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Strategic Materials

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STRATEGIC MATERIALS

ABSTRACT: Strategic materials are those materials, along with research, development, and technology that are critical in ensuring a US competitive advantage, both economically and with respect to national security capabilities. Emerging innovative material technologies are those enabling greater levels of designed-in properties, functionality, and application, as well as the creation of fundamentally new materials. Technological innovations in materials science affect many of the elements of national power. Ultimately, strategic materials are critical transformation enablers – for our society, economy, and national security.

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THE STRATEGIC MATERIALS INDUSTRY

INTRODUCTION

During the past fifteen years, the world has witnessed significant change in the international security environment. Having emerged “victorious” from the decades-long ideological struggle that characterized the Cold War, the United States stands today as the sole military superpower, no longer confronted by a military peer-competitor. Yet threats to our national security continue to evolve and, as we enter a new millennium, we face a world increasingly characterized by complexity, instability, and ambiguity. It is within this framework of a changed global security environment that we embark upon a path of transformation to confront the emerging threats, challenges, and opportunities of the 21^{st} century.

This industry study clearly established that materials will be a key enabler of these transformation efforts. In addition to the direct national security implications, it is evident that the application of strategic materials technologies will have a more dramatic impact on world economies than did the computer and internet during the 1990s. The breakthrough developments in the area of materials technology are expected to continue to accelerate, acting as catalysts for evermore-impressive global economic revolution and growth.

It is difficult to define the boundaries of an “industry” as diverse as that involving *strategic materials*. However, in the pages that follow, we will present an executive summary and overview of the strategic materials industry in a global context, as we discovered it through extensive domestic and international studies and research. Specifically, this discussion will: 1) define the industry; 2) evaluate the current condition, challenges, and outlook; 3) assess the industry’s contribution to national security, our nation’s competitive advantage, and transformation efforts; and 4) discuss policy implications and options to enhance industrial preparedness.

THE INDUSTRY DEFINED

The “strategic materials industry” consists of a diverse group of industries and organizations, along with several evolving technologies, that enhance US economic prosperity and national security. One of our first challenges was determining an appropriate definition of “strategic materials” to frame our analysis. This began with recognition that strategic materials derive their uniqueness and strategic significance by providing a means to reduce constraints placed on us by traditional materials, enabling the ability to custom-design and produce materials possessing desired performance characteristics.

As a result of our investigation and analysis, we have concluded that a definition of strategic materials should address not only the initial raw materials, but also the relevant technologies and end use applications. The materials alone are not what make this industry so significant; it is the knowledge and innovative applications of materials and technology that are key to making them strategic resources. As such, for the purpose of this discussion, *strategic materials* are those materials, along with relevant research, development, and technology, that provide for continued US economic growth and prosperity, and that are critical in enabling and maintaining an American competitive advantage, both economically and with respect to national defense capabilities.

CONVENTIONAL MATERIALS

Conventional materials, to include metals (e.g., steel, aluminum, and titanium), as well as magnetic materials and ceramics, though sometimes perceived as low-tech, inefficient and conservative, represent a vibrant and innovative segment of the strategic materials industry. New and improved methods of extraction, processing, and fabrication are keeping these materials in the mainstream even as more exotic and contemporary materials enter the market in increasingly greater numbers. As the need for more technologically complex and ecologically sustainable products increases, demand for such materials continues to expand across the defense and commercial spectrum.[1] These materials remain significant from both an economic and national security standpoint.

Steel

Overview and Current Condition. With sales exceeding $60 billion annually,[2] the steel industry remains a material of choice for applications such as bridges, ships, commercial structures, and numerous military items. The industry continues to pursue advanced metals processes and products through research and development (R&D) initiatives across the defense and commercial spectrums. For example, over 70 percent of the steel products in use today were non-existent five years ago.[3]

The steel industry is capital and labor intensive, employing more than 140,000 individuals, producing steel bar, sheet, rod, tubing, and wire from three types of mills: integrated mills, minimills, and specialty mills. Today, modern mills are a marvel of computer-controlled processes, employing sophisticated sensors and end-to-end automation of production lines. Yet, regardless of the type of mill, the industry operates on very slim margins.

Challenges and Outlook. While the steel industry is statistically efficient, global competition is intense, and combined with downward price trends, overwhelming. A worldwide glut of steel available for sale has caused a dramatic decrease in the demand for higher cost US steel, causing sales of US steel products to plummet, forcing many US mills into bankruptcy over the last three years. These trends are increasing pressure on the industry to consolidate and become more efficient.

In March 2002, US steel producing companies received temporary relief by the imposition of import taxes on certain categories of foreign steel, the Section 201 Tariff Remedy (these tariffs decrease over three years, until their total removal in 2005). In return for this protection, steel producers have pledged to become leaner and to initiate environmental and productivity improvement projects. However, even with this federal assistance, steelmakers have cut back on large investment initiatives as they continue to fight lower selling prices, higher imports and energy costs, and a sluggish US economy. Capital spending by the North American steel industry dropped from $4.91 billion in 1998 to $2.09 billion in 2001.[4] Additionally, venture capital is almost non-existent and loans are costly due to high risk and low rates of return experienced by the industry.

The Section 201 tariffs have had a predictable domestic backlash. Steel consuming firms (automotive, appliance manufacturers, bridge builders, and others) represent an estimated 12 million business owners and employees. This group has charged that the tariffs have driven up prices and forced many small companies to close.[5]

The American Iron and Steel Institute (AISI) (representing steel producers) has developed a five-year growth plan to improve North American markets, seeking a 5 percent increase in market share in each of the next five years.[6] The AISI growth estimate of 15 million tons relies heavily on key assumptions, such as the automotive industry keeping steel as its material of choice. The plan also presumes continued advancement in designing special alloys for military and critical commercial applications such as highly corrosion-resistant and ultra-lightweight steels.

Steel is a readily available commodity with multiple global suppliers. Our ability to obtain raw bar, sheet, and forgings is virtually unlimited and, in a global economy, there is little fear that all sources for raw steel will simultaneously cease. Steel is not in and of itself a strategic material; rather it is our ability to manufacture or obtain steel in an economically acceptable manner that is the vital element to the US economy and national security.

Aluminum

Overview and Current Condition. Today's largest aluminum producers are multinational companies with global production, fabrication and distribution facilities. 90 percent of the world's primary aluminum production occurs in the US, Russia, Canada, the European Union, China, Australia, Brazil, Norway, South Africa, Venezuela, the Gulf States (Bahrain and United Arab Emirates), India, and New Zealand.[7] Modern aluminum companies tend to be vertically integrated through ownership in all aspects of the aluminum industry, from bauxite mining to semi-fabricated materials, all the way to end-product manufacturing.[8]

Global competition has caused the US's position to wane significantly during the last two decades as China, Australia, Canada and Brazil emerged as major producers and exporters of aluminum in the early 1980s.[9] In fact, the US was the world's leading producer of aluminum metal until 2002, when Canada surpassed the US production rate.[10] A primary reason for this decline is higher US energy costs. Recent expansion and new plant construction have been relegated to areas of the world with access to cheap energy and labor costs.[11]

Challenges and Outlook. Profitability in the aluminum commodity market relies upon efficiency and cost reductions. In such a market, the US has impediments that other countries do not, such as aging smelter infrastructure (the newest smelter is now 30 years old), high labor and energy costs, and increasingly stringent environmental standards that have caused an increase in capital operating costs.[12] Additionally, should Chinese production grow at rates some predict, allowing China to become a primary world supplier of aluminum, its low cost production processes could force prices down, preventing US aluminum companies from remaining competitive.

The Defense Logistics Agency has been authorized to sell the inventory of metallurgical and refractory-grade bauxite in the National Defense Stockpile in fiscal year 2003, due to decisions to rely on the global market to meet US aluminum resource needs. With bauxite resources available around the world, and several close allies (Jamaica, Australia, Canada) providing the US with bauxite, alumina, and aluminum, the global market can meet these needs. Substitutes for aluminum, such as steel, titanium, magnesium, and composite materials could fill the void in many applications, though at an increased cost. US dependence on foreign supplies of alumina and aluminum, as well as high domestic operating costs, are challenges that require US aluminum industry strategic planning and management and government monitoring.

Federal support from the US Department of Energy *Industries of the Future Program* has helped accelerate the development of aluminum technologies critical to public and strategic national interests. This funding, along with collaborative R&D efforts, is providing a foundation to develop the superior quality and functionality of aluminum products that will enhance US producer competitiveness in the global market.

Titanium

Overview and Current Condition. Titanium is attractive to designers and engineers because of its lightweight, corrosion and fatigue-resistance, low-density, and high-strength properties. The density of titanium is half that of copper and nickel and approximately 60 percent of stainless steel; thus it is relatively light given its material characteristics. Aluminum, magnesium, and beryllium are the only base metals that are lighter than titanium, none of which come close to titanium in mechanical performance and properties.[13]

Titanium exhibits the highest strength to density ratio of all metals. Its unique properties make it an ideal material for automobiles, aircraft, military equipment, bicycle frames, golf clubs, and other tubular structures. Titanium itself is not rare but actually very abundant, with large deposits occurring in beach sand; the challenge is addressing high extraction and processing costs. Another unique property of titanium is its low modulus of elasticity, which translates into a natural dampening effect on structural vibrations (e.g., vehicles made of titanium frames have a smoother ride without additional suspension elements). Additionally, titanium is more corrosion-resistant than other materials, especially when subjected to saltwater. Other useful design characteristics are low thermal and electrical conductivity, fracture resistance, non-magnetic and cryogenic properties, non-toxicity, bio-acceptability, shape memory, and hydrogen affinity. Titanium alloys often provide designers the best combination of mechanical properties available among metals.[14]

Challenges and Outlook. The greatest challenges for the titanium industry are lowering the cost of extraction and improving processing and fabrication techniques. Extraction and processing costs are 30 times that of steel and 6 times that of aluminum. When the expense to fabricate parts and structures is factored in, the cost differential worsens. In light of the benefits of titanium, further R&D should be initiated to lower the cost of its extraction, processing, and fabrication.

Propelling the titanium industry forward will require bold leadership and revolutionary innovation. Further advancements in the industry will be realized through increased consumer education, as potential consumers are made aware of its outstanding properties and the benefits to lowering life-cycle costs of systems that employ it. It is clear that innovation is necessary for titanium materials to achieve significant penetration of new markets.[15] Key to the revolution within the US titanium industry will be the cooperation between government, titanium producers, and the product manufacturers to produce and market titanium products. Innovation could be realized sooner if the federal government decided to fund R&D efforts to develop technological breakthroughs and the dollars to recapitalize factories.[16]

Magnetic Materials

Overview and Current Condition. The use of magnets is prevalent in the civilian and military sectors of the US. The magnetic materials industry is dependent upon two types of commodities: 1) basic finished materials, such as steel bars, slabs, and coils and 2) rare earth elements (REE). After World War II, REEs were placed in the National Defense Stockpile. Recently, Congress has authorized the sale of all REEs, citing the end of the Cold War and the belief that these materials are readily available in the global marketplace. Many magnetic materials are dual use, but some are specifically designed with military applications in mind. In this regard, the US must be able to either acquire the necessary materials needed to make all types of magnets or have access to them as finished products, especially those produced from REEs.

The production of REEs around the globe is primarily from the mineral bastänite. Currently, one US company mines a minimal amount of REEs, but ceased production of refined REEs in 1998 due to financial, regulatory, and environmental problems. Currently China is the leading producer and exporter of REEs. Low labor costs, a large supply of materials, and its World Trade Organization membership should assure China remains the leading exporter of REEs for the near future.

A single US company produces the rare earth supermagnet NIB, used in the Joint Direct Attack Munition project that produces ‘smart bombs.’ In 1995, two Chinese companies and a US firm purchased this company. Since then, the company has declared bankruptcy and may move its operations to China.

Challenges and Outlook. The technological significance of REEs in civilian and military applications continues to expand. However, the importance of the ability of the US to acquire REEs in their raw and finished form cannot be underestimated. The use of REEs in many “applications are highly specific” and “substitutes are inferior or unknown.”[17] It is imperative we have unfettered access to the materials needed to make soft, hard, and rare earth supermagnets."

Ceramics

Overview and Current Condition. The ceramics industry is one that conjures up visions of scientists and technologists working diligently to create the materials for tomorrow's applications. Yet, it is appropriate to begin an overview of these materials with a look at the past. The word ceramic may be traced back to its ancient root in Sanskrit meaning "to burn." The related Greek term, "*keramos*" means potter or pottery and was used to describe the action of fire upon various materials.[18] The production of ceramic pottery required a detailed knowledge of the physical properties of different clays and tempering materials, plus knowledge about how these combine and react under specific firing conditions.[19]

From 1974 through the present, the ceramics industry has experienced astounding growth in sales, from $20 million to more than $35 billion.[20] This growth is a reflection of the need for the unique properties of ceramic materials not met by metals and alloys, and evidenced by the assertion that "metals and plastics, in many applications, have now been developed beyond the point of further significant improvement."[21] The categories of ceramics, often called "segments," that make up the industry can be classified as follows: structural clay products, whitewares, refractories, abrasives, cements, and advanced ceramics.

Challenges and Outlook. Ceramics exist to the benefit of all the major industries in the US including aerospace, automotive, medical, information technology, communications, and defense. The applications are innumerable and critical to our exploration, advancement, and quality of life. The market segment that is most promising for the Department of Defense (DOD) is in the area of Advanced Ceramics, which is very R&D dependent. Research is needed not only to learn about the creation of new materials, but also to develop the enabling technologies, equipment, and processes used in the production of the materials. Once a laboratory has proven the ability to create a useful material application, it has further challenges to replicate this reliably in a production setting. Ceramic applications are usually more expensive than the metal products that they compete with and must realize lifecycle cost savings in the overall system to remain advantageous.

A recent trend of disinvestment may be changing as conditions for both private and public investment in ceramic materials science R&D improve. National security concerns are motivating increased expenditures, energy prices are falling, and business profits are showing signs of improvement, all creating a positive environment for increased private sector spending in ceramics R&D.

COMPOSITES

Composites are materials that combine two or more separate components to form a product that is superior to either of the parent components, and to many traditional materials such as steel and aluminum, in mechanical properties and economic value. Enhanced composite properties include greater strength, lighter weight, corrosion resistance, and improved fatigue resistance. They also have improved manufacturing properties that contribute to these enhancements such as ease of molding, the ability to manufacture whole or easily integrated parts, and improved heat resistance and conductivity or acoustical properties. Composites provide for increased flexibility through near limitless improvements to existing materials,[22] giving us the ability to remove constraints placed on us by traditional materials. Composites find their uniqueness and strategic significance in their ability to bring common and uncommon materials together to combine their properties and create products able to meet ever-increasing technological demands. Composites enable advancements in areas such as information, nanotechnology, defense, medical, and electronics industries.

"The US composites industry has accumulated an impressive record of growth, diversification and technical competence since becoming a commercial reality in the 1940s."[23] Since 1960, the composites industry has grown at an average rate of 6.5 percent or approximately twice the growth rate of the US economy.[24] During this same period, while US consumption of steel doubled, the US gross domestic product (GDP) tripled, aluminum consumption quadrupled, composite production increased fifteen fold.[25] The composites industry is responsible for $25 billion of the GDP and employs almost 250,000 people, with an additional 250,000 employed by companies that support composite production. [26]

Metal Matrix Composites

Overview and Current Condition. Metal Matrix Composites (MMC) have as their matrix (binder) materials metals such as aluminum, titanium, copper, and magnesium, reinforced with metals such as silicon carbide, alumina, boron carbide, and graphite. Some of the general distinctions between MMCs and other composite materials are: 1) MMCs evidence higher ductility and toughness than ceramics or ceramic composites, although they have lower ductility and toughness than their respective unreinforced metal matrix alloys and 2) MMCs have temperature tolerances generally higher than polymers and polymer composites but less than ceramics and ceramic composites.

While use of MMCs has not lived up to some initial expectations,[27] future military applications may include: 1) the US Army's Future Combat System; 2) thinner-wall munitions for artillery, allowing room inside the shell to add new technology; and 3) in combination with other composites, lighter personnel carriers.[28] In the private sector, automakers are using MMCs in drive shafts, brake components, cylinder liners, pistons, connecting rods, and push rods; while the construction industry maximizes the low weight, high strength, and high temperature resistance of MMCs to create improved products. With cost reduction efforts, the use of MMC will continue to increase.

A 2001 market study report[29] indicates that the overall MMC market grew to $103 million in 1999, with 62 percent of the volume in ground transportation applications and 26.5 percent in thermal management applications. Aerospace industry uses, including both gas-turbine-engine applications and commercial and military aircraft structures, comprised only 5.4 percent of the volume of the 1999 market. The report projects that by 2004, the MMC market will grow at an average annual rate of 14.1 percent to $173 million. The ground transportation and thermal management markets will hold 70.3 percent and 21.9 percent market share on volume basis, respectively, with aerospace making up 3.3 percent of the market in 2004.

Challenges and Outlook. An ambitious set of challenges and goals for MMCs appears in the Technology Roadmap developed by the Aluminum Metal Matrix Composite (ALMMC) consortium in May 2002. This effort identified three strategic goals to be addressed:[30] 1) reduce the cost of discontinuously reinforced ALMMC to levels comparable to existing alternatives by 2010; 2) develop the necessary infrastructure to provide design confidence in ALMMC; and 3) increase the market size for ALMMC 10 times by 2005 and 25 times by 2010. Continuing MMC R&D efforts to reduce cost and increase quality and production processes should result in increased applications and increased demand.

Ceramic Composites (Medical)

Overview and Current Condition. When considering the possible uses for ceramic composites in the medical field, physicians must keep several key considerations in mind. Any synthetic material implanted in the human body must be biocompatible (i.e., not generating an adverse reaction from the body). In addition, materials used for medical devices or for surgical implants must be non-toxic. Although ceramics exhibit desirable chemical and corrosion-resistant properties, they are brittle and researchers continue to seek ways around this shortfall through ceramic composites.

Because researchers can tailor the properties of ceramic composites to meet various requirements, medical researchers developed bioceramics to meet the growing demand for biocompatible materials. Bioceramics are non-toxic and, if mixed properly, bioinert (not interactive with biological systems), bioactive (durable materials that can undergo interfascial interactions with surrounding tissues), and biodegradable (soluble or resorbable – eventually replaced or incorporated into tissue).[31]

Challenges and Outlook. Medical uses for ceramic composites have existed since the first ceramic knee was implanted in 1972.[32] However, the high stress demands and chemical properties of the human body have limited the applicability of ceramic composites in the medical field. Still, new technological breakthroughs, such as nanotechnology, provide promise for medical ceramic composites. Unfortunately, the lag between ceramic composite development and their fielding will limit their application for the next 5-10 years.[33]

Ceramic composite characteristics such as thermal and chemical stability, high strength, wear resistance, and durability make them ideal materials for surgical implants offering many advantages over other materials. Ceramic composites are harder and stiffer than steel; more heat and corrosion resistant than metals or polymers; less dense than most metals and their alloys; and their raw materials are both plentiful and inexpensive.[34] Medical applications for ceramic composites include hip and knee replacements, hydroxyapatite coatings to promote tissue growth, and bone structural supports. Two of the major dental applications for ceramic composites include dental pins and fillings.

Polymer Composites

Overview and Current Condition. The US is the industry leader in polymer-matrix composite manufacturing. Based on the desirable qualities of polymer composites (strong, lightweight, corrosion resistant, durable, and flexible in design) the composites industry is continuing to grow and has a number of years remaining before it reaches maturity. In addition to the materials, the associated technical knowledge and application of the polymer composites make them significant as a strategic resource. We must safeguard the knowledge and expertise in order to maintain our global advantage in this industry while continuing to develop advanced applications.

The limits on the use of polymer composites are based on the high cost of materials, inefficient processing systems, and lack of education and training in their application. Their properties have historically made them appealing to military and aerospace applications, where mass production in assembly line format is not used excessively and there is a definite need for special use parts that can withstand great heat while lowering weight. Many universities and laboratories are working to improve efficiencies of materials and production, and are actively recruiting students from a wide variety of academic backgrounds to come together in a collaborative effort with government and industry to develop polymer composite materials and improve the production process.[35] Polymer composites have an advantage over traditional materials because they are stronger (when compared on an equal weight basis), can be more easily formed, and their qualities can be manipulated to produce specific material properties.[36] The full extent of how we can combine and employ these materials has yet to be seen, but today they are having significant impact on developments that support future technologies and improve infrastructure.

Challenges and Outlook. Education is essential for the continued growth of polymer composites and advancement in their development. Since the polymer composite industry is reliant on knowledge, collaborative efforts, and the development of new and creative ideas, education is a critical link to continued success in the industry. The education aspect of composites goes beyond the development of new products. Education and training extends to the people who will manufacture and support the manufacture of polymers. Maintenance personnel have to be extensively retrained to provide the appropriate maintenance for the new materials. Like any new or emerging technology, the polymer composite industry is short of qualified and trained personnel to support the infrastructure. The polymer composites industry has not yet reached maturity and the growth potential is enormous. Scientists and engineers continue to improve and create products for advanced as well as everyday applications and develop mass production capability.

EMERGING INNOVATIONS FOR STRATEGIC MATERIALS

Since the dawn of the Bronze Age, materials science and associated materials technologies have played a revolutionary role in transforming the world by fueling societal change, ushering in technological revolution, and enabling a diverse array of economic pursuits. This trend continues today, as materials scientists and engineers are poised to transform the world through continued innovations in materials research, development, and application. Examples of such innovations include biomimetics, nanotechnology, and microelectromechanical systems (MEMS).

Biomimetics

Overview and Current Condition. With brutal efficiency that ensures poor designs do not survive, nature has been creating systems of staggering complexity with a vast diversity of form and function for 3.8 billion years. Today, scientists are increasingly looking at the engineering designs present in biological systems, not to simply "mimic" nature but to provide insight for future development. As a "study of the structure and function of biological substances as models for material design and manufacturing,"[37] biomimetics is more than simply copying nature. Instead, biomimetics involves the careful analysis of biological systems with the goal of understanding the underlying structure or process in order to provide inspiration for the design and manufacture of new and improved products. As a high risk/high payoff R&D effort, biomimetics is an evolving technology with the potential to make significant contributions to US economic security and national defense. A wide variety of research initiatives are currently underway in England, China, Japan, Finland, and Canada, as well as in the US. Examples include: 1) NASA's Morphing Wing Project;[38] 2) an environmentally friendly, allergy-free fiber for vehicle seats patterned after the light reflection capability of the Amazon butterfly;[39] and 3) a camouflage net that changes color in response to its environment inspired by observations of the cuttlefish.[40] These represent efforts to study animals in their natural environment and use mechanical and computing devices to mimic their biological reactions to environmental stimuli.[41]

Challenges and Outlook. In a society that increasingly seeks and expects instant gratification, maintaining interest in, and support of, long-term R&D efforts over the decades it may take to deliver a consumer product may be increasingly difficult. Currently, the lack of a quick return on investment has discouraged investment in biomimetic R&D efforts by the commercial sector. This has resulted in the government becoming the primary sponsor of biomimetic research, with a large portion of the funding going to universities, government labs, non-profit organizations, and private industry.[42]

While the multi-disciplinary groups of scientists involved in biomimetic research are learning a great deal and making significant progress, they often have difficulty communicating their findings to scientists in other fields.[43] The variability of biological systems can be a challenge to scientists used to working with fairly established "laws" and principles, like those found in a traditional field of inquiry such as physics.

Many of the ideas that make up biomimetic research have been present for years, but we are just beginning to implement the technology to make development possible. The emergence of breakthroughs in enabling technologies, such as sophisticated computer modeling, MEMS, and nanotechnology, has further aided biomimetic research. Continued progress in these enabling technologies is essential for the future success of biomimetics.

Nanotechnology and Nanoscale Materials

Overview and Current Condition. Nanotechnology is facilitated by broad interdisciplinary R&D initiatives, and has seen considerable worldwide growth. This emerging technology offers significant potential for transforming the ways in which materials and products are created.[44] With the ability to observe, measure, and manipulate matter on a nanoscale – i.e., 1 to 100 billionths of a meter[45] – nanotechnology presents unique opportunities to alter manufacturing and production processes, and is predicted to usher in a new technological revolution.[46]

Nanoscale R&D is rapidly expanding worldwide (principally in the US, Europe, Japan, and China) in an effort to exploit the infinite opportunities associated with nanoscience and technology. The nascent field of nanotechnology has evolved largely due to the confluence of three key technological streams:[47] 1) improved control of the size and manipulation of nanoscale building blocks; 2) improved characterization (e.g., spatial resolution and chemical sensitivity) of materials at the nanoscale; and 3) improved understanding of the relationships between nanostructure and properties and how these can be engineered. The nanotechnology industry is largely in the pre-product phase of the industry lifecycle, dominated by basic R&D, some applied research, and a limited degree of commercial applications (e.g., bulk materials, coatings, and sensors). Although nanotechnology is still in its infancy, the National Science Foundation estimates it will grow to a $1 trillion dollar worldwide industry within 10 to 15 years.[48] Nanotechnology could be one of the fastest growing industries in history, and a larger economic force than the combined effect of software, cosmetics, drugs, and automobiles.[49]

Challenges and Outlook. Nanotechnology demands teams of experts from multiple technical fields (e.g., physics, biology, chemistry, engineering, materials science, and information technology) working in concert to achieve both scientific discovery and rapid commercial advancement into the marketplace. Federal support of nanotechnology is essential, especially if the US is to maintain a competitive edge against global economic competitors. Additionally, the federal government should be an early adopter of nanotechnology innovations and sponsor global collaboration and dissemination of research results and best commercial practices. There is also a significant role for the government to lead efforts to promote and support the education and training of America's future nanotechnology researchers and innovators.

The synthesis and control of materials at the nanoscale will enable access to new material properties, functionalities, and device characteristics in unprecedented ways. Nanotechnology is predominantly an enabling technology, feeding or supporting many traditional technology fields and industry sectors such as the integrated circuit, chemical, and biotech industries, likely taking on the market structure of the specific industry sector it supports. However, nanotechnology may also been seen as a disruptive technology – redefining, reinventing, or replacing existing manufacturing processes and product lines. The cumulative effects of nanotechnology will significantly change the industrial, commercial, and national security landscapes.

Integrated Microsystems and Microelectromechanical Systems (MEMS)

Overview and Current Condition. MEMS are used in an approach to fabrication based on materials and processes from the microelectronics industry. They convey advantages of miniaturization and multiple components for design and construction of integrated microstructures and electromechanical systems. They are not a single technology, but rather an integration of a diverse family of complimentary technologies (e.g., MEMS usually contain a combination of sensors, actuators, mechanical structures, and electronics). As such, MEMS are an enabling technology that will bring improved benefits to society by increasing performance and functionality of larger systems in numerous industries including telecommunications, automotive, biotechnology, and consumer electronics. Although a fraction of the size, cost, and weight of the ultimate end item, MEMS are critical to a product's operation, performance, reliability, and affordability.

Despite the 2002 economic slowdown, MEMS industry growth continued an upward trend, with many markets embracing MEMS technology. Since 1980, 83 MEMS companies were established in the US, averaging startups of 10 new companies in each of the past three years. Consequently, employment has surged due to this growth in MEMS-focused corporations with MEMS companies employing thirty times more people in 2001 than in 1985, adding 2,100 jobs to the US work force.[50]

Challenges and Outlook. The principal challenge MEMS face is sufficient resources to conduct R&D that will lead to industry expansion and provide access to technology for a wide variety of commercial and DOD applications. In the current state of the industry, MEMS devices (usually specialized for niche markets) are produced in small numbers at high cost. As a result, MEMS devices remain limited to a small segment of the general market. For further commercialization, R&D is needed to develop the technical tools for design, manufacturing, testing, and packaging.

MEMS devices will bring transformational performance to both military and commercial arenas. According to the Defense Advanced Research Projects Agency (DARPA), MEMS-enabled weapons systems, ranging from competent munitions and sensor networks to high-maneuverability aircraft and Identification-Friend-or-Foe systems, will bring new levels of safety, situational awareness, precision strike capability, and weapons performance.[51] MEMS are essential components to achieving transformation objectives and sustaining a military competitive advantage. However, industry is reluctant to invest in R&D at the expense of near-term profits. The future beneficial potential that MEMS can bring to society will not be realized without government intervention to support R&D.

KNOWLEDGE MANAGEMENT

The organizations that this industry study group visited varied in size, ranging from large multi-national corporations and government laboratories with many employees to small organizations with few personnel. Based on our observations of these representative organizations, it appears that no "industry-wide" standard, or common approach to knowledge management (KM) implementation and utilization exists. Yet, while there is evidence of a general awareness of KM, its importance as an enabler, and its role in achieving strategic objectives, we observed a wide spectrum of KM processes and practices.

A common characteristic observed was that an organization's strategic objectives significantly influenced the extent to which KM practices were embraced. The organizations surveyed did not appear to have a holistic strategic mission, vision, or plan for managing and leveraging knowledge, information, or information technology. Rather, organizations appeared to exhibit segmented instances of knowledge sharing and programmatic information exchanges via the internet, e-mail, workshops, conferences, symposia, and journal publications.[52]

The use of an extensive variety of information technology, information management, and KM tools could empower a wide array of strategic materials stakeholders. The key to achieving the competitive edge that KM could provide lies in the realization of the benefits associated with nurturing a knowledge-centric environment and the recognition that KM is not about the technology, but rather the sharing of information and knowledge. Information technology is a critical enabler, but not an end in and of itself. Continued success in the strategic materials industry is dependent on collaborative efforts and the sharing of new and creative ideas to generate the innovation necessary to retain a competitive advantage.

MAJOR CHALLENGES FACING THE STRATEGIC MATERIALS INDUSTRY

The strategic materials industry has not yet reached maturity, appearing to be in the midst of a revolution. While the ability to manufacture basic materials, such as steel or aluminum, is becoming more specialized and efficient, the real excitement is how materials are being manipulated at the molecular level. Innovations in materials science technologies promise a broad range of possible uses that extend existing capabilities and functionality. While the future promise of strategic materials has been professed as virtually unlimited, the road ahead is not necessarily free of challenges. Major challenges facing the strategic materials industry represent a diverse spectrum of significant issues: 1) managing social and cultural impacts of technology; 2) expanding knowledge management efforts; 3) developing necessary human capital; 4) continuing research and development; 5) recapitalizing aging industrial and research infrastructure; 6) growing dependence on foreign supply of raw materials; 7) improving efforts to transition new technology from laboratories to production; and 8) overcoming manufacturing challenges of economically feasible production.

DEFENSE APPLICATIONS OF STRATEGIC MATERIALS

The US military is currently undergoing transformation. More than a force modernization effort, this transformation is a revolutionary overhaul of our military capabilities to meet the challenges of the 21st century. A foundation for these efforts is the application of innovative technologies to enhance capabilities.

Advances in strategic materials and their application to military use will provide stronger and lighter materials, smaller computer components, new sensor technologies and, together with micro electro mechanical systems (MEMS) technologies, many opportunities for miniaturization. Strategic materials have the potential to offer increased projectile velocities; stronger, lighter armor; precision-guidance systems for smaller munitions; and military robots of mini and micro sizes, including biological technical hybrids. Additionally, advances in nanotechnology may enable mass production of sophisticated expendable systems at lower costs.[53]

Survivability on the battlefield – enhanced by effective armor, speed, and mobility – is critical to mission success and personnel safety. However, there are trade-offs that complicate the matter. For example, adding armor to improve survivability conversely increases weight, reduces mobility, and increases detectability. The application of advanced strategic materials can enhance survivability through the use of new armor, which is lower in weight than contemporary armor materials, cost effective, and can defeat chemical-energy and kinetic energy threats. Additionally, rapid forward deployment of forces can be enhanced through the use of innovations such as composite airfield matting, which will facilitate the deployment of forces and overall airfield operations in remote locations.[54]

The military application of strategic materials is already revolutionizing warfare. Technological advances have enabled the US to enjoy a superior technological advantage. Recent breakthroughs in strategic materials and technologies further increase our advantage by improving the lethality, survivability, mobility, command and control, and logistics capabilities of our military forces. Continued R&D in strategic materials military applications will ensure our sustained military superiority and a competitive edge over current and future threats.

GOVERNMENT ROLES

While the future of strategic materials appears promising, the future contains numerous challenges that will require government intervention. The federal government provides support to the constituents of the strategic materials industry in a variety of ways. For the mature, commodity-type materials (e.g., aluminum, steel, and titanium), the appropriate government role is to advocate free trade and global open markets. For the newer materials technology, the federal government supports R&D through direct funding, grants, and other agreements. For the knowledge- and technology-based strategic materials sectors (e.g., nanotechnology, biomimetics, and composites), the government's role is that of continued funding of long-term, high-risk, interdisciplinary basic research and laboratory infrastructure development in government, academic, and private industry institutions.

In all realms, we suggest that the government has a key role to play in facilitating the conversion of science and technology to commercial products. Additionally, we believe that the government has an instrumental role in issues such as: 1) strengthening intellectual property rights; 2) increasing funding of research on social, legal, and ethical implications of strategic materials applications; and 3) improving math and science education for American students, particularly K through 12.

Findings from this industry study validate the need for maintaining federal research budget levels, developing strategies to retain existing talent, and to increase the numbers of students interested in becoming scientists and engineers. Scientific capacity is crucial for the technological advancements that support transformation and sustain a national security competitive advantage.

POLICY RECOMMENDATIONS

Recognizing the national importance of strategic materials also entails acknowledgment that the US is not alone in the quest to discover further breakthroughs and technological innovations. The US is competing with many countries seeking to capture commanding leads. We face the danger of falling behind unless we maintain, and possibly increase, our efforts. It is imperative to our future economic prosperity and to our national security that we maintain the technological advantage.

To address the variety of challenges facing the strategic materials industry, the following policy recommendations are offered: 1) fund long-term, high-risk, basic research and infrastructure recapitalization; 2) improve math and science education; 3) support outreach programs to increase public awareness and understanding of technological innovations; 4) increase funding of research on social, legal, and ethical implications of strategic materials technological advances and applications; 5) sponsor interdisciplinary research; 6) facilitate the conversion of science and technology to commercial products; 7) strengthen the protection of intellectual property rights; and 8) further promote free trade and open global markets.

SELECTED ESSAYS

Essay 1: *Convergence of Materials, Information Technology, and Biotechnology*

The growth of technology in the area of materials, information technology, and biotechnology is expected to accelerate in the next ten to fifteen years. A three-fold confluence of these technologies will act as a catalyst for even more impressive world economic revolution and growth, and are imperative for continued military transformation.[55]

Mihail Roco, nanotechnology advisor to the White House, predicts that because of nanotechnology, we will see more changes in the next 30 years than in the last century.[56] Nanotechnology, like the internet of the 1990s, is poised to be the catalyst in three areas, where it serves as the lens to focus interacting developments in materials, information technology, and biotechnology.

Materials. Materials technology is in the midst of a revolution, where innovative developments are driving advances in how products are manufactured. While the ability to manufacture basic materials such as steel or aluminum is becoming more specialized and efficient, the real story is how materials are being manipulated at the molecular level. This capability is setting the stage for production of stronger materials, microscopic machines and motors, and smaller, cheaper electronics that will further contribute to advances in information technology and biotechnology.

Information Technology. Nanotechnology, particularly in the area of nanofabrication, has the potential to surpass Moore's law by continuing the movement toward smaller and more powerful semiconductors that exceed the limits of silicon chips. The challenge is to exploit nanotechnology to permit the development and large-scale manufacture of nanocomputers. This requires the ability to link molecular-size electronic devices such as diodes and transistors to build desired processors. While researchers are hard at work attempting to develop methods to transition to nanoprocessors, medical researchers are investigating unbelievably small and powerful biomechanical and bioelectrical devices.

Biotechnology. The application of molecular level nanocircuits and nanomaterials has great potential in many areas. However, it will be particularly valuable in the area of biotechnology as we develop tools with a direct application to human health. Application of these tools could assist in earlier detection and treatment of disease by enhancing the ability to see, review, and interpret biological activity at the sub-cellular level. This includes contrast agents for imaging, sensors, and susceptibility testing such as DNA/RNA characteristics linked via nanoprocessors that speed data processing to isolate diseases and focus treatments. Further, materials and electronics technological advancements will lead to improved implants and replacement structures, ultimately developing materials that protect, insulate, and fix the human body at the molecular level.

The interacting trends and convergence of materials, information technology, and biotechnology will have a profound effect on the US economy, military transformation, and national security. Examples of capabilities on the horizon include composite material applications for better and stealthier tanks that are resistant to explosive projectiles; improved body armor; sensor-embedded clothing for soldier health and status monitoring; and an improved ability to treat and repair battle injuries.

Essay 2: *The National Nanotechnology Initiative (NNI)*

In recognition of nanotechnology's potential to revolutionize the way we live, as well as our nation's need to remain strongly competitive in an estimated $1 trillion[57] future market, the National Nanotechnology Initiative (NNI) was established in FY 2001. The focus of the NNI is to invest in fundamental research to further our understanding of nanoscale phenomena and accelerate the transfer of scientific discovery to innovative technology applications.[58] The initiative's investment strategy is designed around the following funding themes: 1) long-term fundamental nanoscience and engineering research; 2) grand challenges (i.e., research on major, long-term objectives); 3) centers and networks of excellence facilitated through interdisciplinary research, networking, and industry partnerships; 4) research infrastructure; and 5) ethical, legal and social implications, and workforce education and training.[59]

As the promise of nanotechnology has become increasingly more apparent, its budget has steadily increased. The President's Budget for 2004 provides $847 million for the NNI, which represents a 9.5 percent increase over 2003.[60] Nanotechnology R&D represents only 0.6 percent of total US Federal R&D spending and approximately 30 percent of worldwide nanotechnology investment.[61]

At present, thirty countries are actively engaged in nanotechnology R&D and total foreign government spending on nanotechnology has tripled in the last five years.[62] In 2002, Japan spent approximately $45 million more than the US. The European Nanobusiness Association stated in a recent report that European-wide spending on nanotechnology R&D would probably be twice that of the US in 2003.[63] It is difficult to compare the administration and quality of foreign nanotechnology R&D programs to that of the US, but it is clear that the sustained growth in funding means that the US is in stiff competition with those countries that devote more resources to nanotechnology research than we do. While the NNI has exceeded the expectations of many involved, there are challenges ahead if our nation is to remain at the forefront of this new technology. The principal challenges the initiative faces are funding and making the best use of limited resources.

Many countries have served notice, as evidenced by the creation of their own nanotechnology initiatives and higher spending levels, that they intend to take a strong competitive lead. The US risks losing its competitive advantage if it fails to keep pace with the spending levels of other countries in this technology race. Because the US was at the forefront of the information revolution, it was able to seize world dominance economically, politically, and militarily. As the information revolution gives way to the nanotechnology revolution, the opportunity for the US to retain or lose economic, political, and military dominance presents itself. It is obvious that capitalizing on a predicted future $1 trillion dollar global nanotech economy will be necessary to the nation's sustained economic growth. Less obvious may be the impact of foreign competition in nanotechnology to US political and military dominance. The CIA estimates that approximately one in four new technologies are likely to threaten US political, economic and military interests by 2015.[64] To assure its place as the world's sole superpower, the US government must make nanoscale R&D a much higher priority. Given the strategic importance of this technology, the NNI should be funded in proportion to its recognized potential value.

With finite resources, departments and agencies participating in the NNI must break down the stovepipes that separate them and share knowledge and resources. Only by leveraging participants' intellectual capital, facilities, and other resources in a well-coordinated effort can the NNI help transform the military and exploit commercialization ahead of the global competition. The directors of the initiative need to develop strategies that provide opportunities for departments and agencies to come together on a regular basis to share their knowledge.

The NNI has launched the US on a path that could contribute to its world leadership in nanoscale scientific research. Through the NNI, collaborative programs between federal, state, academic, industry, and foreign partners have been established. Participants have witnessed scientific breakthroughs and are making steady progress in achieving their objectives. However, as stated earlier, we are not alone in our quest to unlock the secrets of the nano-world. Many countries are also involved in the search. As other countries seek to capture commanding leads, we face the prospect of depending on foreign sources for nanotechnology, watching our economy erode as a technological revolution takes off on foreign shores, and possibly seeing the decline of our national security as other nations acquire technology superior to our own. It is therefore imperative to our future economic prosperity and national security that we prevent this from happening and thus ensure America's strong lead for generations to come.

Essay 3: *Societal Implications of Nanotechnology*

The term "nanotechnology" is becoming ubiquitous, with references to this emerging realm of science appearing in a wide variety of media outlets. The ability to observe, measure, and manipulate matter on a molecular level presents unique opportunities to alter manufacturing and production processes, possibly ushering in a new "industrial" revolution.[65] Based on its expected promise, it has been suggested that over the next 10 – 15 years, nanotechnology will fundamentally transform science, technology, and society.[66]

With a focus on the scale involved rather than a specific end product,[67] thus more of a "how" or a "where" than a "what," nanotechnology is envisioned as an enabler for a wide variety of advances in fields such as telecommunications, medicine, computers, and materials, affecting virtually all sectors of our economy.[68] Yet nanotechnology is opposed by many for the perceived societal, economic, and environmental dangers that it may present – so that "war cries that nanotechnology will unleash unforeseen evils on the Earth and mankind are beginning to match in volume the cheers that paint it as the world's savior."[69]

We are at the threshold of an era in which we may realize the hoped-for benefits of nanotechnology. However, if we are correct about nanotechnology's profound transformational effects, this simply underscores the criticality of recognizing that we cannot simply focus on its technical facets and economic opportunities. Rather, we will only realize the vision of a nano-enabled future if we take appropriate action to identify, examine, and address those social questions, issues, and challenges that accompany the introduction of such radically transformational technology.

Unquestionably, there are a plethora of issues, challenges, and opportunities that must be addressed in order to bring the hoped-for benefits of nanotechnology to fruition. As set forth by James Canton of the Institute for Global Futures, "the challenge before us [is to] build a framework that can nurture and [allow us to] experiment but that has the proper controls in place."[70] With this in mind, certain key fundamental social issues stand out as *linchpins* having the potential to minimize the disruptive effects and thus "make or break" the eventual acceptance of nanotechnology. The following represent three crucial areas of social significance, expected to play a decisive role in determining how the future of nanotechnology unfolds: public acceptance, regulation, and education.

Public Acceptance. The general public is the actual stakeholder in the successes and failures of nanotechnology.[71] Public fears and the opposition surrounding nuclear power and genetically modified foods have severely curtailed utilization of these technologies. This experience suggests that public perceptions could be a powerful force in determining the future of nanotechnology.

Regulation. As public concerns over the perceived consequences of nanotechnology increase, so does pressure for decisive government action, primarily in the form of regulation. Calls for regulation stress that further development be controlled, arguing that: 1) since nanotechnology is a relatively new area of scientific inquiry, we need to proceed with care and should err on the side of caution – e.g., we don't fully understand all the potential risks involved, nor their eventual impact on society, the environment, or the economy and 2) based on the experiences of technologies such as nuclear power and genetically modified foods – where public fears and opposition have curtailed utilization and development – regulation could provide a means to address and assure public concern while still enabling further development of technology (e.g., as has been achieved with recombinant DNA research and development).

Education. Education will play a key role as both a requirement for, and an enabler of, continued advances in nanotechnology. As a *requirement*, adequately educated and trained human resources are paramount for the US to compete in the high-tech global economy where nanotechnology is envisioned to play a significant role.[72] It is estimated there will be a global demand for approximately 2 million nanotechnology workers over the next 10 – 15 years,[73] and that 60 percent of all new jobs in the early 21st century would require skills that only 20 percent of the workforce currently possess.[74] Additionally, education as an *enabler* is key to an informed and aware public whose active participation contributes to the dialogue shaping the future of nanotechnology. The focus here is to ensure that the public's understanding of nanotechnology is formed on the basis of science fact, not science fiction, and to provide opportunities for ongoing dialogue among stakeholders.

While the promise of nanotechnology has been professed as virtually unlimited, challenges exist. Although still largely confined to the domain of speculation, the debate surrounding the promise and unintended consequences of nanotechnology has illuminated the extent to which its impact will be widely felt. This further illustrates the importance that its development must not be left to chance. Ultimately, our collective approach to nanotechnology, and how we adapt to its disruptive influences and unintended consequences, will determine the extent to which we maximize opportunities while minimizing risks. This discussion underscores that we cannot simply focus only on nanotechnology's technical facets and economic opportunities, but rather must take action to address the variety of concerns and challenges that accompany the introduction of a technology that has the potential to radically affect our lives.

THE FUTURE AND THE WAY AHEAD

Materials science technology is rapidly advancing as scientists and engineers continue to seek new and improved processes and product applications to provide previously unachievable capabilities. A convergence of breakthroughs in the areas of nanotechnology, biotechnology, information technology, and cognitive technology is rapidly leading to the ability to assemble new and unique materials at the molecular level. This, in turn, will lead to further advances in a wide variety of products from diverse sectors such as aerospace, automotive, biotechnology, communications, defense, information technology, and healthcare.

The future holds the promise of new materials technologies that will transform society. Futurists predict major scientific, materials-enabled breakthroughs including advances in such exotic areas as:[75] biointeractive materials, biofuel production plants, bionics, cognitronics, genotyping, combinatorial science, and quantum nucleonics. Future technology holds many promises for a society able to harness such innovations.

Historically, such dramatic technological advances usually result in a cultural lag in social adjustment. As researchers study and transition technologies to the commercial sector, societal implications and impacts will need to be assessed and managed. New social and ethical models will need to be developed to address the effects of new technologies. We will also need to be proactive in analyzing system dynamics, anticipating issues, and developing strategies that ensure the preservation of human values in a technologically advanced society.

CONCLUSION

Materials technology is in the midst of a revolution, where scientists are continuing to extend the bounds of knowledge, overcoming limitations previously imposed by conventional materials. These efforts are leading to breakthroughs that allow us to produce new materials with custom-designed properties to meet ever-increasing demands for improved functionality. Advances such as the ability to observe and manipulate materials at the molecular level will revolutionize the production of virtually every manufactured object and usher in a new technological revolution at least as significant as the silicon revolution of the last century.

The debate surrounding the promise, and unintended consequences, of materials science innovations illustrates the extent to which their impact will be widely felt. This shows the importance that such developments cannot be left to chance. Ultimately, our collective approach to how we develop and implement materials science innovations will determine the extent to which we are able to maximize opportunities while minimizing risks. We cannot simply focus on technical facets and economic opportunities, but must take action to address the variety of concerns and challenges that accompany the introduction of such technology that has the potential to radically affect our lives.

The future we will face will be unlike anything we have known before. Our challenge is to best predict future world conditions and prepare ourselves now to take full advantage of them. Continued advances in the materials sciences, along with the innovative application of strategic materials and technologies in the enhancement of all elements of national power, will continue to be revolutionary and transformational.

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