomaterials	Develop non-destructive quality control testing methods for intermediates containing nanomaterials for producers and users	High Priority
Lack of process control methods for nanomanufacturing processes Characterization Needs	Medium Priority: Develop process control technologies for nanomanufacturing processes	Medium Priority
	Develop accelerated test procedures for nano coatings and nano structured surfaces	Medium Priority
	Investigate/ understand macro effects	Medium Priority
	Develop nano-based sensor technology to sense power stand-by mode and automatically step-down power-pull requirements	Medium Priority
	Develop nanotechnology based sensors to enable real-time on-line measurement of process variants	Medium Priority
Modeling		
Lack of algorithms and codes for nanotechnology models	High Priority: Develop mathematical algorithms and codes needed to create nanotechnology models	High Priority
Lack of ability to model across scales	High Priority: Develop multilevel, multiscale integrated models which work together across different nano fields	High Priority
Lack of predictive modeling for structure/property relationships for industrial materials	High Priority: Develop models which allow the prediction of the properties of products incorporating nanomaterials so that "Nanomaterials by Design" works. (Joint Semi/Chem effort working with NIST).	High Priority
Modeling issues	Develop a database of nanomaterial properties	Medium Priority
	Fund modeling projects	Medium Priority
	Develop process simulation via parametric studies	Medium Priority
	Develop reliable ground state structure/ energy prediction in vacuum solution	Medium Priority
	Rational modeling for discovery of heterogeneous catalysts	Medium Priority
	Model kinetic control and processes	Medium Priority
	Develop computationally designed coating for wear and tribology	Medium Priority
	Develop reaction transition state barrier modeling methods	Medium Priority

Technical RD&D Barriers and Needs Identified to Accelerate Commercial Nanomanufacturing (Cont.)

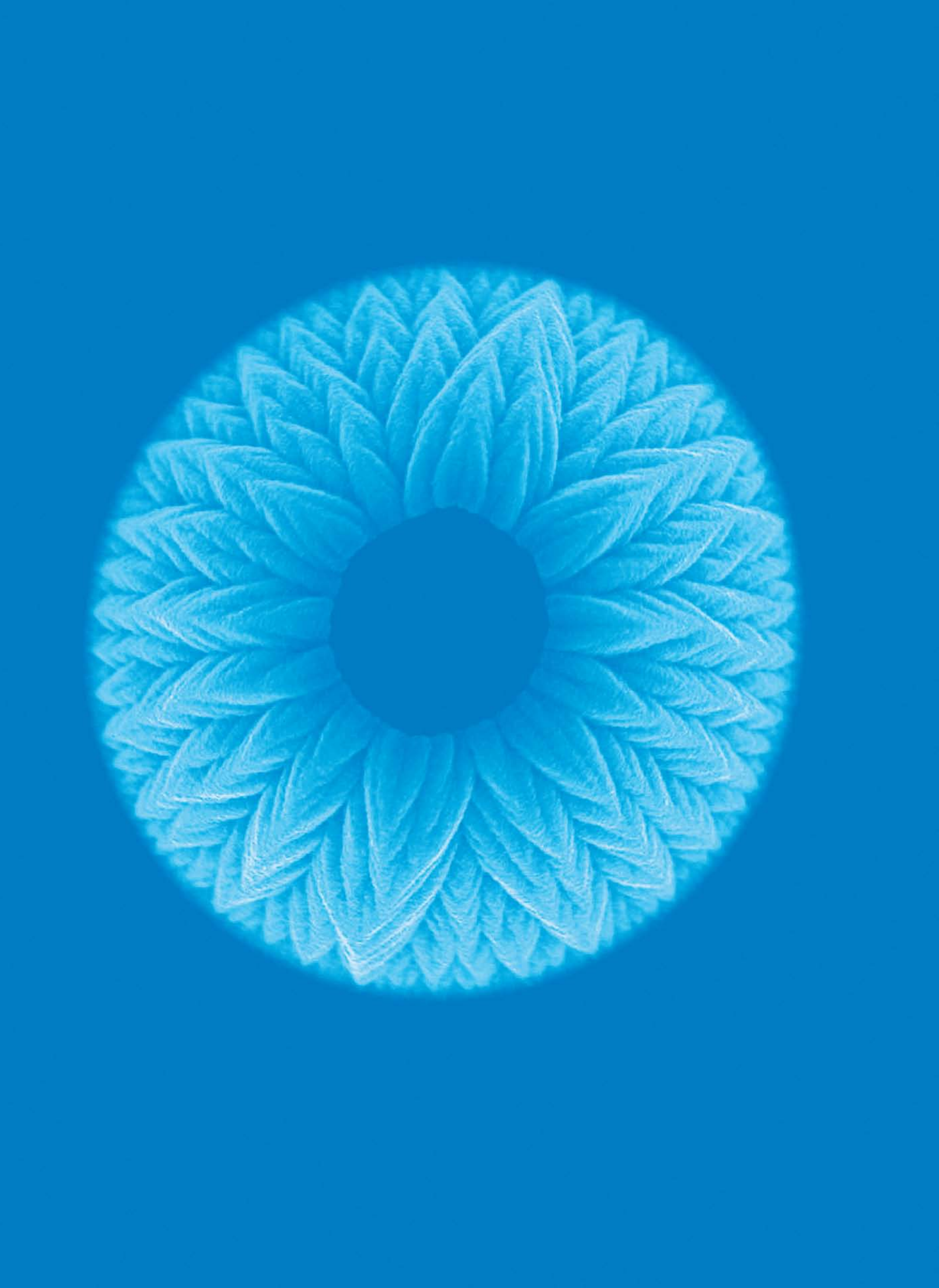
Barriers	Strategies	
Infrastructure		
Lack of reliability of nanomaterial supply	Fund a center to assist with scalability	High Priority
	Focus grant renewal on reproducibility	Medium Priority
	Qualification and certification of nano suppliers	Medium Priority
	Develop standards	Medium Priority
	Establish “Manufacturer of last resort”	Medium Priority
Lack of reliability of production/scale-up of products containing nanomaterials	Establish pilot facilities for testing/process development/ demonstration of nanomanufacturing	High Priority
	Establish “scale up” benchmarks to reduce risk	High Priority
Economic Uncertainties (Lack of established infrastructure)	Provide process development and nanomaterials production centers to assist suppliers in improving their processes and reduce risk	High Priority
	Use market pull instead of technology push in nanotechnology adaptation, e.g. cost of raw material	Medium Priority
	Investigate recycling costs	Medium Priority
	Perform Life Cycle Analysis of nanoproducts including energy analysis	Medium Priority
	Investigate economics of scale-up	Medium Priority
Funding Opportunities and Strategic Partnerships		
Lack of funding for applied R&D for commercialization (“valley of death”)	Fund start-up corporate collaborations	High Priority
	Fund government-sponsored incubation parks	High Priority
	Fund applied R&D to cover gap between presently funded pure research and demonstrations	High Priority
	Use Advanced Technology Programs “key factors” and/or funding model	Medium Priority
	Collaborate internationally and with DOD to assure broad support and understanding	Medium Priority
	Help identify lead users of technology	Medium Priority
Lack of commercial influence on basic research funding	Establish industry advisory boards	High Priority
	Establish industry participation in proposal review process	High Priority
	Establish integration/collaboration between DOE nanoscience program and applied programs	High Priority
	Feedback to ensure funding matches priorities	High Priority
	Input requirements into NNI reauthorization	Medium Priority

Technical RD&D Barriers and Needs Identified to Accelerate Commercial Nanomanufacturing (Cont.)

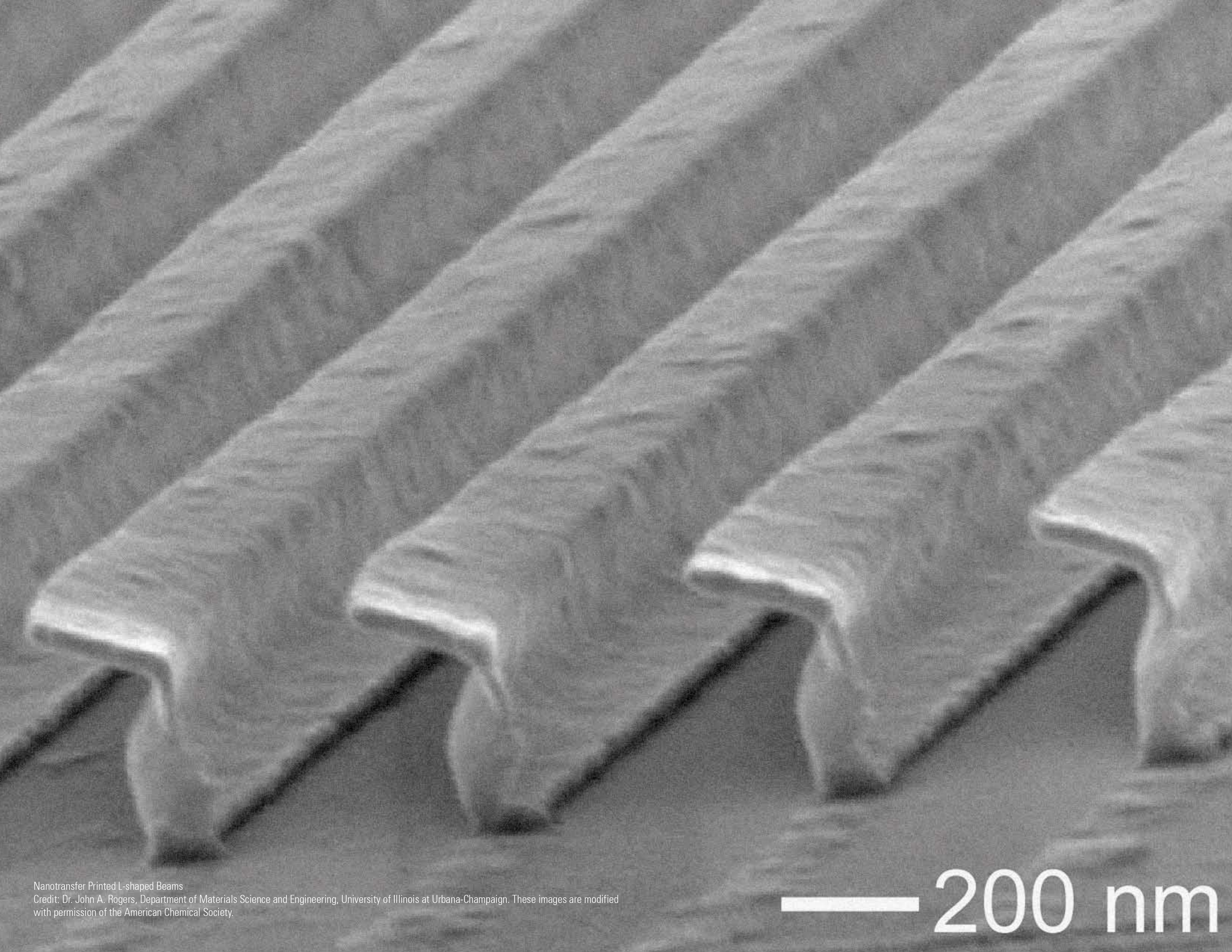
Barriers	Strategies	
Need to improve information exchange	Recommend new hires have industry experience	Medium Priority
	Share cross-cutting technologies across industries	High Priority
	Summarize/coordinate roadmaps	Medium Priority
	Publish a document that highlights successes (catalysis, separation science, nanoelectronics, etc)	Medium Priority
	Centers of Excellence	Medium Priority
Intellectual Property (IP) Rights		
Sharing and valuing intellectual property	Provide incentives for academic-industry partnerships	High Priority
	Find and promote best practices for TTOs	Medium Priority
	Work with USPTO to speed patent process	Medium Priority
	Facilitate resolution of patent thickets	Medium Priority
	Reduce government's IP rights	Medium Priority
Policy		
Lack of policy drivers for innovation	Commitment from DOE to fund R&D and infrastructure (20 years from conception to commercialization)	High Priority
	Develop incentives for companies and consumers to change from traditional technologies/products to energy efficient ones through communications and policy (such as Energy Star)	High Priority
Regulatory uncertainty	Provide data and handling guidelines to industry	High Priority
	Establish nano ASTM standard	High Priority
	Identify lead agency	Medium Priority
	Evaluate standardization efforts	Medium Priority
	Offer EHS testing to grant recipients	Medium Priority

Endnotes

1. Unpublished data from DOE and NSF.
2. Focus on energy: Nanotechnology R&D can solve energy crisis, Small Times, August 13, 2004.
3. Gillet, 2002, National Nanotechnology Initiative Grand Challenge Workshop, 2005.
4. Clough, 2005, Testimony to the Subcommittee on Technology, Innovation, and Competitiveness; Senate Committee on Commerce, Science and Transportation by Dr. Wayne Clough, President, Georgia Institute of Technology, June 8, 2005.
5. LANL, 2006, “Estimated Energy Savings and Financial Impacts of Nanomaterials by Design on Selected Applications in the Chemical Industry” http://www.chemicalvision2020.org/pdfs/LANL%20Nano%20Rept%20Final%204-17-06.pdf.
6. LANL, 2006, “Estimated Energy Savings and Financial Impacts of Nanomaterials by Design on Selected Applications in the Chemical Industry”.
7. EPRI “Cost of Corrosion in the Electric Power Industry,” Report No. 1004662, October, 2001.
8. LANL, 2006, “Estimated Energy Savings and Financial Impacts of Nanomaterials by Design on Selected Applications in the Chemical Industry”.
9. Nanotechnology for the Forest Products Industry: Vision and Technology Roadmap. March, 2005 Agenda2020 Technology Alliance.
10. LANL, 2006, “Estimated Energy Savings and Financial Impacts of Nanomaterials by Design on Selected Applications in the Chemical Industry”.
11. Industrial Technologies Program “Materials for Separation Technologies: Energy and Emission Reduction Opportunities”, May 2005.
12. Lawrence Livermore National Laboratory, 2006, Press Release 5-18-06, http://www.llnl.gov/pao/news/news_releases/2006/NR-06-05-06.html.
13. NEI, 2007, http://www.neicorporation.com/prod_fluids.htm.
14. Nanotechnology Now; Feb. 19, 2007, http://www.nanotech-now.com/news.cgi?story_id=20587.
15. Industrial Technologies Program, 2006, Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery.
16. Gillet, 2002, Nanotechnology: Clean Energy and Resources for the Future, Foresight Institute, http://www.foresight.org/impact/whitepaper_illos_rev3.PDF .
17. (Boeing, 2007) http://www.boeing.com/commercial/787family/background.html.
18. United States Display Consortium, www.usdc.org.
19. United States Display Consortium, www.usdc.org.
20. “Our Solar Power Future: The U.S. Photovoltaics Industry Roadmap Through 2030 and Beyond,” 2004,http://www.sandia.gov/pv/docs/PDF/PV_Road_Map.pdf.
21. National Nanotechnology Initiative Grand Challenge Workshop, 2005, Nanoscience Research for Energy Needs, Department of Energy, Office of Basic Energy Sciences, http://www.sc.doe.gov/bes/reports/files/NREN_rpt.pdf.
22. Basic Energy Sciences Workshop on Superconductivity, Basic Research Needs for Superconductivity, 2006, http://www.sc.doe.gov/bes/reports/abstracts.html#SC.



"Nano flower", Credit: ©Ghim Wei Ho and Prof. Mark Welland, Nanostructure Center, University of Cambridge.



Nanotransfer Printed L-shaped Beams

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