Materials and Society
From Research to Manufacturing

Report of a Workshop

Committee on Materials and Society: From Research to Manufacturing

National Materials Advisory Board
Solid State Sciences Committee of the Board on Physics and Astronomy
Board on Manufacturing and Engineering Design

Division on Engineering and Physical Sciences

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Preface

The Committee on Materials and Society: From Research to Manufacturing was appointed by the National Research Council (NRC) to convene a workshop in the spring of 2002. The purpose of the workshop was to bring together government policy makers, members of the materials research and manufacturing communities, and end users of materials to review, consider, and discuss the current state of materials science and engineering in the United States and the challenges in the coming years. This workshop was part of an ongoing series at the National Academies that have been convened approximately every 2 years by the Solid State Sciences Committee and the National Materials Advisory Board.

The Solid State Sciences Committee and the National Materials Advisory Board were joined in presenting the 2002 workshop by the NRC's Board on Manufacturing Engineering and Design and by the University Materials Council. The University Materials Council is composed of department heads, chairpersons, directors, and group leaders from academic programs in the materials field at U.S. and Canadian universities.

The agenda for the 2002 workshop was designed by the Committee on Materials and Society to address the role of materials against the backdrop of such pressing national concerns as the September 11 attacks on the United States, the escalating use of energy across the country, and rapid transitions in the materials science and engineering workforce and education strategies. The workshop highlighted such advances in materials research as optical sensors for biological weapons and improved surface treatments to improve engine efficiency in commercial vehicles. The future of materials science in such new industries as nanotechnology and biotechnology was also addressed.

Although the committee as a whole organized and approved the agenda for each session of the workshop, the session chairs (see the table below) were responsible for communication with and coordination of the speakers in their respective sessions. In addition, different committee members were appointed as rapporteurs for the individual sessions. The rapporteurs were responsible for taking notes and for summarizing the general themes presented during the session. They also took responsibility for choosing appropriate quotes and illustrated data from the speakers for this final report.

The agenda presented opportunities for participants to discuss their own issues and challenges as materials professionals, along with the issues raised by the workshop speakers, with invited congressional staff and leaders of government agencies that support materials research and development. These interactions resulted in much lively discussion, and the Committee on Materials and Society observed that many themes recurring during the course of the event.

In writing this report, the committee sought to summarize themes as reflected in the presentations and discussion during the workshop. The chapters in the report are intended to encapsulate the essential ideas presented during the workshop so as to give the reader an overall sense of the presentations, the panel discussions, and the attendant question-and-answer sessions. Only material presented at the workshop is presented in this report; other information, including more recent data, is not included.

The committee members responsible for each session are listed in the following table.

Session	Chair	Rapporteur(s)
Setting the Scene	Bob Pfahl and Henry Rack	Julia Phillips
Materials and National Security	Julia Phillips	Ashok Saxena
Materials in Commercial Vehicles	Harry Cook	Jay Lee
Materials in Energy Systems	Jay Lee	Frank Disalvo
Workforce and Education Issues	Ashok Saxena	Lee Magid
Congressional Staff Panel	Sylvia Johnson	Bob Pfahl and Henry Rack
Materials in Future Industries	Lee Magid	Sylvia Johnson
Government Agency Panel	Frank DiSalvo	Harry Cook and Joel Yudken

Acknowledgments

The Committee on Materials and Society: From Research to Manufacturing gratefully acknowledges the participants and exhibitors for their participation in this year's workshop. The committee would also like to acknowledge the following individuals, who prepared presentations for the event:

Rod Alferness, Lucent Technologies,
Duane Dimos, Sandia National Laboratories,
Dan Doughty, Sandia National Laboratories,
Mildred Dresselhaus, Massachusetts Institute of Technology,
Gregory Farrington, Lehigh University,
Sharon Glotzer, University of Michigan,
Andrew Hunt, Microcoating Technologies,
Fran Ligler, Naval Research Laboratory,
Lyle Malotky, Transportation Security Administration,
John Moran, Consultant,
Cherry Murray, Lucent Technologies,
Venkatesh Narayanamurti, Harvard University,
William P. Parks, Jr., Department of Energy,
Gary Rogers, FEV Engine Technology, Inc.,
John Stringer, Electric Power Research Institute,
Alan Taub, General Motors,
David Tirrell, California Institute of Technology,
Julia Weertman, Northwestern University,
R. Stanley Williams, Hewlett-Packard Laboratories, and
Wm. A. Wulf, National Academy of Engineering.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Peter R. Bridenbaugh, Alcoa (retired),
Sol M. Gruner, Cornell University,
Gary L. Messing, Pennsylvania State University,
Paul S. Peercy, University of Wisconsin,

Frank Stillinger, Princeton University, and
Kathleen Taylor, General Motors (retired).

Although these reviewers have provided many constructive comments and suggestions, they were not asked to endorse the report, nor did they see the final draft before its release. The review of this report was overseen by Maxine Savitz**,** Honeywell Corporation (retired). Appointed by the National Research Council, Dr. Savitz was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The workshop on Materials and Society: From Research to Manufacturing would not have been possible without the dedicated efforts of several members of the National Academies' staff, including Toni Maréchaux, Teri Thorowgood, Michael Moloney, and Emily Ann Meyer. Their tireless efforts are greatly appreciated. In addition, the committee thanks the Department of Defense, S&T Reliance Subarea for Materials and Processes, for its interest, support, and assistance throughout the project.

Sylvia M. Johnson
Chair
Committee on Materials and Society:
From Research to Manufacturing

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The Impact of Materials

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Wm. A. Wulf, National Academy of Engineering
Cherry Murray, Bell Labs, Lucent Technologies

Setting the Scene: Impact of Materials
Session Chair—Henry Rack, Clemson University

How Materials Contribute to Society, Venkatesh Narayanamurti, Harvard University
Drivers in Materials Research, Mildred Dresselhaus, Massachusetts Institute of Technology

PRESENTATIONS

> When historians look back at the latter half of the 1990s a decade or two hence, I suspect that they will conclude we are now living through a pivotal period in American economic history. New technologies that evolved from the cumulative innovations of the past half-century have now begun to bring about dramatic changes in the way goods and services are produced and in the way they are distributed to final users. While the process of innovation, of course, is never-ending, the development of the transistor after World War II appears in retrospect to have initiated a special wave of innovative synergies. It brought us the microprocessor, the computer, satellites, and the joining of laser and fiber-optic technologies. By the 1990s, these and a number of lesser but critical innovations had, in turn, fostered an enormous new capacity to capture, analyze, and disseminate information. It is the growing use of information technology throughout the economy that makes the current period unique.
>
> Alan Greenspan
> "Technology Innovation and Its Economic Impact"
> Address to the National Technology Forum, St. Louis, Missouri
> April 7, 2000

Materials research and development has been described as making fundamental contributions to many, if not most, of the innovations to which Mr. Greenspan refers in the above quotation. In much the same way as advances in materials enabled the development of transistors, materials scientists and engineers are working to address the new challenges faced by society now. Today, for example, our society is facing the new challenge of countering terrorism, and many discussants at the workshop believed science offers one of the most effective ways to combat that threat. Contributions from materials science and engineering will be key to this effort; they will, for example, play a role in innovative sensors, protective equipment, and hardened structures.

Many additional social needs continue to challenge scientists and engineers to seek innovative technological solutions, many of which will involve increasing the functionality of a material while maintaining or lowering its cost of manufacture. In many instances, the impact a new material can have is unpredictable. The modern interplay between fundamental research and applications contradicts the traditional view of a linear progression from discovery through development to commercialization. For example, the fractional quantum Hall effect, whose discoverer was awarded the 1998 Nobel Prize in physics, was discovered in experiments on semiconducting layers of unprecedented purity and structural perfection. These material developments were motivated not so much by the search for new physical phenomena but by the desire for high-performance electronic devices. While incorporating scientific advances into new products can sometimes take decades and follow unpredictable paths (as illustrated in Figure 1-1), progress can also bring unexpected bonuses such as the emergence of new properties of scientific interest.

The role of materials in the evolution of technology is exemplified in the story of the discovery and exploitation of the transistor. The transistor is often considered to be the base technology for the Information Age.[1] The ability of this single device to have such unique characteristics—and, as a result, such an overwhelming impact—was due in no small part to the very special materials properties of silicon and its oxide. The Bell Telephone Laboratories were central to the development of these silicon-wafer materials and of transistor devices. However, over the past two decades, since the breakup of AT&T and subsequent deregulation of the telecommunications industry, research facilities such as Bell Labs have changed their fundamental focus to a much more short-term, market-driven outlook. This transition raises the question of how and where the next new technology will emerge to enable the next generation of discovery.

Another interesting example of an enabling technology is the quantum corral. This advance, which consists of atoms individually positioned on a surface and promises to allow the manipulation of individual electrons, could pave the way for rapid developments in nanotechnology, but little development has yet occurred. Such technologies may be slow to reach commercial application because industrial research capabilities are increasingly focusing on short-term needs.

Nonetheless, just as past materials discoveries led to mature industries like semiconductors and magnetics, exciting new areas are emerging. Some of the most promising opportunities are at the intersection of traditional research fields such as materials science and biology. The opportunities include such groundbreaking developments as bioactive medical devices and microbes for mineral processing.

[11]Alan Taub, GM Research and Development, presentation at the workshop. Available at <http://www7.nationalacademies.org/nmab/Alan%20Taub.pdf>. Slide 6. January 2003.

In some cases, the search for dramatic advances is motivated by the impending physical limits of some critical technologies. For example, both new materials and the new architectures enabled by those materials will be needed to accommodate the rapidly increasing demand for high-capacity data storage. Several new materials and tools were identified in presentations at the workshop that may facilitate impressive technology gains like those we have come to expect.

Speakers at the workshop also noted that the erosion of industry support in basic materials science research might delay the potential contributions of new developments. Increased foreign government and industry support can also potentially mitigate the impact of delayed U.S. contributions.

Ultimately, society and economics will demand certain characteristics from materials of the future. The industrial sector frequently uses the words stronger, lighter, and cheaper to characterize new development. Several speakers at the workshop identified demands for new technology in national security, energy security, and environmental quality. These new technologies, will, in turn, demand new materials.

Several presentations at the workshop emphasized the increasingly interdisciplinary nature of materials science and engineering and the growing diversity of expertise on the part of those who participate in materials research. In spite of the tremendous opportunities, the field faces a shortage of talented, well-trained scientists and engineers. Participants in the discussion also noted the dramatic decrease in recent years in the percentage of U.S. citizens pursuing degrees in the physical sciences and engineering. Several felt that if this problem is not addressed, the United States will not retain its global leadership position in materials science and engineering or in the economically important industries that flow from the field.

Comments from the Speakers

"The 'dot.com bust' of the last year demonstrates eloquently that we do not live in a virtual world, and that everything is made of something."

—Venkatesh Narayanamurty, Harvard University

"Magnetic storage is now cheaper than paper storage, and more advances are coming. All these technologies are based on improvements in materials science."

—Cherry Murray, Lucent Technologies

"Today's students will develop such exciting new materials as carbon nanotubes and materials systems that self-assemble."

—Mildred Dresselhaus, Massachusetts Institute of Technology

"While the United States develops a research and development agenda for counter-terrorism, scientists and engineers from the Academies will provide a valuable contribution."

—Wm. A. Wulf, National Academy of Engineering

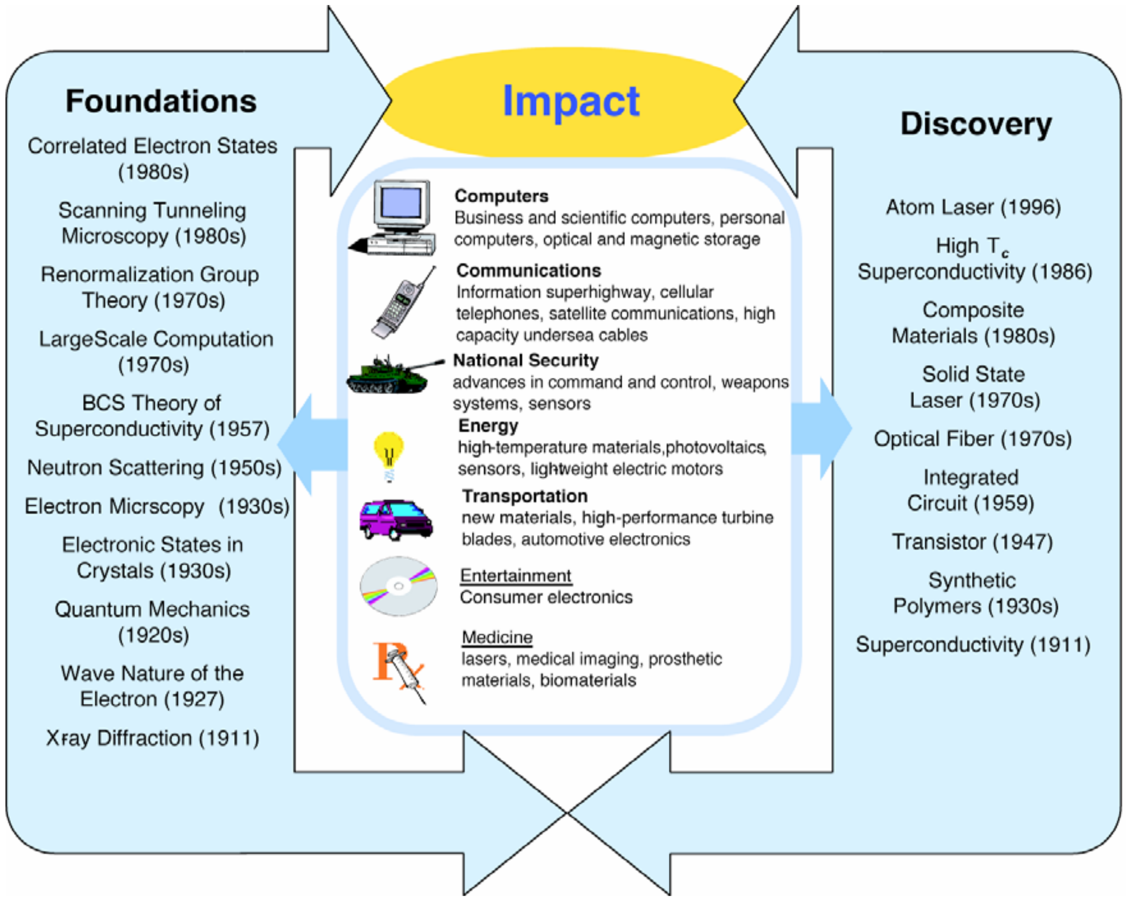

FIGURE 1-1 Impact of materials on society. The incorporation of major scientific advances into new products can take decades and often follows unpredictable paths. Supported by the basic scientific foundations of condensed-matter and materials physics, the discoveries shown in this figure have enabled breakthrough technologies in virtually every sector of the national economy. The two-way interplay between these discoveries and scientific foundations has proved to be a powerful driving force in this field. The most recent fundamental advances leading to new foundations and discoveries have yet to realize their potential. SOURCE: NRC, 1997. The Physics of Materials, p. 29, Washington, D.C.: National Academies Press.

2

The Role of Materials in Critical Infrastructure

The stability of the nation's critical infrastructures and its economic health rely in many ways on an improved understanding of the behavior of materials and on the development of new processing and products. For example, some of society's most pressing needs for new technology are in the areas of energy systems and national security, especially in the wake of September 11, 2001. New materials also play a continuing and important role in enabling advances in the manufacturing sector, especially commercial vehicle production, which is a key part of the nation's economic infrastructure.

MATERIALS IN NATIONAL SECURITY

Session Chair—Julia Phillips, Sandia National Laboratories

Materials Issues in Microsystems for National Security, Duane Dimos, Sandia National Laboratories
Advanced Sensors for Counterterrorism, Frances Ligler, Naval Research Laboratory
Transportation Infrastructure and Security, Lyle Malotky, Transportation Security Administration

The national security environment is complex and full of difficult challenges for materials scientists. In all of the key tasks involved in national security, i.e., surveillance and assessment, protection of assets and infrastructure, and the use of weapons for defending and defeating, materials science and engineering play an important role.

As an example, improved surveillance and threat assessment, a national need certainly made more urgent by the events of September 11, 2001, will require development of the key microchemical analytical systems that are at the heart of handheld components with multifunctional capability. The development path for such a system is shown in Figure 2-1. The materials that emerge when such systems are developing will have roles in communications, chemical and biological warfare sensors, and other surveillance equipment. The primary materials advances relevant to this technology are miniaturized optics and fluidics. The materials must be inexpensive and rugged, which suggests polymeric materials may be promising. However, given that very few currently available plastics are suitable for optical devices, improvements—specifically in optical properties and ease of processing—are key to their application for biowarfare detection. Another possibility is the development of biological materials that exhibit a specific response to a biochemical; this is a growing field of research.

In only the past few years, users' needs and perceptions about detection devices in security applications have changed considerably. Among the new requirements for these systems are full automation, simplicity of use in the field, minimal logistical burden, absence of false positives, proper sensitivity for rapid screening, appropriate size and weight, and sustainability. All of these requirements present substantial challenges for materials engineers.

In the area of aviation security, the goal is to prevent an explosive material from getting on board an airplane or, failing that, to minimize the damage caused by an explosion. The latter goal calls for more impact-resistant aircraft and toughened containers for cargo on the aircraft and requires the development of hard, lightweight materials. A key challenge is to reduce cost while maintaining robustness.

In the area of building security, an emerging priority is the development of materials and structures with improved fire resistance as well as structural materials and window glass that are not only fracture-resistant but that shatter into dust-sized particles on breaking. Advances by the materials community in these areas will be an important part of the overall protection strategy.

Finally, weapons for defending against and defeating an enemy will require lightweight structural materials and miniaturized electronics for such applications as unmanned vehicles and aircraft. Another need is for very hard materials that are also lightweight; such materials are needed for use as earth and rock penetrators to breach targets that may be buried or protected with materials that are hard to penetrate.

Some issues cut across all of these applications. The ability to predict the reliability of materials' properties is becoming a science in its own right. Surety is important, for example, in the case of weapons in long-term storage or when nanostructured materials are used in a building expected to have a lifetime of many years.

One impediment to fostering within the private sector the kind of innovation discussed here might be the very practical issue of development costs, which can be high for new innovative materials solutions. Another might be the low number of units manufactured for security applications. A small manufacturing contract may not be of sufficient interest to a large company, and small companies may not be able to produce the quality and quantity needed for such high-precision components. One solution is finding dual-use technologies and exploring the possibilities for contract manufacturing. Finding an appropriate manufacturer that can fit the product into its mix can mean spin-off benefits for both military and commercial uses and can bring the cost of development down. One example of this would be applying the technology used for an implantable glucose monitor to the manufacture of a handheld device for monitoring levels of biological agents.

Comments from the Speakers

"Materials science plays an integral role in every step of the national security scene."
—Duane Dimos, Sandia National Laboratories

"Materials advances will drive advances in biowarfare detection."
—Frances Ligler, Naval Research Laboratory

"Bulk explosives detection approaches need better sensors and must take full advantage of available computer technologies."
—Lyle Malotky, Transportation Security Administration

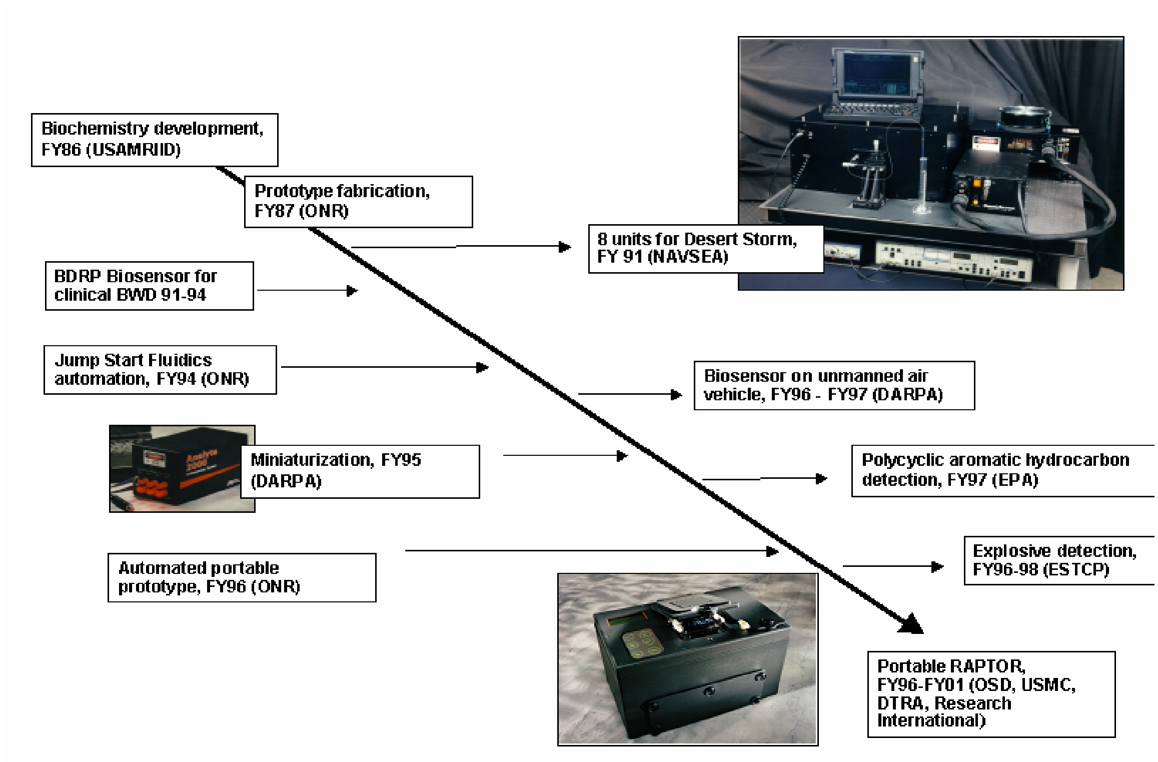

FIGURE 2-1 Steps in the research, development, and commercialization of a sensor system for biological weapons. Research leading to the product is shown on the left; products are shown on the right. This schematic demonstrates how many different agencies and laboratories must cooperate to implement a new technology in the field. These organizations include the Biological Defense Research Program (BDRP) of the Naval Medical Research Institute (NMRI); the Defense Advanced Research Projects Agency (DARPA); the Defense Threat Reduction Agency (DTRA); the Environmental Protection Agency (EPA); the Environmental Security Technology Certification Program (ESTCP); the Naval Sea Systems Command (NAVSEA); the Office of Naval Research (ONR); the Office of the Secretary of Defense (OSD); the U.S. Army Medical Research Institute of Infectious Diseases (USAMRIID); and the U.S. Marine Corps. SOURCE: Frances Ligler, Naval Research Laboratory.

MATERIALS IN COMMERCIAL VEHICLES

Session Chair—Harry Cook, University of Illinois

Energy/Fuel Efficiency in Commercial Vehicles, Gary Rogers, FEV Engine Technology, Inc.
Materials in Commercial Autos and Trucks, Alan Taub, General Motors

Since 1974, General Motors has improved vehicle fuel efficiency 132 percent for passenger vehicles and 75 percent for trucks.[1] Better lightweight and functional materials offer further opportunities for improvements by enabling more efficient vehicle propulsion and reductions in vehicle weight.

Developments in lightweight structural materials—including high-strength steels, composite materials, aluminum and magnesium alloys, and tire materials—have led to a reduction in vehicle weight. These materials contribute to lightweight components in the body, chassis, and powertrain of today's vehicles. A few of them are identified in Figure 2-2.

Functional materials can be found throughout an entire automobile. They are used, for example, in fuels and lubricants and catalysts and particulate traps, which lead to increased efficiencies in internal combustion engines and in aftertreatment exhaust systems. They are also used in batteries, fuel cells, and hydrogen systems for energy storage and conversion; in sensors, actuators, and microelectromechanical systems (MEMS) devices for automotive electronics; and in optical components, coatings, and structural materials.

Simulation tools can help optimize materials properties such as stiffness, strength, and design thickness, thereby helping to improve the structural integrity of a vehicle. Novel and hybrid material structures could be fabricated by low-cost and robust processes. For example, modeling has enabled thinner castings using the lost foam process; these thinner castings reduce the weight of an engine block dramatically. The fabrication process uses patterns made from expanded polystyrene in a cavityless mold. The foam pattern is replaced by molten metal to produce the casting. Another modeling success is hydroformed frames that can double their torsional rigidity, resulting in a potential 15 percent weight savings as well as improved safety and ride quality. Hydroforming uses water pressure to efficiently and effectively force sheet metal into a die to produce complex shapes.

Aluminum is still an important vehicle component, and magnesium is beginning to be used. Replacing a stamped part with a casting can enable part consolidation and can facilitate assembly. The use of reinforced reaction-injection-molded snap-on outer panels has also reduced the weight of vehicles. Other advances include aluminum alloy pistons; thin-wall, cast-iron exhaust manifolds; thinner glass windshields and backlights; and titanium exhaust systems.

Future improvements may include using nanocomposites to achieve much lighter weight and functional benefits such as thermal insulation or integrated sensors. For example, it is predicted that nanocomposite thermoplastic olefin parts will be more than 20 percent lighter.[2]

In engine technology, reductions in weight and friction have resulted in substantial fuel consumption savings over the last decade. Analysis shows that in the next 10 years, a further fuel consumption saving of approximately 10 to 15 percent could be achieved with these technologies.[3]

The further reduction of friction has the largest potential for improving today's engines. Reduced friction in drive trains, pistons, and bearings can be achieved, for example, by reducing the weight of dynamic components. Engineers can also use smart materials that change their properties in response to engine temperature or speed.

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[2]Alan Taub, GM Research and Development, presentation at the workshop. Available at <http://www7.nationalacademies.org/nmab/Alan%20Taub.pdf>. Slide 26. January 2003.

[3]Gary Rogers, FEV Engine Technologies, presentation at the workshop. Available at <http://www7.nationalacademies.org/nmab/Gary%20Rogers.pdf>. Slide 17. January 2003.

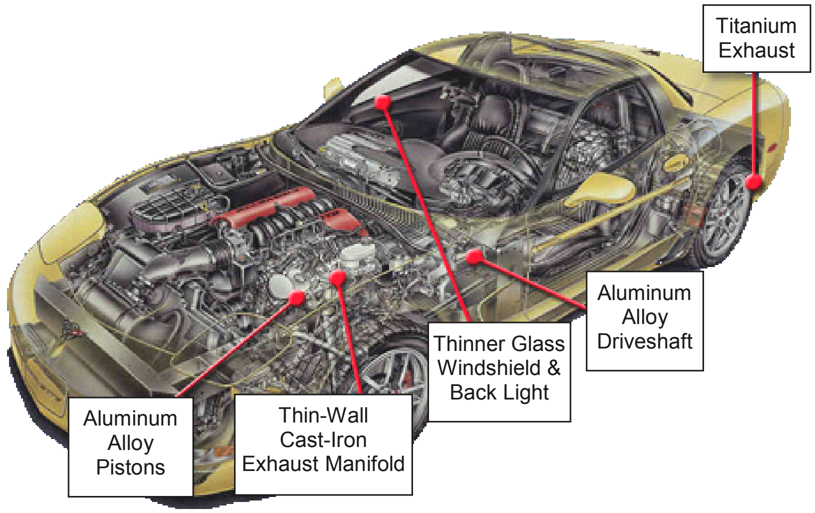

FIGURE 2-2 Some advanced materials applications in the automotive industry. SOURCE: Alan Taub, GM Research and

In the development of both hybrid electric and fuel cell power systems, overcoming the materials problems is critical. Challenges for fuel cell performance include electrode catalyst formulations for higher reaction rates and lower costs and polymer electrolyte membrane materials for proton conduction in fuel cells. In addition, stable dielectric coolants are needed, as well as low-temperature catalyst formulations for fuel processors and low-cost, high-temperature heat exchangers.

Comments from the Speakers

"Whenever cost can be reduced, that's important."
—Gary Rogers, FEV Engine Technologies

"The automotive industry is both a mature industry and a growth industry."
—Alan Taub, General Motors Corporation

MATERIALS IN ENERGY SYSTEMS

Session Chair—Jay Lee, University of Wisconsin at Milwaukee

Conventional Power Generation Technology, John Stringer, Electric Power Research Institute
Alternative Energy Technologies, William P. Parks, Jr., Department of Energy
Portable Power, Daniel Doughty, Sandia National Laboratories

The world's civilization and economy are dependent upon the secure and reliable production, distribution, and consumption of energy in forms practicable for both industrial and private use. Throughout the world, energy consumption continues to rise, as illustrated in Figure 2-3. Today the average annual per capita consumption of electrical power is near 2,100 kilowatt-hours. By 2050, it is expected to exceed 6,000

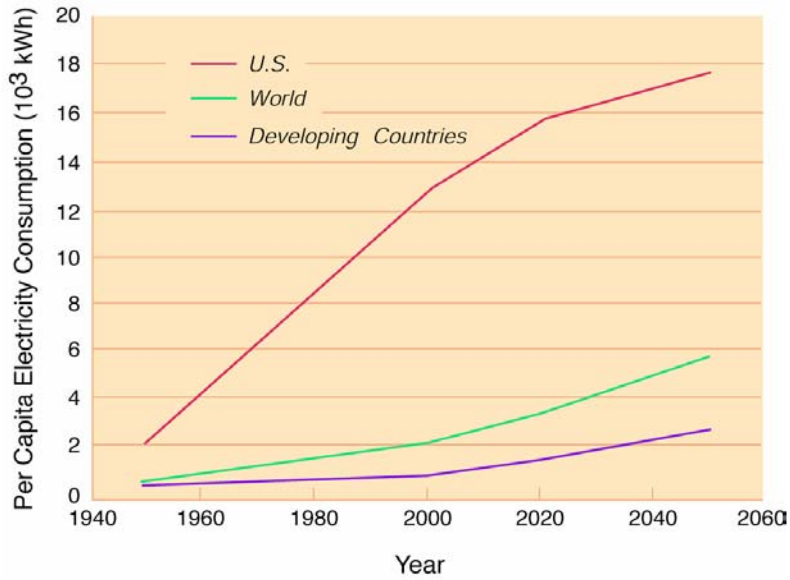

FIGURE 2-3 Worldwide per capita electricity consumption, 1950-2050.
SOURCE: John Stringer, Electric Power Research Institute.

kilowatt-hours per person.[4] Currently, coal-fired plants account for 50 percent of U.S. electrical production.[5]

The scientific and technological response to the forecasted needs must include increased efficiency in the generation and use of energy. It must also embrace the development of new, large-scale energy sources, including new fuels and new generation schemes. The current energy economy is largely based on fossil fuels, but continued long-term reliance on these sources poses environmental concerns and is increasingly sensitive to geopolitical events.

The environmental concerns include carbon dioxide generation and thermal and material by-products or waste (such as mercury or radioactive components in coal-fired plants). They cannot be entirely eliminated but, at some economic and political cost, can be reduced. One barrier to developing more efficient, less polluting energy resources is the lack of materials that enable the specific advance or technology.

Important power sources for the future are likely to include biopower, hydrogen, wind, geothermal, solar, and hydropower. The technologies to efficiently and cost effectively generate and distribute the energy from these sources require advances in the properties of the relevant materials and their application. For example, superconducting materials can virtually eliminate transmission losses but are still not sufficiently mature for widespread application. Distributed-generation technologies such as small gas turbines, Stirling engines, or fuel cell systems must be become easier and cheaper to manufacture in order to outweigh the economies of scale larger generation systems enjoy.

The economically important field of portable power includes applications such as batteries for internal power storage and fuel cells for external storage. While the ranges and sizes of power needed in these systems dictate the potential solutions, performance is dictated by material composition. The properties of anodes, cathodes, and electrolytes,

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[4] John Stringer, Electric Power Research Institute, presentation to the workshop. Available at <http://www7.nationalacademies.org/nmab/John%20Stringer.pdf>. Slide 4. January 2003.
[5] John Stringer, Electric Power Research Institute, presentation to the workshop. Available at <http://www7.nationalacademies.org/nmab/John%20Stringer.pdf>. Slide 5. January 2003.

for example, determine the voltage and capacity of batteries and fuel cells, and the power produced depends on the resistance. Most materials advances in portable power today are in the field of electrolytes and electrocatalysts.

The need for new materials solutions is also relevant to current generation systems. For example, the efficiency of energy generation increases as the temperature of the process increases. However, the operational temperature limits are set by the availability of materials and by their economic and environmental processing costs.

Lighter weight materials are needed for windmill blades, and advanced and affordable semiconductor materials are needed for photovoltaic and thermovoltaic generators. Progress is also being made in developing other power-related materials with applications in a variety of systems, including high-heat-tolerant electrical transmission cables, energy storage systems, motors, efficient hydrogen storage systems, and improved catalysts for efficient chemical transformations.

The ultimate source of energy for our society is the Sun. Converting the Sun's energy that reaches our planet into electrical and chemical energy has frequently been proposed as the only long-term solution to world energy needs. It is unlikely that we can meet the energy needs of the near future, let alone attain the ultimate goal of reliance on solar techniques, without many of the above-mentioned materials advances.

Comments from the Speakers

"Rising energy consumption coupled with a growing world population and increased awareness of environmental issues poses significant challenges to economic and political systems both domestically and internationally."

—John Stringer, Electric Power Research Institute

"Materials dictate the performance of the power source, and the ranges of power dictate potential solutions. "

—Dan Doughty, Sandia National Laboratories

"Power is not only technologies, but also includes the fuels, the generation, the delivery, the storage, the end-use, and all the policies, regulations, and international issues that surround them."

—Bill Parks, Department of Energy

3

The Role of Materials in Future Industries

Session Chair—Lee Magid, University of Tennessee, Knoxville

Nanomaterials, Julia Weertman, Northwestern University
Biomaterials, David Tirrell, California Institute of Technology
Optical Materials, Rod Alferness, Lucent Technologies
Computational Materials Science, Sharon Glotzer, University of Michigan

Progress in industry and manufacturing and the nation's economic health rely on the continual discovery, development, and use of new materials for new products. Some of today's most exciting and groundbreaking science is focused on nanomaterials, biomaterials, and materials for optical communications. As in all areas of cutting-edge research, computation is playing an increasingly central role in the development and understanding of materials systems.

NANOMATERIALS

Nanomaterials are a relatively newly recognized class of materials. They were defined in this workshop as any material having at least one dimension less than 100 nanometers. While some naturally nanostructured materials are in use in commercial applications, artificially manufactured nanomaterials have demonstrated some particularly interesting and promising properties. Some examples of nanomaterial structures are shown in Figure 3-1.

Nanolayer materials, such as those composed of thin layers of copper and nickel, can be much stronger and harder than either of the two components alone. This strengthening results from the disruption of some of the stress relief mechanisms in the crystalline structure. Layered materials can also exhibit a high resistance to corrosion, and there is evidence that the use of nanolayers can improve the fatigue life of components. Nanolayered semiconductor materials are being used to produce efficient electronic and optoelectronic devices such as diode lasers.

Nanoparticle materials are attractive for nanoabrasive polishing, for highly targeted drug delivery, and even for cosmetics such as sun block. Nanohole materials find application as molecular sieves and nanograined materials, i.e., small-grain-size, three-dimensional materials that exhibit significant increases in strength.

Nanotube materials consist of sheets of carbon atoms seamlessly wrapped in cylinders only a few nanometers in diameter but up to a millimeter long. The number of both specialized and large-scale applications of nanotubes is growing constantly. Their properties can be controlled by changing the orientation of the carbon sheet. Nanotubes can be made to be semiconducting or conducting and have been used to strengthen polymers. They can also be used as tips or probes for microscopy.

Nanomaterials show great promise in new applications and new manufacturing processes, but many problems and challenges remain. The development and application of nanomaterials will need techniques to produce powders of high quality in sufficient quantities and at a low enough cost to improve the low fracture toughness and poor ductility of three-dimensional materials, to address the difficulty of assembling nanocomponents, and to improve the thermal stability of nanostructures.

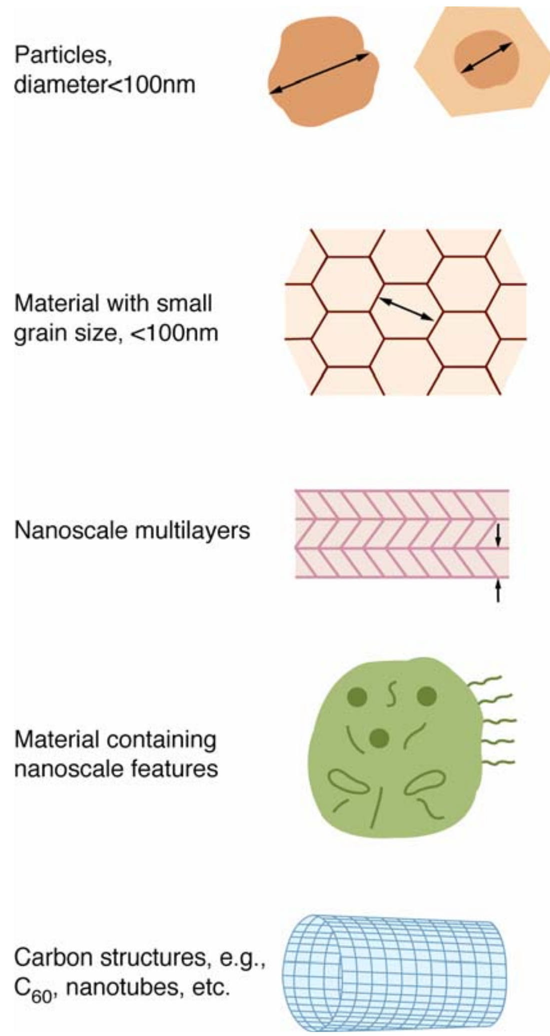

FIGURE 3-1 Examples of some basic nanomaterial structures. SOURCE: Julia Weertman, Northwestern University.

BIOMATERIALS

Biomaterials include, among many things, the medical implants carried by millions of Americans. Some biomaterials are made from components whose usefulness has been discovered by serendipity. An example is polymethyl methacrylate, or superglue, which is used in intraocular lenses. Another is shape-memory alloys, once a curiosity but now used to keep aortal stents round. The potential for newly engineered materials to solve many of the challenges for new implanted devices is enormous.

Drug delivery systems have great commercial and societal impact. Traditional internal drug delivery methods use polymeric materials that dissolve or diffuse the drugs. One new approach is the use of microneedles, currently made from silicon, that can inject drugs painlessly. Another approach is the "pharmacy on a chip," where conventional lithography makes many reservoirs on a chip and electrical impulses selectively rupture a membrane and deliver the required dose of the chosen drug.

Materials for implementing the array technologies needed for genomic and proteomic studies present new challenges. Making arrays of genes is relatively straightforward, because all genes have very similar chemistries. However, forming protein arrays is much more difficult, because proteins vary so widely. Moreover, simple polymer substrates cannot provide the amount of information required. New materials with new surface properties are needed.

Microfluidic devices can move fluids through a maze of microscopic channels and chambers that have been fabricated with the same lithographic techniques used today for microelectronics production. They can be used, for instance, to separate cells, and they can have input channels as small as 10 micrometers. Although microfluidic devices are cost competitive with conventional cell sorters, materials challenges still limit the speed and capacity of the microfluidic approach.

The assembly of hybrid organic and inorganic materials exploits the ability of a small amount of organic material to organize the inorganic component of a hybrid material. An exciting example of an application for this type of structure is the use of peptides to distinguish gallium arsenide from silicon and silicate.

MATERIALS FOR OPTICAL COMMUNICATIONS

Materials advances have enabled some of the great leaps in electronic switching and communication over the past 30 years, as shown in Figure 3-2. In order to continue this daunting trend, today's devices are moving steadily toward materials that use optical characteristics to increase their functionality.

Optical materials that are already being implemented in communication systems include erbium-doped fibers that permit optical signals to be amplified without the use of electronics. Implementation of this technology can lead to increases in capacity by a factor of close to 1,000 when combined with wavelength-dispersive multiplexing, which uses up to 80 or so multiple wavelengths, with each wavelength carrying a separate communications channel. The resultant increase in power can mean that signal boosters are needed only every 50 miles, allowing telephone calls and e-mails to be transmitted optically across oceans or continents without going through an electronic system.

These and other innovative fiber materials are being used today. However, over long distances, intrinsic fiber material nonlinearities fundamentally limit the system performance. New materials and approaches to overcome these limitations and provide linearity include photonic band gap materials and "holey" fibers. Fabrication of holey fibers—fibers designed with tiny holes along their length—is difficult, but the payoff of being able to engineer the fiber properties is considerable.

New systems are increasingly needed for routing the communications along these high-capacity networks. These systems now resemble highways with complex interchanges where signals are split and rerouted toward their final destination. One enabling technology is MEMS, which can make such high-capacity switches with very low losses and switching densities unmatched by electronic switches. The arrays of mirrors can easily be scaled up, and switch times of milliseconds, while slow, are sufficient.

Optical signal devices hold great promise for replacing electronic switching devices. Optical-controlled switching will require a nonlinear gate material, a materials technology that remains immature. Because optical-optical nonlinear interactions are weak, such devices use proportionally more power. Advances in gate materials will be needed to increase their efficiency.

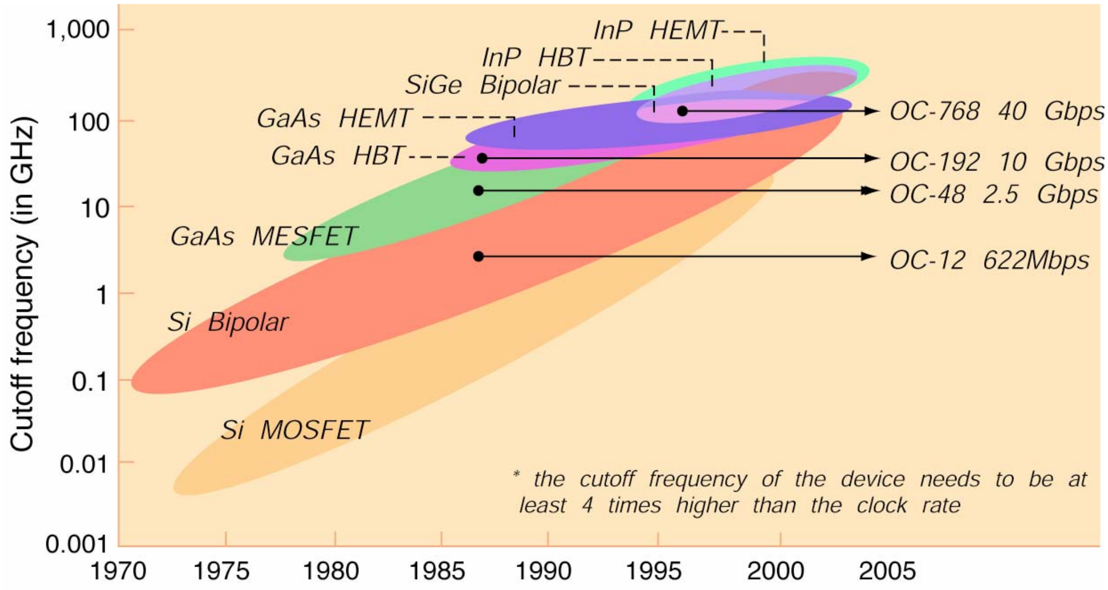

FIGURE 3-2 Technology roadmap for lightwave electronics, showing the data rate capabilities enabled over the past 30 years. The materials used for electronics have ranged from silicon to gallium arsenide to indium phosphide. The devices these materials are used in are also many: They include bipolar transistors, metal oxide semiconductor field-effect transistors (MOSFETs), metal electron semiconductor field-effect transistors (MESFETs), heterojunction bipolar transistors (HBTs), and high-electron-mobility transistors (HEMTs). The transmission characteristics these materials have enabled in optical carriers (OCs) have improved from less than 500 million bits per second (Mbps) to over 40 billion bits per second (Gbps). SOURCE: Cherry Murray, Lucent Technologies.

COMPUTATIONAL MATERIALS SCIENCE

Computational approaches have made tremendous progress at all length scales relevant to materials. These include the macroscale (human dimensions), the microscale (atomic dimensions), and the mesoscale, which bridges the two regimes.

At the macroscale, researchers have long used such traditional methods as finite element analysis to predict mechanical and other properties of materials. These methods are now being coupled with image processing approaches to impart additional physical detail to the models.

At the smallest scales, quantum mechanical ab initio (or electronic structure) calculations have predicted optical spectra in nanoscopic quantum dots. These models also predict the great mechanical strength of carbon nanotubes. Despite the excitement surrounding new materials, the simulation capabilities of these relatively new methods are currently limited to small calculations, typically for less than a thousand atoms. Improved algorithms and computer speeds will be needed to model larger systems.

Bridging the considerable gap between quantum mechanical simulations of small collections of atoms and macroscale calculations of materials properties are the molecular and mesoscale simulation methods. These may include tens of thousands to a billion atoms simulated using particle-based or field-based methods. Such methods can provide insight into materials phenomena on the scale of several nanometers to several hundreds of microns, and on time scales from picoseconds to seconds or even hours, depending on the material or process modeled. Dendritic growth during solidification and polymer phase separation, for example, is often modeled with these methods.

A goal for computational materials science is to play the same role in materials as molecular modeling does in the pharmaceutical industry. Challenges to reaching this goal include developing approaches to seamlessly integrate multiscale simulation methods and techniques to handle large quantities of data, training researchers, and sustaining the multidisciplinary infrastructure needed to attack and solve the problems.

In general, the development of reliable mesoscale theory and methods will aid the better understanding and development of complex materials such as self-assembled nanotubes and quantum dots, bioinspired and biological materials, and nanoengineered materials designed molecule by molecule.

Over the next decade, the use of computational methods to design, discover, and optimize nanomaterials, biomaterials, and optical materials will become increasingly prevalent. One workshop participant cited the view that the United States economy was built on materials: steel, aluminum, glass, cast iron, and plastics. Although these industries are still responsible for much of our growth, the new materials that are the subject of this report will play an increasingly important role.

Comments from the Speakers

"Computational approaches to simulate materials and anticipate behavior enable a modern approach to materials design, discovery, and optimization."

—Sharon Glotzer, University of Michigan

"The enormous advances in optical communication systems over the past 5 years are largely due to materials advances on many fronts."

—Rod Alferness, Lucent Technologies

"Nanomaterials are an exciting but very disparate class of materials which come in an ever increasing array of forms with a wide variety of applications."

—Julia Weertman, Northwestern University

"Biomaterials encompass the traditional bioengineering of medical implants to newer areas of drug delivery, tissue engineering, materials for array technologies, microfluidics, and hybrid materials."

—David Tirrell, California Institute of Technology

4

Perspectives

WORKFORCE AND EDUCATION PERSPECTIVES

Session Chair—Ashok Saxena, Georgia Institute of Technology

Large Industry Perspective, R. Stanley Williams, Hewlett-Packard Laboratories
Small Business Perspective, Andrew Hunt, Microcoating Technologies
Educating a New Workforce, Gregory Farrington, Lehigh University
Training Our Current Workforce, John Moran, Consultant

A growing obstacle reported by many U.S. industries is finding qualified scientists and engineers to fulfill their research and development needs and maintain the U.S. lead as a technology innovator. In 1998, this outcry resulted in the expansion of a visa program to allow almost 200,000 foreign specialty workers per year to temporarily enter the United States and work here for up to 6 years.

In 2000, the 5.3 million high-tech workers represented 10.6 percent of the manufacturing workforce. More importantly, these workers were responsible for 50 percent of the acceleration in the growth of productivity during the 1990s.[1] At the beginning of the 21st century, when the United States is poised for a new industrial revolution driven by innovations such as nanotechnology, significant impediments—specifically, the scarcity of a workforce—remain to realizing this opportunity.

To fully exploit the potential of the latest technological and scientific innovations, many see the need for an investment to be made in the coming years similar to the federal investments of the 1960s, which drove the age of microelectronics and provided the infrastructure for new industries. However, the trends in federal research support by discipline FY1970 to 2002 show funding in mathematics and physical sciences flat or declining, while funding in biological sciences has increased.[2]

Since 1986, the number of B.Sc. degrees awarded has decreased by 21 percent in engineering, 19 percent in math, and 12.6 percent in the physical sciences, while increasing 55 percent (as of 1996) in the biological sciences. This is shown in Figure 4-1. One workshop speaker observed that students seem to follow federal research support, yet this same participant speculated that there is significant evidence that the job

[1]S. Williams, Hewlett-Packard Laboratories, presentation at thie workshop. Available at <http://www7.nationalacademies.org/nmab/Stan%20Williams.pdf>. Slide 5. January 2003.
[2]S. Williams, Hewlett-Packard Laboratories, presentation at the workshop. Available at <http://www7.nationalacademies.org/nmab/Stan%20Williams.pdf>. Slide 9. January 2003.

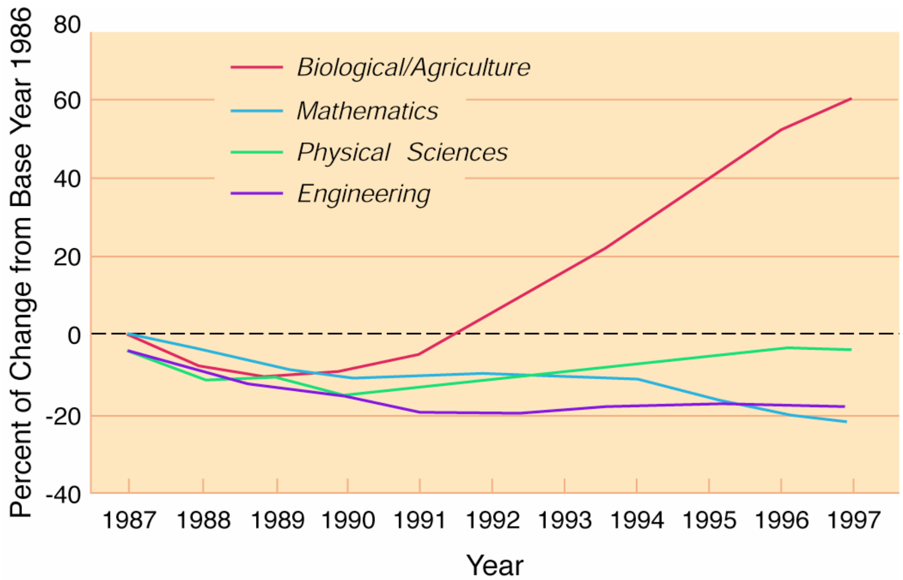

FIGURE 4-1 Growth in science and engineering degrees, indexed to 1986. Except for life sciences, undergraduate degrees in science and engineering have been flat or declining. SOURCE: Council on Competitiveness, 2001, U.S. Competitiveness.

opportunities are not in biology.[3] Another speaker at the workshop discussed similar education and corporate employment trends, which show a significant mismatch between the graduates being produced and the workforce needs of the economy. This presentation prompted a variety of comments during panel discussions.

Speakers and discussants postulated that in order to attract more students into the physical sciences and engineering, it is vital that the curriculum in U.S. universities be interesting from the first semester on, with opportunities for faculty-student interaction and the involvement of local industry.

Many students come to the university environment with prior experiences and expectations, including what they want to study. A variety of factors may direct them toward or away from materials. For many reasons, recruitment into the materials science and related fields is a struggle. One speaker at the workshop asserted that women especially are not sufficiently encouraged to study materials science.

That many of the brightest U.S. students are choosing legal, banking, investment, business, or medical jobs may be partly due to their belief that salaries in these fields are significantly higher than for scientists and engineers. Also, students may stay away from materials science because the time needed for a material to penetrate the market is estimated at 20 to 30 years. This type of statistic will turn away entrepreneurial students.

While foreign-born Ph.D. graduates have long played a prominent role in the success of the national research complex, concern was evinced at the workshop that the United States is becoming overdependent on this foreign workforce. As recruiting a U.S.-educated workforce becomes more difficult, corporate research laboratories may consider moving offshore to be near their primary sources of scientists and engineers.

[3] S. Williams, Hewlett-Packard Laboratories, presentation at the workshop. Available at <http://www7.nationalacademies.org/nmab/Stan%20Williams.pdf>. Slide 12. January 2003.

With the continuing decline in the supply of skilled workers, one speaker at the workshop stated that the United States would have to retrain the current workforce and renew apprenticeship programs. He added that today, fewer and fewer skilled workers are trained every year and a critical point is near. New efforts, such as the 1998 Workforce Improvement Act, may be needed to attract students into the skilled workforce and to retrain our current workforce to satisfy the continuing needs of the manufacturing industries.

Significant challenges must be met to guarantee a continuing supply of an educated and trained workforce for the materials research, development, and manufacturing complex. The consequences of inaction could be serious for the long-term health of the U.S. economy, and the solutions will involve educators, industry, and government. If the United States is not a developer of technology, it is in danger of becoming an importer and buyer of technology.

Comments from the Speakers

"The biggest problem we face is finding the right people."

—R. Stanley Williams, Hewlett-Packard

"Filling slots for undergraduate biological sciences has been likened to fishing with a net: one simply scoops them up. In the physical sciences—including materials science—recruiting undergraduate majors is much harder, more like fly fishing for one fish at a time."

—Gregory Farrington, Lehigh University

"There is a drain of the U.S. brain trust away from physical sciences and engineering."

—Andrew Hunt, Microcoating Technologies

It is the workforce that turns technology into products.

—John Moran, Workforce Specialist

U.S. CONGRESSIONAL PERSPECTIVES

Session Chair—Sylvia Johnson, NASA Ames Research Center

Jon Epstein, Office of Senator Bingaman
Carolyn Hanna, Senate Armed Services Committee
Diane Auer Jones, U.S. House Subcommittee on Research

> "Ideas, understandings and technologies spawned by research and development were critical to our triumph in the Cold War and will be just as essential to winning the war against terrorism and to curing numerous domestic and global social ills."
>
> —Congressman Sherwood Boehlert, Ideas and Estimates, 2000

Many members of Congress and their staff members see funding for science and technology as critical to the nation's future, for the following reasons:

- The economy depends on such areas as information technology and nanotechnology;
- National security depends on work in such vital areas as cybersecurity;
- The population's health and well-being depend on genomics research and climate change research; and
- Improved math, science, and engineering education depends on federal support, from the kindergarten classroom to the postdoctoral laboratory.

Science and technology spending currently constitutes 2.7 percent of Department of Defense funding, and a growing contingent of members of Congress would like to see that share rise to 3 percent. In FY2003, a $1 billion increase is planned in this area, which will bring total funding for defense science and technology to almost $10 billion. Proposed increases, supported by several members of Congress, would also mean that funding for the National Science Foundation would increase significantly in FY2003.

Congressional leaders are also very concerned about workforce issues in the United States. The elected leadership is aware that hiring qualified workers remains difficult, both domestically and abroad. The Technology Talent Act provides funding to institutions of higher education to increase the number and quality of science and engineering graduates.

The speakers mentioned that the focus of research is another issue discussed regularly on Capitol Hill. For example, most new Department of Defense research is interdisciplinary, with both nano- and biomaterials playing a major role.

The congressional staff attending the workshop reminded the participants that members of Congress are interested in striking the appropriate funding balance not only between different scientific fields or disciplines, but also between basic and applied research and between core programs and special initiatives (past funding trends for several fields are shown in Figure 4-2). Congress, they said, looks to the scientific community for guidance in determining appropriate funding levels based on research demands and potential for advancement within that discipline. This guidance must be based on evidence—for instance, requesting an increase in materials research funding solely because life science funding was increased is not appropriate. Specific increases must be based on a sound analysis of the goals and initiatives of the field or related fields and on national needs. *Astronomy and Astrophysics in the New Millennium*, the National Academies' most recent decadal survey of astronomy and astrophysics, is a good example of a document that clearly outlines and defends the goals and recommendations of the science community.

The materials research community, by making Congress and the public aware not only of past successes but also of short-term and long-term research goals and of the potential impact of materials science, could greatly increase the visibility of materials science and engineering. These discoveries have impacted our quality of life, improved health-care delivery, advanced technology, and improved national security,

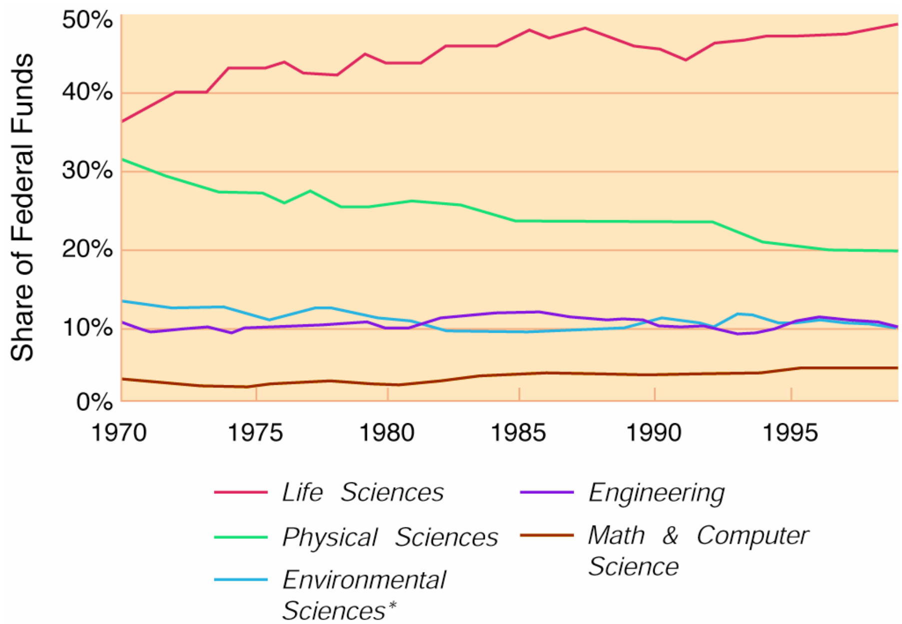

FIGURE 4-2 Percent of federal research funding by field. SOURCE: Office of Management and Budget analysis of data from the National Science Foundation publication *Federal Funds for Research and Development, Federal Obligations for Research by Agency and Detailed Field of Science and Engineering, Fiscal Years 1970-2000* (NSF 01-306).

In the same way that sequencing the human genome generated public interest in and understanding of a once-obscure laboratory procedure, the potential for revolutionary advances from nanomaterials and other state-of-the-art technologies could attract similar awareness and understanding of materials science. Right now, congressional leaders are interested in making everything lighter, faster, and stronger to perform their missions more effectively, and they need to understand how advances in materials science will advance science and technology to that end.

Comments from the Speakers

"The Senate budget committee increased the discretionary cap for the Department of Energy's basic and applied research by $4 billion over the next 10 years—so at least on the Senate side there is support for increased levels of funding physical sciences research."

—Jonathan Epstein, Professional Staff, Senator Jeff Bingaman

"Most new Department of Defense Research is interdisciplinary. The life sciences community and physical sciences community need to get talking."

—Carolyn Hanna, Senate Armed Services Committee

"With private sector laboratories focusing increasingly on applied research and development, it is now more important than ever to provide federal support for basic research and to encourage long-term public private partnerships that will drive tomorrow's breakthroughs in science and technology."

—Diane Auer Jones, House Subcommittee on Research

FEDERAL AGENCY PERSPECTIVES

Panel Discussion Leader—Frank DiSalvo, Cornell University

Patricia Dehmer, Department of Energy
Robert Eisenstein, National Science Foundation
Charlie Harris, National Aeronautics and Space Administration
Lewis Sloter, Department of Defense
Leslie Smith, National Institute of Standards and Technology
John Watson, National Institutes of Health

Many programs in the federal agencies are responding to the drivers discussed in Chapters 2 and 3 of this report. For example, changes within the Office of Basic Energy Sciences in the Department of Energy have included funding for larger interdisciplinary groups and interdisciplinary conferences; investments in nanoscience centers; and development of such user facilities as neutron scattering, light sources, and scanning probe microscopy. Trends in federal research funding by agency are shown in Figure 4-3.

Both the Department of Energy and the National Science Foundation are looking at ways of enabling scientists around the world to work together. The National Science Foundation funds research ranging from fundamental science to device development. The five priority areas driving the NSF are information technology, nanoscale science and engineering, biomaterials, 21st-century workforce, and mathematics.

The goal of contributing to national needs is shared by the National Institute of Standards and Technology. NIST is responsible for standards and measurement systems and develops enabling technologies for the entire economy. Growing research areas at NIST are biological applications, array technologies, and combinatorial methods.

Materials are an enabling technology for mission-oriented agencies. For these agencies, both researchers and program managers must focus on not only new science but also on how materials perform within the design constraints. All military departments that have a science and technology component participate in some way in materials research. Some defense materials programs focus mainly on achieving advances in basic science; others focus on enabling the accomplishment of mission goals or helping to provide new military capability.

Discussants at the workshop commented that funding for basic and applied research at NASA had been slow to grow over the past 10 years because of flat budgets and budget shortfalls for such large projects as the International Space Station. This situation presents enormous challenges to NASA, which is committed to new ways of doing business. The agency plans to engage a wider group of participants and stakeholders to increase science, research, and development efforts. Drivers for NASA research and development include the need to get innovations in materials into production more quickly than the current average of 14 to 15 years.

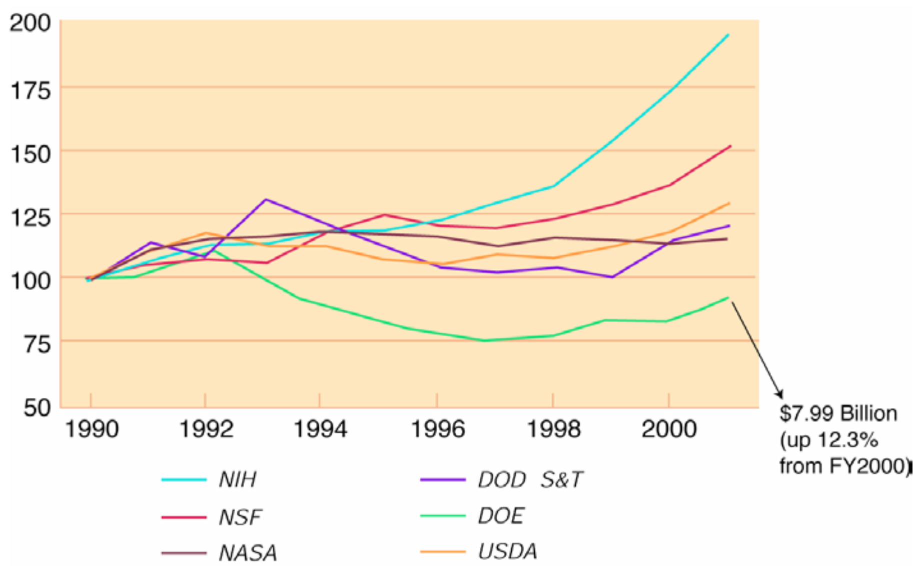

FIGURE 4-3 Trends in federal research and development funding, 1990 to 2001. From top to bottom on right (2001), the lines represent the science and technology budgets for the National Institutes of Health (NIH), the National Science Foundation (NSF), the U.S. Department of Agriculture (USDA), the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE) Office of Science. SOURCE: American Association for the Advancement of Science analyses of research and development from data in AAAS Reports VIII-XXV. Figures for 2001 are estimates based on congressional appropriations.

The National Institutes of Health has a research budget approaching $27 billion. Novel enabling materials are needed to realize many health initiatives, including tissue engineering, nanoscience, and reparative medicine. However, materials science is scattered throughout the NIH and is not optimally coordinated. Some is in the newly formed National Institute for Biological Imaging and Bioengineering, but most is distributed among the other institutes and centers.

Comments from the Speakers

"A new infusion of $25 million for nanotechnology generated 750 proposals, but only 75 could be funded."

—Patricia Dehmer, Department of Energy

"At NSF, about $300 million is spent on materials research, and 98 percent of this funding goes to universities."

—Robert Eisenstein, National Science Foundation

"NASA is a mission agency and focuses on systems rather than disciplines. This is reflected in its investment strategy and research portfolio."

—Charlie Harris, National Aeronautics and Space Administration

"This year, about $500 million is targeted for materials science and technology, representing a large, robust, and stable portfolio that supports the mission of the Department of Defense."

—Lewis Sloter, Department of Defense

"Material researchers need to amplify the message that materials represent an enabling technology to mission-oriented agencies."

—Leslie Smith, National Institute of Standards and Technology

"A major challenge for NIH is getting talented bioengineering and materials scientists to enter public service."

—John Watson, National Institutes of Health

5

Summary

The presentations, displays, and discussions held during the workshop emphasized the pivotal role of materials in enabling advances and new technology in areas as diverse as national security, energy, vehicles, biomaterials, and optical networks and communications. Many presentations linked past and ongoing materials successes with future needs for materials and revealed fertile ground for future materials research and development. An opinion expressed frequently by many of the participants was that enhancing society's awareness of the role of materials in the technology people use every day is crucial to creating a climate that will enable materials scientists and engineers to continue to make these contributions.

It was suggested that insufficient funding and the decline in the available workforce with training in physical sciences will limit progress in promising areas of materials research. Materials science and engineering is an amalgam of many of the physical sciences but with a specific focus on the application of science and engineering to materials and on the application of materials to science and engineering. The many studies and surveys discussed at the workshop documented the decrease in students, especially domestic students, studying these disciplines. Anecdotal evidence presented by both large and small companies reinforced these observations.

Reasons proposed at the workshop for the decline in the available workforce included funding shortfalls, a failure to engage potential students at the right time, the perception that the physical sciences are difficult, and the long training period. Several presenters and discussants mentioned the interdisciplinary nature of materials science and engineering, which calls for students who are not only capable of such study but also willing to spend many years in on-the-job training to gain experience in the field.

Several presentations reported that research funding for physical sciences has not grown at the same rate as that for the biological sciences. However, it was not made clear that funding parity was an appropriate goal—instead it was stated that a "correct" level of funding, based on economic, societal, and technical needs, must be determined.

The workshop identified some unfilled research, development, and technology needs in the field. However, several speakers and participants at the workshop discussed the need for a more in-depth analysis. Some speakers referred to the NRC decadal survey on astronomy and astrophysics, citing its considerable usefulness to Congress in supporting research initiatives in that field.[1]

The NRC published decadal studies in materials science and engineering in 1974 and 1989 and in condensed matter and materials physics in 1999. Many aspects of the study of materials science and engineering over that time period were presented at the workshop, highlighting the changes in the field as it gained an identity and matured into a

[1]National Research Council, 2001, Astronomy and Astrophysics in the New Millennium, Washington, D.C.: National Academy Press.

respected field of study. Several presentations emphasized the increasing diversity of the field and the multi- and interdisciplinary expertise of the people who participate in materials science and engineering.

Several speakers and panel members stated that a study identifying new directions in materials science and engineering and prioritizing materials research needs would be useful to both the community and the Congress. Like their colleagues who had previously assessed the field, these speakers viewed the understanding and application of the relationships among synthesis, process, structure, and properties of all materials—the basis of materials science and engineering—as key components.

The status of education and the workforce in materials science and engineering was discussed throughout the workshop. The discussions ran the gamut from kindergarten through grade 12, technical training, undergraduate, graduate, and continuing education and retraining of the current workforce. Many discussants provided anecdotes or suggested actions that could be taken to address the decreasing numbers of trained professionals and overall workforce deficiencies. However, these participants also suggested that a better assessment and definition of the supply and demand for persons with training in materials would benefit the field considerably.

APPENDIXES

Appendix A

Further Reading:
Related Reports from the National Academies Press

Advancing Materials Research (1987)

Astronomy and Astrophysics in the New Millennium (2001)

Condensed-Matter and Materials Physics: Basic Research for Tomorrow's Technology (1999)

Driving Innovation Through Materials Research: Proceedings of the 1996 Solid State Sciences Committee Forum (1996)

Harnessing Light: Optical Science and Engineering for the 21st Century (1998)

International Benchmarking of U.S. Materials Science and Engineering Research (1998)

Materials and Man's Needs (1975)

Materials in a New Era: Proceedings of the 1999 Solid State Sciences Committee Forum (1999)

Materials in the New Millennium: Responding to Society's Needs (2001)

Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials (1989)

Physics in a New Era: An Overview (2001)

The Physics of Materials: How Science Improves Our Lives (1997)

Trends in Federal Support of Research and Graduate Education (2001)

NOTE: All reports are available from the National Academies Press at <http://www.nap.edu>.

Appendix B

Agenda of the Workshop

MARCH 27-28, 2002
WASHINGTON, D.C.

March 27

7:00	Registration Begins	
8:00	Welcome and Remarks	Sylvia Johnson Chair, Workshop Planning Committee

Keynote Addresses

Session Chair—Robert Pfahl, National Electronics Manufacturing Initiative

8:10	Wm. A. Wulf	National Academy of Engineering
8:30	Cherry Murray	Bell Labs, Lucent Technologies

Setting the Scene: Impact of Materials

Session Chair—Henry Rack, Clemson University

8:50	How Materials Contribute to Society	Venkatesh Narayanamurti Harvard University
9:20	Drivers in Materials Research	Mildred Dresselhaus Massachusetts Institute of Technology
9:50	Panel Q&A	
10:10	*Break*	

Materials in National Security

Session Chair—Julia Phillips, Sandia National Laboratories

10:40 Materials Issues in Microsystems for National Security — Duane Dimos, Sandia National Laboratories

11:00 Advanced Sensors for Counterterrorism — Fran Ligler, Naval Research Laboratory

11:20 Transportation Infrastructure and Security — Lyle Malotky, Transportation Security Administration

11:40 Panel Q&A

12:00 *Lunch*

Materials in Commercial Vehicles

Session Chair—Harry Cook, University of Illinois

1:15 Energy/Fuel Efficiency in Commercial Vehicles — Gary Rogers

1:35 Materials in Commercial Autos and Trucks — Alan Taub

1:55 Panel Q&A

Materials in Commercial Vehicles

Session Chair—Jay Lee, University of Wisconsin at Milwaukee

2:15 Conventional Power Generation Technology — John Stringer, Electric Power Research Institute

2:35 Alternative Energy Technologies — William P. Parks, Jr., Department of Energy

2:55 Portable Power — Daniel Doughty, Sandia National Laboratories

3:15 Panel Q&A

3:35 *Break*

Panel Discussion on Workforce and Education

Session Chair—Ashok Saxena, Georgia Institute of Technology

3:55 Large Industry Perspective — R. Stanley Williams, Hewlett-Packard Laboratories

4:10	Small Business Perspective	Andrew Hunt Microcoating Technologies
4:25	Educating a New Workforce	Gregory Farrington Lehigh University
4:40	Training Our Current Workforce	John Moran Consultant
4:55	Panel Q&A	
5:30	*Reception*	

March 28

7:00 *Continental breakfast*

Congressional Staff Panel Discussion

Session Chair—Sylvia Johnson, NASA Ames Research Center

8:00 Panel**:**
Jon Epstein, Office of Senator Bingaman
Carolyn Hanna, Senate Armed Services Committee
Diane Auer Jones, U.S. House Subcommittee on Research

Materials in Future Industries

Session Chair—Lee Magid, University of Tennessee at Knoxville

9:00	Nanomaterials	Julia Weertman Northwestern University
9:20	Biomaterials	David Tirrell California Institute of Technology
9:40	Optical Materials	Rod Alferness Lucent Technologies
10:00	*Break*	

10:20 Computational Materials Science — Sharon Glotzer, *University of Michigan*

10:40 Panel Q&A

Federal Agency Panel Discussion

Session Chair—Frank DiSalvo, Cornell University

11:00 Panel:
Patricia Dehmer, Department of Energy
Robert Eisenstein, National Science Foundation
Charlie Harris, National Aeronautics and Space Administration
Lewis Sloter, Department of Defense
Leslie Smith, National Institute of Standards and Technology
John Watson, National Institutes of Health

12:30 *Adjourn*

Appendix C

WORKSHOP ORGANIZERS

NATIONAL MATERIALS ADVISORY BOARD

The National Materials Advisory Board is the preeminent source of independent materials assessments for the nation. Board studies deal with the entire life cycle of materials, from mining and synthesis to manufacturing, service performance, and recycling/disposal. The board achieves a balanced view by having access to the expertise of all sectors of society concerned with materials. The board's structure and mode of operation enhance the quality of its output while minimizing the influence of vested interests. Board assessments of new materials and processing methods focus attention on policy issues with significant technology content. Board activities should create broader awareness and advocacy for materials issues. Board output can assist decision makers in setting priorities for optimum deployment of the available resources.

www.nationalacademies.org/nmab

SOLID STATE SCIENCES COMMITTEE

The Solid State Sciences Committee, part of the NRC's Board on Physics and Astronomy, is a continuing interdisciplinary body whose members have expertise in solid-state physics, solid-state chemistry, electronic materials, metallurgy, polymers, and the basic materials science aspects of ceramics. The committee identifies and makes recommendations on the needs of the materials research, development, and applications communities, particularly in connection with research opportunities and support, and it provides guidance to federal agencies regarding their materials science research programs.

www.nationalacademies.org/bpa/sssc

UNIVERSITY MATERIALS COUNCIL

The University Materials Council is composed of department heads, chairpersons, directors, and group leaders from academic programs in the materials field in U.S. and Canadian universities. The council meets twice a year, once in the spring and once in the fall. It serves as a forum for department heads, chairs, and directors of materials programs to share best practices in areas such as student recruitment and discuss issues such as accreditation from the Accreditation Board for Engineering and Technology (ABET), emerging research areas, ideas for curricular improvements, patent right policies in universities, implications of the latest materials-related studies, and the health of research funding for materials science and engineering, as well as a variety of other issues of interest to the academic community. It also conducts surveys to benchmark enrollments, degrees awarded, faculty salaries, research funding, and graduate student stipends and holds discussions at its meetings on the latest trends gleaned from the surveys. The council also maintains liaisons with prominent materials societies and with bodies such as the National Materials Advisory Board and the Federation of Materials Societies.

www.tms.org:100/

BOARD ON MANUFACTURING AND ENGINEERING DESIGN

The Board on Manufacturing and Engineering Design provides independent assessment of technical and public policy issues relating to product design and realization. Composed of leaders in manufacturing, engineering design, and complementary fields from academia and industry, the board provides a unique perspective on technical, economic, social, and policy issues. The board carries out studies, workshops, and other activities to foster a better understanding of manufacturing and design issues. Its projects engage balanced groups of experts to develop insightful analyses of the role of manufacturing and engineering design in our world.

www.nationalacademies.org/bmed

Appendix D

Exhibitors

To assess a broad cross section of the materials enterprise, the committee also invited several small businesses involved with a wide range of materials types and applications to display their products and discuss their prospects during the workshop.

Advanced Ceramics Research
http://www.acrtucson.com

FM Technologies
http://www.fm-technologies.com

Gemesis Corporation
http://gemesis.com

Industrial Science and Technology Network
http://www.istninc.com

Materials System, Inc.
http://matsysinc.com

MicroCoating Technologies
http://www.microcoating.com

Powdermet, Inc.
http://www.powdermetinc.com

Starfire Systems, Inc.
http://www.starfiresystems.com

Technanogy
http://www.technanogy.net

Triton Systems, Inc.
http://www.tritonsystems.com

Appendix E

Acronyms

AAAS	American Association for the Advancement of Science
ABET	Accreditation Board for Engineering and Technology
BDRP	Biological Defense Research Program
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DOE	Department of Energy
DTRA	Defense Threat Reduction Agency
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FY	fiscal year
GaAs	gallium arsenide
Gbps	billion bits per second
HBT	heterojunction bipolar transistors
HEMT	high-electron-mobility transistors
InP	indium phosphide
kWh	kilowatt-hour
Mbps	million bits per second
MEMS	microelectromechanical systems
MESFET	metal electron semiconductor field effect transistors
MOSFET	metal oxide semiconductor field effect transistors
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea Systems Command
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NMRI	Naval Medical Research Institute
NSF	National Science Foundation

OC	optical carrier
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
S&T	science and technology
Si	silicon
USAMRIID	U.S. Army Medical Research Institute of Infectious Diseases
USDA	U.S. Department of Agriculture
USMC	U.S. Marine Corps