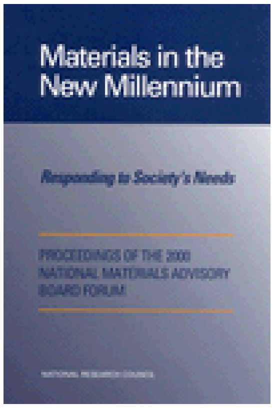

# Materials in the New Millennium: Responding to Society's Needs

Proceedings of the 2000 National Materials Advisory Board Forum, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

# Materials in the New Millennium

## Responding to Society's Needs

### Proceedings of the 2000 National Materials Advisory Board Forum

National Materials Advisory Board
Division on Engineering and Physical Sciences
National Research Council

NMAB-501

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* Forum Planning Group.

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# Preface

The 2000 National Materials Advisory Board Forum was held on February 8 and 9, 2000, at the National Academy of Sciences in Washington, D.C. Participants included more than 180 congressional and agency staff, industry leaders, and scientists and engineers from across the spectrum of the materials research community (see p. 50). The purpose of the forum was to bring the importance of materials to the attention of policy makers and to promote interactions between policy makers and the materials community. Participants were asked to address four key themes:

- the critical role of materials in advancing technology and enhancing the nation's economy, security, and health
- industrial and societal needs that will require materials development in the new millennium
- materials research areas with the greatest potential for meeting those needs
- federal and industrial research initiatives that can help the materials community meet those needs

To help focus the discussions, special sessions were convened to address the current and future roles of materials in four selected areas: information technology, health and biotechnology, national security, and energy and the environment. We hope to cover other areas in future years. In each session there were brief presentations by invited speakers, followed by panel discussions.

The NMAB thanks the speakers and panelists (see p. 47), exhibitors (see p. 49), planning group (see p. *iv*), and others who helped to make the forum a success. We would also like to acknowledge the work of the NMAB staff, including Daniel Morgan, Teri Thorowgood, and Sharon Yeung.

These proceedings are a factual summary of what occurred at the forum in February 2000. Summaries of individual talks were prepared by the members and staff of the NMAB and edited by Sylvia Johnson and Daniel Morgan. The proceedings were reviewed by Edgar A.Starke (University of Virginia, Charlottesville) and Kenneth L. Reifsnider (Virginia Polytechnic Institute and State University, Blacksburg).

Participants in the forum made uniformly positive comments on the selection of topics and the quality of the talks and discussion sessions. They were particularly pleased that the forum brought together the diverse segments of the materials community in a single, unifying event. The NMAB intends to make this the first of many such meetings. To find out more or to give us your ideas for the next forum, please send e-mail to <nmab@nas.edu> or call 202–334–3505.

Edgar A.Starke, Chair
National Materials Advisory Board
Sylvia M.Johnson, Chair
Forum Planning Group

# Contents

# Keynote Address

*The keynote address was presented by Pete Domenici. Senator Domenici, who has represented New Mexico in the U.S. Senate since 1972, chairs both the Senate Budget Committee and the Energy and Water Development Subcommittee of the Senate Appropriations Committee. He has long been known for his commitment to science and technology and is a strong proponent of research. Because the President's budget was released on February 7, 2000, the day before the forum, Senator Domenici's schedule required that he present his remarks by video.*

Thank you for the invitation to join you this morning. Much as I'd like to be with you in person, this is a very busy time in my role as chairman of the Budget Committee. We have hearings virtually every day as we work to complete the committee's work in March. And since the president is scheduled to release his budget proposal the day before you hear this talk, you can be assured that during the presentation of this video I'll be very busy studying those documents.

Your forum, "Materials in the New Millennium," should lead to some fascinating discussions. Materials science underpins every product and process on which our modern society depends. As I visit the universities and laboratories in my home state, I'm constantly reminded of the importance of your work to develop advanced materials and to better understand the science of current materials.

Just recently, I was at Sandia National Laboratories in Albuquerque and saw a demonstration of photonic crystals. These marvelous miniature structures offer the promise of controlling light the same way that conventional semiconductors enable us to control electrical signals. They may be used for ultrahigh-speed transmission and processing of signals in advanced instruments, including future generations of computers.

**Materials science underpins every product and process on which our modern society depends.**

That work is closely related to Sandia's work in the broad field of microsystems. I've been amazed to see their progress in integrating tiny machines onto silicon chips. When those miniature machines are coupled on the same chip to electronics for detection and analysis, we will have amazing capabilities that will lead to whole new generations of products and tools. The materials challenges that must be faced in perfecting these miniature systems will be daunting.

On the same trip, I also participated in celebrating the second year of a new brain imaging project led from Albuquerque. The work couples two spectacular technologies, functional magnetic resonance imaging, or fMRI, and magnetoencephalography, or MEG. By using both technologies, researchers obtain details of neural activity in the brain.

**More and more of my colleagues are recognizing the role that advanced technologies play in the strength of our national economy.**

MEG and fMRI use two extremes of magnetic fields. fMRI uses some of the largest commercial magnets available. MEG senses the tiny magnetic signals from individual neurons. Both technologies faced immense materials challenges. I also found it interesting that the ceramic material used in the MEG work was first developed for kitchen cookware—providing a good example of the versatility of advanced materials.

Turning to a very different materials problem, I discuss the status of the stockpile stewardship program of the U.S. Department of Energy (DOE) on every visit to Los Alamos. In that program, the weapons labs are faced with the challenge of ensuring the safety and integrity of our nuclear stockpile in the absence of testing. As you well know, weapons by their very nature are constructed of unstable materials—radioactive materials that change as they decay, along with various plastics that behave in unpredictable ways over time. These are also materials issues that members of your profession are asked to understand.

Some of the tools that you use in your research reside at the national laboratories that are funded through my Energy and Water Development Subcommittee. Neutron scattering sources, like LANSCE at Los Alamos, or advanced light sources, like those at Brookhaven or Argonne, are important in your work.

Progress in your field depends on adequate funding, from both government and private sectors. I'm pleased with some of the progress we've made in the last year. Congress provided healthy increases in most areas of science and technology for the current fiscal year. In fact Congress increased the overall federal research and development budget by about 7 percent above the president's request for this current year and about 5 percent above last year's funding level.

The largest increase this year went to the National Institutes of Health (NIH), with a 12 percent increase above the president's request and more than 14 percent above the previous year. The National Science Foundation (NSF) is up more than 5 percent from the previous year. Defense science and technology accounts also fared very well, with an 11 percent increase over last year and a 17 percent increase over the president's budget. Many of these accounts provide funding for your materials research.

When Congress approved the appropriations for this year, with such generous support for science and technology, some people argued that we were sacrificing the balanced budget. I'm especially proud that the latest estimates from the nonpartisan Congressional Budget Office (CBO) confirm statements that I've been making for many months. The CBO figures prove that we provided these excellent increases for science and technology with a balanced budget and without spending a dime of the Social Security surplus. In fact, the latest CBO figures confirm a $23 billion non-Social Security surplus for this year.

In the past year, there were two other bills that I'd like to briefly highlight. I was an original cosponsor of S. 296, the Federal Research Investment Act, which calls for doubling federal support for science and technology over about 12 years. That bill passed the Senate last year. In fact, it had more than 40 sponsors by the time it was finally debated, showing that more and more of my colleagues are recognizing the role that advanced technologies play in the strength of our national economy.

The most important part of this bill was simply the fact that it raised the prominence of federal support for science and technology and that it highlighted the importance of treating such federal expenditures as investments in our nation's future rather than as entitlements. It also set up mechanisms to ensure that any increases stayed within budget limits that maintained a balanced budget—after all, we've worked too hard for too many years to achieve this budget balance, and that balance needs to be guarded with the utmost care in the future.

Another key part of this bill suggests increases in funding across a broad spectrum of scientific areas. That's important because we've been accelerating medical research very rapidly recently. Over the past few years, the growth rate for medical research has been about twice that for all other areas. There's no doubt that the medical research is important—but many of the latest breakthroughs depend on advances in a broad range of specialties. If we focus too much on strictly medical research, we don't advance the other sciences in tandem, and we may miss opportunities for new breakthroughs.

The bill also supports research ranging from fundamental research to precompetitive engineering studies. That's important because I want to ensure that we don't identify some new phenomenon and then stop supporting it before it reaches the product stage where it has an impact on the general public and generates new well-paying jobs.

**You have many success stories that should be provided to the public.**

The Research Investment bill is now in the House, where Representative Wilson has introduced it. That bill deserves your active support.

Last year, I also sponsored major changes in the research and experimentation tax credit. The philosophy behind this credit—that it's in the nation's interest to encourage private research—is sound. But there are many aspects of the credit that need modernizing, with the most serious issue being that the credit has never been permanent. My bill, S. 951, made a number of changes in the way the credit is calculated, and it received strong bipartisan support.

Without a permanent credit, companies can't build long-term research strategies, so the current credit really hasn't been as useful as it might be. It has other weaknesses, too. Its value depends on how much a company's research expenditures have grown since a base period starting in 1984. As 1984 recedes into the distant past, this calculation becomes less and less relevant to modern business conditions. Thus one of my initiatives was to establish a new current baseline for the credit. I also inserted provisions to encourage creation of research consortia and to encourage contract research at universities, small businesses, and national labs.

S. 951 was not enacted last year, but it helped create a climate for the first long-term extension of the credit, for five years. I remain hopeful that my bill will be considered in the remainder of the 106th Congress so that the nation's research climate can be improved with the changes that it includes.

You're hearing this talk the day after the president's budget is delivered to Congress, and I'm taping this speech before I've seen the budget. But based on both the State of the Union address and various leaks on the president's new programs, I'm sure there are many new initiatives suggested in his budget.

Some of these new initiatives increase the federal investment in science and technology. I expect to see proposals for significant increases in the NIH and NSF budgets. You can be sure that Congress will study these proposals very carefully. In light of the superb congressional support for science and technology in the past, some of these initiatives may be accepted. Congress may even increase some of the president's recommendations, as they have in past years. Or we may establish new programs in alternative areas. But you can also be sure that the Congress will insist that we maintain a balanced budget—and considering the hype surrounding the multitude of new programs he's proposing, the president may be less concerned about budget balance than Congress will be.

One of the initiatives that President Clinton has discussed involves nanotechnology. That's the same area that I highlighted in my opening remarks when I mentioned Sandia's work on photonic crystals and microsystems. You already know about my excitement for this area. Materials science is a vital contributor to the success of this new field.

As we look into the future, projections based on our continued economic strength paint a very rosy picture. We can anticipate a dramatic reduction in the public debt as a fraction of the gross domestic product, even as we maintain the security of the Social Security system. There will be opportunities for selected budget increases that stay within a balanced budget. Science and technology budgets in general, and your materials science budgets in particular, will be strong competitors for some of these increases.

You have many success stories that should be provided to the public, where your work on advanced materials has enabled new technologies, new products, and new processes that have helped maintain our superb economic success and standard of living. You can cite examples that range from our modern automobiles and airplanes to modern medical technologies to the personal computers that are found everywhere today.

Your work truly has an impact on virtually every part of our modern civilization. I encourage you to join with other scientists in sharing your information with the public and helping more people understand the vital relationship between science and technology and the economic success we've enjoyed as a nation.

***Pete Lyons,*** *the senator's key aide for science and technology issues, responded to questions and comments after the video presentation. An edited summary of that discussion follows.*

Question: What is the proposed budget for the nanotechnology initiative, and how much of that funding is new?

Answer: Funding for DOE is $87 million. The NSF and other agencies will add to that number. There is likely to be a fair amount of new money as well as redirected old money. The senator is very excited about nanotechnology.

Q: The DOE budget shows a 13 percent increase for science and technology. What are the affected areas?

A: It appears that magnetoencephalography is zeroed in the president's budget. That will be carefully reviewed. We will be examining the approach to nuclear waste issues, an area of particular interest to the senator. In particular, we will be exploring alternate paths for handling waste materials, an area that was zeroed in the president's budget. Senator Domenici is trying to help the community to develop a better scientific basis for setting radiation standards, an area where the budget was reduced. The National Spallation Neutron Source, which received marginal funding last year, is up $163 million in the current budget proposal, but the senator will be carefully reviewing this item. He has proposed that there be a separate department for security in DOE, and this will also be an area for review.

**Technology advances have accounted for between 50 and 70 percent of the improvement in our standard of living since World War II.**

Q: How can we help the senator in his efforts to support science and technology?

A: Technology advances have accounted for between 50 and 70 percent of the improvement in our standard of living since World War II. Work together, with others in the materials community or with other scientific groups, to increase awareness of this link. Work with other members of Congress to educate them.

Q: Could you speculate on the status and health of the doubling bill in the House?

A: As written, the bill cuts across multiple committee jurisdictions. Committees tend to be protective of their areas of purview, so there may be challenges in getting the bill out of committee. The bill is written to spread increases in research funding across a wide range of disciplines.

Q: Could you clarify “a wide range of disciplines”?

A: For the agencies in the bill, research funding will double over the next 12 years. If an agency gets ahead of that schedule, it is dropped out of the calculation until the others reach the same percentage increase. As well as supporting a wide range of technical areas, the bill covers the full range from fundamental research through precompetitive engineering. We do not want to drop support for good ideas before they reach the precompetitive phase.

Q: Is the senator’s support for the full range from fundamental research through precompetitive engineering a widely held view in Congress?

A: Many members of Congress do not understand the whole spectrum and tend to favor fundamental research. Research is a complex process that does not always fit well into simple categories. Some members of Congress still need more education.

Q: What kinds of input do you get from individual scientists?

A: Scientists in New Mexico know Senator Domenici well and like him. That kind of rapport may be harder in larger states. I encourage scientists to give their input to members of Congress as well as their staff. The more you interact, the better. I would also note the helpful role of the congressional fellowships program run by the American Association for the Advancement of Science. If those assignments were for two years rather than one, the fellows would be even more effective, and more members might use them on their staffs.

# Setting the Scene

*After Senator Domenici's keynote address, the forum moved into a series of talks designed to set the scene for the following two days. First,* ***Thomas W. Eagar*** *of the Massachusetts Institute of Technology (MIT) addressed the most fundamental question of all: Why are materials important to society? Dr. Eagar is the POSCO Professor of Materials Engineering at MIT, where he heads the Department of Materials Science and Engineering. He was elected to the National Academy of Engineering in 1997 for his contributions to the theory and practice of welding. Dr. Eagar is a member of the National Materials Advisory Board.*

***Arden L. Bement, Jr.,*** *of Purdue University examined the timeline of materials development and factors that affect successful progress from the laboratory to the marketplace. Dr. Bement is one of the Distinguished Professors of Engineering and head of the School of Nuclear Engineering at the University. He has also served as vice president of science and technology at TRW and deputy undersecretary of defense for research and engineering. Dr. Bement's research interests are primarily in electroceramics. He is a member of the National Academy of Engineering.*

***James C. Williams*** *of Ohio State University presented an overview of past successes and future opportunities for structural materials. Dr. Williams is the Honda Professor of Materials at the University. He was previously general manager of the Materials and Process Engineering Department at GE Aircraft Engines. His interests include the structure-property relationships of high-strength materials, the performance of materials in extreme environments, materials processing, government policy as it affects materials, and the management of high-technology organizations. He is a member of the National Academy of Engineering and a former chair of the National Materials Advisory Board.*

***James W. Mitchell*** *of Lucent Technologies presented an overview of past successes and future opportunities for functional materials. Dr. Mitchell is director of the Materials Processing Research Laboratory at Bell Laboratories in Murray Hill, New Jersey. His research interests include the use of microwave discharges and plasmas for materials synthesis, the development of methods for ultrapurifying reagents and research chemicals, and the development of environmentally responsive methods for producing electronic chemicals. Dr. Mitchell is a member of the National Academy of Engineering.*

***Thomas A. Weber*** *of the National Science Foundation addressed the government's role. Dr. Weber has held a variety of positions at the Foundation, where he is currently director of the Division of Materials Research. His research interests are in computational chemistry and materials, particularly the use of computer simulation to study air pollution,* *polymers, glasses, liquids, metals, and semiconductors. In 1994, Dr. Weber was awarded the Meritorious Executive Presidential Rank Award.*

*The session ended with a panel discussion. The following are summaries prepared by the editors who adapted them from the remarks made by the individual presenters.*

## WHY MATERIALS?

The ages of mankind are labeled by their dominant materials: the Stone Age, the Bronze Age, the Iron Age, and now the Silicon Age. Why? Because materials define the sophistication and wealth of nations. Materials create wealth, improve our standard of living, and are key to meeting society's needs, from national security and communications to health and housing.

Traditional materials are primarily structural—steel, aluminum, concrete, polyethylene, glass. Although they are familiar, their properties have been improved dramatically in the past two decades, while their costs have fallen and their production has become more environmentally sustainable. Novel materials are primarily functional, with optical, electronic, magnetic, or biological properties or unique environmental properties, such as resistance to high temperatures.

National leadership in manufacturing and trade requires leadership in materials. Materials are essential throughout industry, in fields such as telecommunications, health care, energy, and automobiles. In these and many other areas, materials with high added value and high functionality strengthen existing industries and preserve the jobs they provide, while creating new products that enable the development of new industries and new jobs.

The future promises both the creation of novel materials and the greater availability and affordability of traditional materials. The sustainability and quality of life of an increasing proportion of the world's population will depend on whether these promises are achieved. The United States should be the leader in developing and applying these materials for the benefit of the entire world.

## THE TIMELINE OF MATERIALS DEVELOPMENT

Implementing new materials is a slow process. Bringing a new consumer product from invention to widespread adoption typically takes 2 to 5 years, but doing the same for a new material may take 15 to 20 years. The problem is especially challenging for advanced materials, which are inherently distant from the market, do not yet have established proofs of principle, and thus involve greater market uncertainty and business risk. As a result, advanced materials seldom attract venture capital. According to David Morgenthaler, founder of Morgenthaler Ventures, a venture capitalist should *very often* invest to improve or update a product, broaden a product line, or apply a product to a new application, *often* invest in using technology to develop a new product, but only *rarely* invest in developing an enabling technology.

Shifting commercial and military priorities have made long lead times an even greater problem. One can no longer just provide a superior material and assume someone will use it. A 20-year development time is beyond the planning horizon of most businesses. Twenty years is too long for technology push to bring a new material to market, and it leaves too much time for other alternatives to emerge.

Numerous other factors also inhibit the commercialization of new materials. Market demand for new materials is often overestimated. Their initial cost is usually high, even if overall life-cycle costs are low, and product liability insurance is expensive. Designing with new materials can be complex, and standards and statistical databases are usually absent. Manufacturers that adopt a new material may need new manufacturing tools and new inspection methods. Secondary processing and recycling are often difficult. Environmental and arms export regulations may present barriers. Government testing, evaluation, inspection, and approval may cause delays. Intellectual property issues must be addressed. All these factors magnify the problem of long lead times.

The problem can be boiled down to two dilemmas. First, the market will not accept a new material until its cost falls, but its cost will not fall until the market accepts it. Second, designers will not select a new material until it is evaluated in service, but a new material cannot be evaluated in service until a designer selects it.

Resolving these dilemmas requires cutting development time at least in half. Doing this will require a combination of approaches, involving technology, management, and government. Technology can contribute by anticipating application problems earlier in the R&D process, developing material models that are linked better to design objectives, and developing more efficient methods for variation reduction and probabilistic verification of product and process designs. Management approaches include encouraging collaboration between materials developers and users, putting earlier emphasis on cost reduction, focusing on demonstrations of specific components, and seeking patient capital to enable infrastructure development. Government can contribute by encouraging partnerships for infrastructure development and early technology insertion, providing patient capital at the proof-of-principle stage, and more closely assessing the economic risks of regulations, policies, and practices that could slow the development cycle.

## STRUCTURAL MATERIALS

Traditionally, structural materials have enabled new products or improved performance through lower weight, higher strength, higher temperature tolerance, longer life, or unique combinations of structural and functional capabilities. Today, structural materials are also required to make products more affordable. They must be cheaper to produce, enhance component manufacturing by being net-shape capable, and lower the cost of ownership.

Materials enabled most of the great engineering achievements of the twentieth century. Without materials improvements, seven of the top ten accomplishments would have been impossible: the Apollo moon landing, the airplane, the transistor, the Manhattan Project, the integrated circuit, the airplane jet engine, and the communications satellite. The other three— digital computers, television, and the Panama Canal—all benefited from better materials, too, even if they did not absolutely require them.[1]

Structural materials are still essential for competitive products, but today new materials must be mature at introduction. Their technical capabilities must be clearly understood. Their failure modes must be thoroughly characterized. Their cost and supplier base must be known and stable. They must add value that outweighs any increased cost. And the risk of introducing them, both real and perceived, must be low. As a result, incrementally improved materials with a history of prior use are more readily accepted than completely new materials.

This new demand for maturity at introduction requires changes in traditional materials development practices. Past practice was to introduce a new material, modify it somewhat during a prototype phase, and finalize it just prior to production. New commercial products today have a faster development cycle and usually less risk tolerance. For example, jet engines are now developed in 30 months rather than 60, largely because of improved computational design tools. Improved methods for materials development have not kept pace with this compression of the product cycle, however. The development of new materials for jet engines typically still takes at least 60 months. Materials scientists and engineers must address this mismatch in timing and learn to develop new materials in half the time and at half the cost.

Improved computational tools are the most promising approach and must become the grand challenge for materials research. This multifaceted problem includes:

- modeling the composition of matter to guide changes in alloy chemistry
- modeling processes to accelerate convergence of the process window
- modeling properties to reduce testing time and the cost of property data
- building error analysis into all models

Models that permit high-confidence interpolation would be an excellent start. Bottom-up prediction or high-confidence extrapolation will come later. The infrastructure to start this effort exists now, but meeting the challenge will take substantial time and resources, comparable in magnitude to those required for the human genome project.

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[1] This top ten list was chosen by readers of *The Bent,* the journal of the engineering honor society Tau Beta Pi. Available at <http://www.tbp.org/pages/news/Archives/Top10.pdf>. Accessed August 2001.

## FUNCTIONAL MATERIALS

The world is in the midst of a communications explosion fueled by more than 100 years of invention and innovation. Communications services are now so easily accessible that it is easy to forget how sophisticated the underlying hardware is. Functional materials are essential to that hardware. In fact, communications is a perfect example of a high-technology industry enabled by advanced functional materials and their processing.

*Challenges.* Advances in functional materials will be key in many future applications. Some examples:

- nanotechnology and microelectromechanical systems (MEMS) for ultrahigh-density interconnects
- membranes and other materials for small, low-cost fuel cells in portable electronics
- organic circuits for “electronic paper”

*Opportunities.* Some technologies, if they became available, would find immediate use in applications that already exist today. Some examples:

- mechanistic control of materials chemistry at high temperatures
- photodefinable planar optical materials
- low-cost nonmetal substrates with high thermal conductivity
- photonic bandgap materials
- materials with tunable properties

*Dreams.* It is easy to dream about the future of communications. Here are some dreams that would have important implications for functional materials:

- wireless Internet connectivity anywhere, anytime
- people communicating directly with computers
- systems on a chip

## THE ROLE OF GOVERNMENT

The National Science Foundation, like other government agencies involved in science and technology, must maintain a balance among competing demands. It must address both science and engineering, it must support both research and education, and it must balance the needs of people, instrumentation, and facilities. In doing all this it strives to meet three goals:

- a diverse, internationally competitive workforce of scientists, engineers, and citizens
- discovery in the service of society
- state-of-the-art, broadly accessible databases and shared tools for research and education

Working toward these goals, as an agent for the government’s investments in research and education, means seeking a broad portfolio of integrated investments, providing opportunities across the spectrum of science and engineering, and ensuring excellence through competitive merit review.

One cannot predict the future, but three research areas—the terascale, the nanoscale, and complexity—will be key starting points for the coming decades. As computers become capable of processing terabits of data at teraflop speeds, terascale computational science will provide new insights in areas from climate prediction to economics. Materials science is one of the areas with the most to gain from these new capabilities.

Ideas such as molecular wiring and quantum corrals have already made clear the potential impact of the nanoscale on materials science. The president's recently announced nanotechnology initiative focuses on five areas: biosystems ($20 million), structures and quantum control ($45 million), device and system architectures ($27 million), environmental processes ($15 million), and modeling and simulation ($15 million). Materials are a key component of all five.

The idea of complexity reflects the wide range of scales in our physical environment, from the molecular to the global. Complexity is becoming a guiding principle in materials science, as it is in many other fields.

Education will be as important as research to our future success. The National Science Foundation seeks both to provide the twenty-first-century workforce with knowledge, people, and tools and to enable citizens of all ages to become literate in science, mathematics, and technology. Its approaches to meeting these goals include research on the science of learning, better education of teachers, and increasing diversity by widening access and opportunities.

Reflecting proudly on its first 50 years and forward to its next 50, the NSF seeks above all to follow the lead of Wayne Gretzky, who said, "I skate to where the puck is going, not to where it's been."

## PANEL DISCUSSION

Question: It has been suggested that Moore's law will run out in about 2010. Photonics may also hit the wall about then. If it takes 20 years to introduce new materials, is the planned level of investment enough to meet future challenges?

Weber: I'm glad to get this level of investment! Unfortunately, many people assume that materials will "just be there." This indicates a lack of understanding. The nanotechnology initiative is a good start. An important point is that this initiative comes from the White House, which sees it as an economic issue.

Q: We have heard discussions of structural materials and how they differ from electronic materials, for which the value added is higher. Are we focusing too much on materials instead of systems? How do we encourage entrepreneurial behavior in large companies or divisions and make it successful? The role of a top-level champion is crucial in technology implementation, but it is difficult to find in U.S. industry. If fuel economy and emissions requirements get much tougher in the next 10 to 15 years, for example, then the emphasis will be on alternate energy systems.

Weber: The issue requires a better understanding of the value to the customer of the new product or improvement, as well as the size of the market that may be affected. We are stressing more joint ventures at the precompetitive stage.

Q: Can you provide an example of the new paradigm for getting new materials implemented and into production more quickly? Williams: An example that gets part way there could be the use of forging-casting models. Both GE and Pratt & Whitney require their suppliers to have some level of process modeling and variation control to ensure product consistency.

Mitchell: Another approach may be to use combinatorial methods to screen a wide range of possible material compositions and then to select just a few for further evaluation and optimization.

Eagar: In lithium-ion batteries, the conventional thinking was that performance was controlled by the cation lattice. Computer simulations showed the anion lattice to be the controlling aspect. The theory and model predicted better performance from aluminum-lithium-cobalt systems, and this was verified by tests. This may be the first time a first-principles model preceded the actual development of a material.

Bement: Investment casting may be a good example, too. Defense Advanced Research Projects Agency (DARPA) programs have promoted best practices in industry, including greatly advanced capabilities in mold design and process control.

Q: Materials with magnetic properties have seen a resurgence of interest recently after a dearth of support earlier. Why this renewed interest?

Eagar: Sales of magnetic materials are actually greater than sales of electronic materials, although they are usually less visible. Most sales go to motors, transformers, and so on, for power systems. More and more businesses are investing, so market size is the driver.

Q: We have heard where nanotechnology is going. Are we ahead of or behind the rest of the world in this area?

Weber: A recent study indicates that our level of investment is about the same as that in Western Europe and Japan. As far as getting advances to market, the United States is doing better than Western Europe but worse than Japan.

Q: There may be a different view of the materials dilemma described in Arden Bement’s talk. An alternative approach is to increase risk tolerance by using smaller companies, which, if successful, are then assimilated into larger companies. Universities feed their ideas and students into these smaller companies, thereby linking fundamental research with product development. What is government’s role in promoting this model? What practices should the government adopt?

Bement: This is a food chain model. Current models favor more teaming with big companies—the Advanced Technology Program, for example. We have a different paradigm for advanced materials to do better than the food chain model.

Mitchell: In very competitive technologies, if you do not incorporate new ideas into products and go to market in 18 months, you miss the window of opportunity. You have to bring the business unit and the market along at the same time as you do the development work. Successful companies are able to keep their focus on pioneering research *and* get their results into products.

Williams: The window of opportunity depends on when you decide to start the clock, of course. Regarding small companies, all federal agencies have Small Business Innovation Research (SBIR) set-asides. If an innovation requires a lot of capital, small companies have a hard time handling the financing, and venture capitalists often do not like those kinds of ventures.

Eagar: The reduction in industrial investment in materials has had an important effect on universities. Since there has been no pull for Ph.D.'s in corporate research labs, the ratio of master's degrees to doctorates has been increasing. Students who might previously have pursued a Ph.D. now get an M.S. degree in engineering and then an M.B.A. Then they go to work in the investment arena, where they make more money and have more responsibility.

Q: Displacing old materials with new ones has been a challenge. Is there a conundrum to nanotechnology, namely that the large sunk investment in silicon plants will make companies resist change? Or will a new set of companies arise?

Eagar: Companies often have a difficult time changing. I suggest you read *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail,* by Clayton M.Christensen.

Weber: Some companies do not change, and those companies go out of business. But we are always looking to the future. Competitive pressures are often the impetus for transforming old technologies and extending their life. An example of this is the continuing success of silicon versus gallium arsenide, despite predictions of silicon's demise.

Q: At Lehigh, we teach students about the fiber-composite fan blades that almost caused the demise of Rolls Royce and about the airframe companies' aluminum-lithium alloy development program. How do you approach these episodes in your models?

Williams: One has to understand the failure modes of materials and have a high enough level of confidence to act based on that understanding. Regarding the specific examples you mention, the GE90 engine has successfully used a fiber composite for blades. For aluminum-lithium alloy development, there was probably overoptimism about the how easily the technical challenges could be overcome.

Q: The time-to-market situation varies widely between fields. How does NSF's investment strategy reflect this variation? What is the government plan for infrastructure areas and for slower-moving industry segments? Weber: This challenge is one of many that NSF must address. Our intent is certainly to keep programs going in metals, ceramics, and so on. When a particular material is challenged, threatened with displacement, it tends to improve, so we must address a wide range of processing issues, availability, and so on, as well as new materials, such as polymer composites. NSF tries to keep a balanced portfolio based on the challenges it sees. Today nanotechnology is one such challenge.

Q: What does the panel think of the chemistry content in the education of materials scientists and engineers?

Bement: Purdue's departments are big enough to have their own materials groups. They have woven together a consortium across the campus to provide chemistry information in several areas, such as synthesis research models. This seems to be working effectively.

Q: Jim Williams mentioned a threefold improvement in the thrust-to-weight ratio of jet engines, but the slope of the improvement graph was dropping to near zero. Why?

Williams: Some of the slowing may be because we are still using the same classes of materials. Efforts to improve these materials further have not been very successful, so perhaps we need new materials. Also, the emphasis has shifted from improved performance to lower cost with equal performance.

Bement: We often overlook the business implications of risk and uncertainty. We can offer a real technology advantage, but when all the costs are summed up, it may still be a nonstarter.

Q: We are confronted by a workforce shortage in electronic materials. How can NSF help with this as we try to wire up the country?

Weber: A shortage of people is a problem, but we will also find smarter ways to solve the problem and, thereby, probably reduce the need for people. In the longer term, NSF is concerned about the intellectual base of the country. In the past, we have relied on immigration, but that is changing, and we have to figure out how to meet our needs ourselves.

Q: We see more integration of teams in photonics, for example, than in structural materials. Is this a result of our education system?

Bement: Design processes are different for electronics than for structural systems.

Q: Ceramics are a mature technology. Metals are a mature technology. Silicon has been around for nearly 50 years. What if silicon stops being the driving force?

Eagar: Moore's law is going to fail, and the law of diminishing returns will eventually apply. Biomaterials is an exciting area. Photonics is an exciting area. Nanotechnology is a surrogate for these areas. But we can't ignore the older materials and will need a balanced view.

Mitchell: Materials are not exciting by themselves. It's what you do with them that's exciting. Silicon became a unique material because of what we can do with it. So I have no specific answer regarding what the new materials will be, but new societal needs will create needs for new materials.

Bement: There are limitations in nature, but solutions may be different. For example, we may get around apparent limitations by using networks rather than single devices. We have to be able to understand the limitations early enough to pioneer the correct path.

# Recent Studies and Symposia

*A brief session focused on two reports of recent studies and symposia.* ***Dale F.Stein*** *of Michigan Technological University reviewed the results of a study he chaired recently. Dr. Stein is an emeritus professor of mechanical engineering at the University, where he was head of metallurgy engineering from 1971 to 1979 and president of the university from 1979 to 1991. He was elected to the National Academy of Engineering in 1987 for his work on materials deformation and fracture. Dr. Stein chaired the recently released National Materials Advisory Board study* Materials Science and Engineering: Forging Stronger Links to Users *(National Academy Press, 1999). His talk was a summary of that report. The following description is based on the executive summary of the report.*

***R. G. "Gil" Gilliland*** *of Oak Ridge National Laboratory reported on discussions at a symposium on future materials needs. Dr. Gilliland is associate laboratory director of the Energy and Engineering Sciences Directorate of the Laboratory. Before joining Oak Ridge he held positions in industry and at the University of Wisconsin. Dr. Gilliland was on the organizing committee of Materials XXI, a symposium sponsored by ASM International a few weeks before the forum.*

*The following are summaries prepared by the editors who adapted them from the remarks made by the individual presenters.*

## MATERIALS SCIENCE AND ENGINEERING: FORGING STRONGER LINKS TO USERS

This report[2] is about relationships among the producers and users of materials —how to understand them and how to nurture them (Figure 1). It is also about the process of innovation, from the generation of knowledge through the development and application of a material to the ultimate integration of the material into a useful product. Figure 2 is a simple linear depiction of the phases of this process. Development processes in the real world are more like a series of iterative decision loops than Figure 2 suggests, and the report includes real-life case studies that provide a more accurate nonlinear depiction.

The committee developed the following definition, which both set bounds

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[2] National Research Council. 1999. Materials Science and Engineering: Forging Stronger Links to Users. Washington D.C.: National Academy Press.

on its task and captured the complexity of materials science and engineering:

To extend the usefulness of all classes of materials, the field of materials science and engineering seeks to understand, control, and improve upon five basic elements:

- the life-cycle **performance** of a material in an application (i.e., in a component or system)
- the **design** and **manufacture** of a component or system, taking advantage of a material's characteristics
- the **properties** of a material that make it suitable for manufacture and application
- the **structure** of a material, particularly as it affects its properties and utility
- the **synthesis** and **processing** by which a material is produced and its structure established

A new material or process is unlikely to be researched by the MS&E community and adopted by industry unless it satisfies the perceived needs of both groups. Successful commercialization by industry is driven by four forces: desire for cost reduction, desire for improvement in quality or performance, societal concerns manifested either in government regulation or in self-imposed changes to avoid regulation, and crises. Substantially different forces drive R&D: the availability of funding, the desire to expand the basic knowledge base, an educational mission, the desire for professional recognition, and the availability of equipment. Because of these differences, stronger linkages both within the MS&E community and with others who affect the community are key to accelerating the rate of introduction of new materials into the economy.

A key goal is to overcome the barriers to R&D in Phase 2 (material/process development). This phase is the "valley of death," during which the driving force for innovation changes from "technology push" by researchers to "product pull" by end users. Accelerating this transition requires an environment in which (1) innovations are desired and anticipated by those who will use them and (2) researchers address business considerations early in the development process.

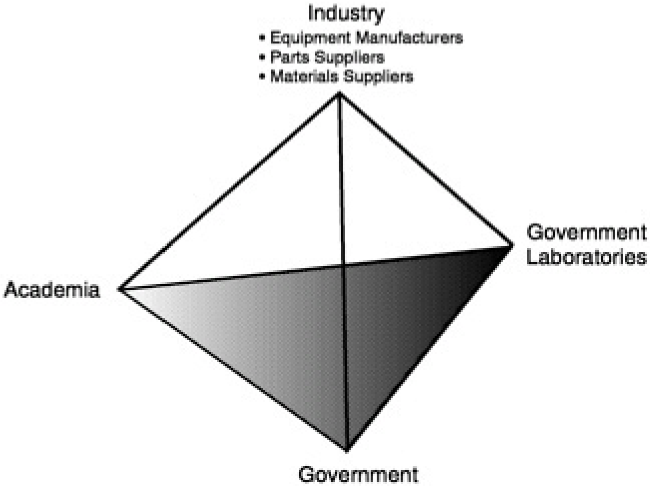

FIGURE 1 Relationships in the materials science and engineering community.

To establish product pull early in the process—in Phase 1 (material concept development) or perhaps even Phase 0 (knowledge-base research)— the following should be given priority: the following should be given priority

- consortia and funding mechanisms to support precompetitive research
- industry road maps to set priorities for materials research
- university centers of excellence to coordinate multidisciplinary research and facilitate industry-university interactions

To improve the transition from Phase 2 to product implementation, the following should be given priority:

- collaboration with end-user industries to identify the data product designers need to assess new materials and processes
- investigation of ways to improve the research infrastructure for materials suppliers and parts suppliers
- extension of the patent-protection period, especially for applications that require lengthy certification
- development of industrial ecology as an integral part of the education and expertise of both researchers and product designers
- development of a regulatory climate based on constructive cooperation and goal setting

The study also includes more detailed findings and recommendations. It is available at <http://books.nap.edu/catalog/9718.html>.

## MATERIALS XXI

The purpose of Materials XXI was to identify market needs for the twenty-first century. Presentations addressed the following topics:

- communications/electronics
- aerospace and defense
- energy
- future needs of developing nations
- ground transportation
- agricultural equipment
- heavy/capital equipment
- infrastructure/construction/residential

Issues discussed at the symposium were the subject of subsequent editorials in the ASM journal *Advanced Materials & Processes*. For more information, contact Peg Hunt at <mwhunt@po.asm-intl.org> or 440–338–5151.

FIGURE 2 Notional phases of the materials innovation process.[2]

# The Role of Materials in Information Technology

*The forum included topical sessions on the current and future role of materials in four selected areas. The first of these sessions, on information technology, began with an overview by* ***Andrew E. Lietz,*** *president and chief executive officer of HADCO Corporation, a manufacturer of printed circuits and electronic interconnection devices. He is also a member of the Board of Directors of the National Electronics Manufacturing Initiative (NEMI).*

***Paul S. Peercy*** *of the University of Wisconsin gave a technical perspective. Dr. Peercy is dean of engineering at the University in Madison. Until September 1999 he was president of SEMI/SEMATECH, a nonprofit technical consortium of more than 150 U.S.-owned and -operated companies that constitute the equipment and supplier infrastructure for the U.S. semiconductor industry. He has also been director of microelectronics and photonics at Sandia National Laboratories.*

***Lawrence Dubois*** *of the Defense Advanced Research Projects Agency (DARPA) gave a perspective from the federal government. Dr. Dubois recently became vice president of the Physical Sciences Division of SRI International. At the time of the forum he was director of the Defense Sciences Office at DARPA. The Defense Sciences Office is responsible for an annual investment of nearly $300 million in technology development, including the development of defense applications for advanced materials.*

*The session concluded with a panel discussion. The following are summaries prepared by the editors who adapted them from the remarks made by the individual presenters.*

## MATERIALS AND ELECTRONIC INTERCONNECTS

Interconnect technology is as fundamental to the electronics industry as semiconductors. Demand for electronics-based products is driving rapid growth in the interconnect industry, and the emergence of new applications is driving rapid change. Staying competitive requires meeting demands for circuit miniaturization, speed and bandwidth, environmentally friendly production, and lower production costs, all of which require new materials and processing technologies. Moreover, in today's global marketplace, U.S. manufacturers need advanced technology to compete against products from countries with lower manufacturing costs.

Improved dielectric materials will increase circuit densities by reducing feature sizes for component interconnection and attachment and enabling microvias and higher layer counts. The electrical characteristics for these materials include lower dielectric constants, improved bulk properties related to signal loss, and controlled impedance. Improved thermal characteristics include thermal stability, fire retardance, and higher operating temperatures. Mechanical requirements include improved dimensional stability, thickness control, and conductor adherence. Chemical properties include moisture stability and better resistance to process chemicals. Last but not least, materials must be available at low cost and in high volume.

A key cost-reduction goal is to reduce component counts for board assembly by embedding passive components into boards. This will also require new materials with specific capacitance, resistance, and inductance properties, as well as improved dimensional stability and adhesion. Mixed-polymer dielectric composites will be important, particularly as low-cost alternatives to the fluoropolymers now used for high-frequency circuitry.

Basic materials research for printed wiring boards must include improvements in the robustness of metal-polymer and matrix-polymer interfaces, improved photoresists and etchants and other process consumables, and active “smart” composites and interfaces to enhance interconnect performance and processability.

Manufacturers also need new materials and processing techniques to respond to environmental concerns. Materials substitution is one important approach, particularly lead-free alloys and nonhalogenated resins. Going beyond substitution will require the development of new processing chemistries.

U.S. interconnect companies have been less aggressive than their global competitors in implementing new technologies at high volume. Resources to support R&D are extremely limited, especially for smaller firms, so rapid commercialization of technological advances is critical to maintaining competitiveness. Substantial investment by the semiconductor industry has resulted in a deep materials and processing knowledge base that has greatly accelerated commercialization of integrated circuit designs. The interconnect industry must make analogous efforts to reduce the cycle time for implementing new materials from years to months.

## MATERIALS RESEARCH FOR COMPUTING AND COMMUNICATION

The contribution of the electronics industry to the gross world product reached a new high of 2.8 percent in 1999 and seems sure to continue rising. Despite its worldwide sales of $998 billion, the industry depends on an inverted pyramid of successively smaller industries. Materials constitute the tip of this pyramid, at $22 billion, including $3 billion in the United States. For example, half the cost of electronic packaging is for materials. The United States leads the world in introducing new electronic materials, and according to Texas Instruments, high-technology products account for 45 percent of the growth of the U.S. gross domestic product.

The rate of progress in the speed of silicon chips, the communications capacity of optical fiber, and the density of information storage continues to accelerate—approximately doubling each year and following Moore's law with remarkable fidelity. Several times more transistors already exist on an 8-inch wafer of state-of-the-art memory than there are people on Earth. Optical fiber is being installed worldwide at a rate of 2,000 kilometers per hour.

In about a decade, all of these technologies will be approaching what today appear to be fundamental limits. Transistor dimensions will approach a few atomic layers, and according to the road map of the Semiconductor Industry Association, Moore's law will slow down. In place of continuing improvement in chip performance, progress will depend on continued improvements in chip architectures and more efficient utilization of semiconductors. Driven by improvements in materials technologies, prices will continue to drop, with the cost per instruction per second for processors, and per bit per second for communications, falling by four orders of magnitude in 20 years. Continued improvement will be achieved by the development of new dielectrics, better reliability, advances in interconnection technology, and the design of full systems on a chip.

## MATERIALS, MATERIALS PROCESSING, AND THE FUTURE OF INFORMATION TECHNOLOGY

New materials create new technologies, and new technologies create new materials. The bottom-up approach starts with new materials and phenomena, such as nanomaterials and spin effects, and develops new technologies that they enable. The top-down approach starts with new architectures and new algorithms, such as fault tolerance and quantum computing, and develops new materials to meet their requirements. The two approaches complement and reinforce each other.

DARPA-supported research follows both these paths. In an example of the former, giant magnetoresistance materials have enabled the development of low-cost magnetic random access memory (RAM) that is nonvolatile, radiation hard, as fast as static memory (SRAM), as dense as dynamic memory (DRAM), and infinitely cyclable. Spin effects in semiconductors will lead to revolutionary advances in photonics and electronics, including high-performance lasers, very dense quantum-dot memories, and other applications yet to be considered.

DARPA's program in molecular electronics is an example of the second approach. Molecular electronics is made possible by new fabrication technologies and driven by technological needs, such as the skyrocketing cost of circuit fabrication, the demand for enhanced computing power, and fundamental roadblocks facing silicon technology. The goal of the program is to demonstrate computational functionality in defect-tolerant architectures fabricated by direct assembly of molecular devices. Molecular logic gates, single-bit and two-bit memories, and interconnects have already been demonstrated.

## PANEL DISCUSSION

The above talks were followed by a panel discussion. A summary of the discussion follows.

Materials technologies become much more difficult at scales smaller than 100 nm. Moore’s law may continue to apply for several more decades, but it may be driven by improved architectures. Andy Lietz indicated that the short time horizons on Wall Street present industry with a difficult challenge when seeking money for development.

An emerging trend in the U.S. electronics industry is outsourcing of manufacturing, testing, and so on. Although this results in the effective use of capital and high productivity, it does not favor the support of long-term materials research, which typically takes 15 to 20 years to achieve maturity. In printed-circuit technology, more than 50 percent of manufacturing takes place in Asia. These trends suggest that the United States might not be competitive in this industry in the future.

Interconnect technologies that require materials development include backplanes, integrated circuit (IC) chip assembly, high-speed laminates, surface mount technology, and embedded passive and high-speed connectors—faster, lighter, cheaper, more reliable, and environmentally sound! In all cases, materials development is focused on current needs, and little longer-term research is under way. To overcome the dilemma, consortia of industry, government, and academia should be established to provide a long-term focus, establish road maps, reduce risk, and capture emerging product opportunities.

# The Role of Materials in Health and Biotechnology

*The second topical session examined the role of materials in health and biotechnology. The overview talk in this session was presented by* ***Robert Z. Gussin*** *of Johnson & Johnson, where Dr. Gussin is the corporate vice president of science and technology. In that position, he serves as the company's chief scientific officer. He also holds adjunct professorships in pharmacology at Michigan State University and the University of Utah.*

***Galen D. Stucky*** *of the University of California, Santa Barbara, provided a technical perspective. Dr. Stucky is a professor in the Department of Chemistry, the Materials Department, and the Biochemistry and Molecular Biology Program of the University. The focus of his recent research has been on understanding how nature assembles organic and inorganic biomaterials and the molecular design and assembly of hierarchically structured three-dimensional devices.*

***Robert Langer*** *of the Massachusetts Institute of Technology provided a second technical perspective. Dr. Langer is the Kenneth J.Germeshausen Professor of Chemical and Biomedical Engineering at MIT. His research interests include polymers for controlled release of proteins and macromolecules and the development of new biomaterials. He is a member of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.*

***John T. Watson*** *of the National Institutes of Health (NIH) described a government view. Dr. Watson is the head of the Bio engineering Research Group and acting deputy director of the Division of Heart and Vascular Diseases of the National Heart, Lung, and Blood Institute of NIH. His education includes graduate degrees in both mechanical engineering and physiology. His research interests include medical implant design and science, biomaterials, imaging, and heart failure. He is a member of the National Academy of Engineering.*

*The session ended with a panel discussion. The following are summaries prepared by the editors who adapted them from the remarks made by the individual presenters.*

## MATERIALS AND HEALTH: AN OVERVIEW

Biomaterials incorporated into medical devices have had at least as great an impact on health care in the twentieth century as have pharmaceuticals. Virtually all types of material systems have been used in health care applications, including metals and alloys, ceramics, polymers, composites, and biologically derived biomaterials. Both bulk and surface properties must be carefully selected and designed for suitability of service and compatibility with biological systems.

Among metals and alloys, there are four common systems: stainless steels, cobalt-chromium alloys, titanium and its alloys, and more recently some aluminum-zinc systems. In hard tissue, metals and alloys are used for fixation and joint replacement. In the vascular system, they are employed in stents and heart valves. Stents are also used in the bile duct and urinary tract. Dental applications may involve some of these same alloy systems as well as gold, amalgams, and tantalum. Platinum and platinum-iridium alloys are used frequently in implantable conductors, such as pacemaker leads.

The most common biomedical ceramics are alumina, zirconia, silicon nitride, and carbon. These materials may be completely bioinert, surface-active, or fully resorbable. Bioinert materials are often used in orthopedics. Surface-active materials, such as bioglas and ceravital, dense nonporous glasses, and hydroxyapatite, are used in coatings, in dental applications, on bone plates and screws, and sometimes for bone filling. Resorbable ceramic materials, including phosphates, oxides, and corals, are used to repair bone damage, for bone filling, and even for drug delivery.

A wide range of polymers are used in medical devices, both implantable and extracorporeal, with applications from kidney dialysis to heart valves. They can be inert, surface-modified, degradable, erodable, absorbable, or resorbable. Degradable and erodable materials are distinguished from absorbable and resorbable materials in that the latter leave no residue after their chemical breakdown. As a result there is no long-term foreign-body reaction and no nidus for microbial colonization. Historically, suture materials have been the most successful application of resorbable polymers. Future applications will include scaffold materials for tissue engineering, as well as vehicles for implantable drug delivery.

Composite materials are used most frequently in hard-tissue applications, including ceramic composites for dental applications and fiber-based composites for orthopedics.

Biological materials fall into several categories: hard-tissue, soft-tissue, blood-derived, plant-derived, and other naturally derived chemicals. The most common examples are collagen-derived materials used for hemostasis, tissue filling and enhancement, drug delivery, and other applications.

Recent research trends that will challenge materials designers include the development of implantable biosensors, artificial muscles, drug delivery hydrogels, wound dressings, sealants and adhesives, tissue augmentation and regeneration, immunoisolation devices, and specific surface chemistry modifications. Many of these trends will be pursued through the broad field of tissue engineering. Skin, bone, and cartilage applications have been most successful to date, but the focus of research is shifting toward tissue-engineered organ replacements. In general, the objective of tissue engineering is to reinstate tissue function, facilitate tissue transplant, provide localized drug delivery, facilitate organ reconstruction, and implement cell and gene therapy.

In summary, advances in biomaterials design have great potential for contributing to advances in health care.

## TECHNICAL PERSPECTIVE 1

The biological world has much to teach us about the synthesis of materials, not just materials for medical applications, but also so-called biomimetics or bio-inspired materials.

A living cell can be considered a tiny materials factory, a single system capable of synthesizing and processing materials with a three-dimensional hierarchical structure. Synthesis takes place on the nanoscale and can assemble composites with an asymmetric distribution of reinforcing materials in an organic matrix. Interconnects can be managed at a molecular level. The “factory” is self-repairing and self-correcting and performs much of its synthesis in a parallel-processing mode.

One such biological factory is the diatom, which can both produce silica and extrude polysaccharide. In fact, diatoms extrude polysaccharide through submicron pores, an enviable example of nano-processing. Aida, in Japan, has demonstrated a similar catalyzed microextrusion polymerization process of polyethylene resulting in improved structural properties.

This biological example should inspire and encourage us to pursue nanoscale chemistry and processing. Specifically, we should be encouraged about the prospects for molecular design and processing of three-dimensional silicate surfaces and the prospects of doing such processing in biologically compatible conditions rather than at elevated temperatures. One biologically inspired system is an organic matrix block copolymer nanocomposite with potential applications in optical limiter coatings, wave guides for microlaser arrays, sol-gel encapsulation of enzymes, and bio-sensors.

Other biological inspirations include species with so called “electrocyte” cell arrays capable of delivering electrical power in excess of a kilowatt for substantial periods, such as 80 seconds. The three-dimensional hierarchical structure of so many biologically produced materials has already inspired some novel polymeric MEMS applications using two-photon optical curing with resolutions of 0.2 microns laterally and 0.28 microns in depth.

## TECHNICAL PERSPECTIVE 2

To date the overwhelming majority of materials used in health care applications, including alloys as well as polymers, were derived originally for nonmedical purposes. For example, the diaphragm material used in the first implantable artificial heart was a polyurethane of the same type used in women’s undergarments. Now more than ever, we need a process of rational design for materials for in vivo use.

Certain examples of this new paradigm for materials selection and design already exist. In drug delivery, polyanhydride materials were designed to be surface rather than bulk eroders. Therapeutic chemicals trapped in a polyanhydride matrix can thereby be released at a controllable rate. Depending on the polymer design, complete dissolution can be programmed to take from two weeks to four years. This technology has already been applied for brain cancer therapy, with early results showing as much as a fivefold improvement in the survival of tumor victims. The technology has been approved by the Food and Drug Administration.

Another example of materials designed for in vivo application is the so-called chemical microchip. This device permits externally controlled administration of microdoses of pharmaceuticals at the specific implant site.

A third example is in the growing field of tissue engineering. For many tissue-engineered products, cells are grown on a scaffold of polymer materials, such as polylactic-glycolic acid (PLGA). With intentional design of new scaffold materials, one can envision changing the rate of degradability, improving biocompatibility, designing suitable physical properties for the substrates, and even being able to attach specific ligands selectively. Our research team’s inventory already includes at least 24 different tissues.

## GOVERNMENT PERSPECTIVE: MATERIALS FOR A HEALTHY LIFE

As Dr. Langer noted, current synthetic materials for in-vivo applications were not initially designed for such purposes and are therefore imperfect in their biomedical application. Another concern is that biomaterials research has relatively low visibility. When developing new materials systems, the research and development community should start with patient needs rather than looking for solutions off the shelf. Patient needs that will motivate new material designs include quality of life, performance, safety, failure risk, lifetime, and need for replacement. Recent work on a synthetic ion channel has raised hopes for new materials that will emerge from the marriage of nanotechnology and biology.

Since 1997, the National Institutes of Health has become increasingly active in support of biomaterials research. The Bioengineering Consortium initiated in 1997 is intended to support bioengineering partnerships performing design-directed research. The NIH-sponsored Biomaterials and Medical Implant Science Coordinating Committee met in early 2000 to discuss ways to improve implant performance. It recommended a national educational program and an implant-retrieval information system.

## PANEL DISCUSSION

Question: The so-called “valley of death” between research and commercialization seems especially troublesome in the biomedical field. Can you comment on steps to overcome the difficulty of going from research to practice?

Langer: Biomedical engineering departments in academia are trying to focus more on applications and are beginning to have some success. Small biotechnology start-up companies are also becoming increasingly effective in pulling technology from the universities.

Watson: It would be helpful if engineers in all disciplines had some background in biology.

Gussin: I, too, would recommend some background in biology for engineers. Johnson & Johnson is deliberate about assembling teams that include both engineers and clinicians.

Q: What about the difficulties associated with FDA approval? How limiting are these?

Langer: The FDA approved polyanhydride with a total development cost of something under $10 million. The FDA can put good ideas on a fast track.

Comment: It is important to note that the FDA approves devices, not materials.

Q: The university engineering curriculum is already quite full. To make room for biology in the curriculum, what would you take out?

Watson: Take out chemistry.

Langer: Biology is already part of the curriculum at MIT for all engineers.

Q: But making room for biology in the MIT engineering curriculum meant eliminating electives unless freshmen arrive with advanced placement credits in chemistry.

Q: What about the financial risk to corporations (such as Dow Corning) that could supply or develop new implant materials?

Watson: Dow Corning changed its design from a proper one to a poorer one and began to experience design failures. I do believe that certain disorders suffered by women with failed implants are related to the silicone materials.

Gussin: Because of the threat of litigation and the fact that for large materials producers the biomaterials market is small, businesses are reluctant to look at new materials except perhaps those that could have an impact on life-threatening conditions.

Comment: Many large companies have pulled out of their activities in biomedical research, development, and production. We should be concerned that some of these, the very best in our nation, are not participating in this important field.

Q: Is the NIH interested in supporting nonmedical research built on a biomaterials foundation—sensors based on antigen-antibody interactions, for example?

Watson: Probably not, unless the applications occur as a direct spinoff from a biological or biomedical research effort.

Q: How do we work the problem the other way?

Stucky: Develop and offer interdisciplinary courses at the university level. Make sure future workers understand two languages, engineering and biology. Look for and accommodate spinoffs in both directions, biomedical and nonbiomedical.

# The Role of Congress

*This session examined the role of Congress in materials science policy and funding for research and development. Three Congressional staff members participated in a panel discussion.*

***Arun Seraphin** was a fellow in the office of Senator Joseph Lieberman (D-Connecticut). His fellowship was sponsored by the Materials Research Society. Before coming to Capitol Hill, he was at the Institute for Defense Analyses, a think tank that provides technical support for the U.S. Department of Defense. His research expertise is in electronic materials. Dr. Seraphin is now on the professional staff of the Senate Armed Services Committee.*

***Scott Lockledge** was a fellow in the office of Representative Vernon Ehlers (R-Michigan). His fellowship is sponsored by the American Chemical Society. Before coming to Washington, Dr. Lockledge was in industrial research at Malco Chemical Company and PT Corporation. Most of his research was on corrosion.*

***Michal Freedhoff** is a member of the minority staff of the Energy and Environment Subcommittee of the House Science Committee. Dr. Freedhoff first came to the Congress in 1996 as a fellow sponsored by the Materials Research Society and the Optical Society of America. Her research was on the optical properties of nanocrystals.*

*The following are summaries prepared by the editors who adapted them from the remarks made by the individual presenters.*

In his opening remarks, Dr. Seraphin noted the imbalance in congressional attitudes toward the health sciences and the physical sciences. To elevate interest in the physical sciences, he suggested building coalitions like those that support biomedical research and generally being more politically savvy—taking more advantage of positive newspaper editorials and opinion polls about research and making more congressional visits, for example. R&D funding will be a key issue this year, as always; overall, prospects look good, but the proposed budget for defense science and technology is disappointing. The doubling bill mentioned by Senator Domenici will be a focus of Dr. Seraphin's efforts this year.

Dr. Lockledge's opening remarks highlighted congressional interest in K-12 science education, which was a major recommendation in last year's congressional science policy report. The forthcoming National Science Education Act will focus on finding, training, and keeping science teachers, as well as on developing a national consensus about the content, sequence, and scope of mathematics and science education. Other issues that Dr. Lockledge expects to deal with this year include climate change, genetically modified food, stem-cell research, nanotechnology, and funding for the national laboratories.

Dr. Freedhoff noted the dramatic recent shift in Washington's perception of science and technology. Both political parties now give top priority to high-technology issues. Alan Greenspan mentions science and technology in his remarks about the economy. The president talks about technology in his speeches. For the first time, companies from Silicon Valley are opening Washington offices. This transformation presents the materials science and engineering community with a tremendous opportunity to convey its message to policy makers.

Question: Materials are not generally included in the science curriculum. How can this be changed?

Lockledge: Our schools certainly need a lot of very fundamental reform, but there is serious debate about the federal role here. Decisions about education are made at the local level in most states, and this makes any sort of national change difficult. A lot can be done by scientists themselves, however. For example, professional societies can develop curricula and make them available, and working scientists can go into schools and participate in classroom activities. I used to participate in a program called Science Is Fun, doing chemistry demonstrations for third graders, and they just ate it up.

Q: How effective in the Congress are reports prepared by the NMAB and other groups? What kinds of reports are most effective?

Freedhoff: Before coming to the Congress, I put together some one-page handouts for the American Institute of Physics, and they have been very useful for congressional staff when members are giving speeches, offering amendments, and so on. Generally, though, long reports are more useful in the agencies than on Capitol Hill. There are exceptions. Those who are already engaged, such as those of us here today or staffers charged with putting together speech materials, do find longer, more detailed reports useful. So the scientific community needs to find a way to enlarge the circle of interested parties. A good approach is for an affected constituent to bring a report to his or her congressional office.

Seraphin: In our office, I often prepare a summary for the senator, just a page or two, generally from the executive summary or some photocopied figures. Members are very good at taking home a notebook full of memos and coming back the next day with perceptive questions. Then if the topic comes up later, I know where to get more information. Most staffers find it really useful to have contacts who will give straight answers when needed.

Q: Is the Congress aware of the funding situation for materials research in the Department of Defense and the role this funding plays in education?

Seraphin: Some offices are aware. Why not bring one or two well-spoken students along when you make a congressional visit? That would help.

Freedhoff: Generally, the congressional perception is that NSF and NIH are the agencies that fund university research. A few fundamental advances, such as the Global Positioning System and the Internet, are known to be the result of DOD funding, and I would encourage you to make more use of these examples.

Q: Why are civilian agency budgets in science and technology going up at the same time as the DOD science and technology budget is going down?

Seraphin: The simple answer is that the Cold War is over. The Pentagon is concerned about readiness, pay raises, and maintenance, and the Joint Chiefs tend not to have technical backgrounds, so there are no strong advocates for science and technology.

Q: Dr. Freedhoff mentioned that some congressional offices do take an interest and will read reports on science and technology. How many?

Seraphin: Not many. The Senate Science and Technology Caucus has 6 members out of 100.

Freedhoff: The House Science Committee has 45 to 50 members, and there are other groups, such the Military R&D Subcommittee of the Armed Services Committee. Plus some members have districts that include a major university or a national laboratory or a high-technology company. But the interests of these members vary; they follow some issues more closely than others.

Lockledge: Out of 535 members in both chambers, the ones with a genuine interest in science and technology can be counted on two hands. The rest who take an interest do so for political reasons, because of what is happening in their district. What we need to do is boost that political interest and raise its profile.

Q: What about the doubling bill, H.R. 3161?

Lockledge: The bill is basically symbolic. It doesn’t do the hard work of deciding specifically what areas need funding and when and how. The reality is harder than just saying we will double everyone’s budget.

Q: In general, our community has done a poor job of promoting public awareness of materials and their roles and benefits. How can we do better?

Seraphin: In the biomedical area, a group called Research! America has shaped an effective message using television and newspaper advertising and activities on Capitol Hill and in congressional districts. I understand that Mary Good, the former under secretary for technology of the U.S. Department of Commerce, is talking about developing a similar organization for the physical sciences. That would be a great start.

Comment: One could replicate a program in Michigan in which scientists and engineers meet with their local representatives in their district offices— not in Washington, because of the constant time conflicts there. The contacts are organized through Sigma Xi. To be most effective, don’t do it for just your own company or university, don’t do it for just your own field, and don’t do it in Washington.

Freedhoff: Invite members to visit your lab, tour your university, give a talk at your company. These things can heighten awareness much more than an office visit in Washington.

Q: What about earmarks and “pork”? Is the situation getting better or worse?

Freedhoff: The Science Committee is certainly concerned about this, but unfortunately George Brown is no longer with us, and no one has yet risen to the occasion as he used to.

Lockledge: Let me take a contrariant view. Something that has really struck me since coming to Capitol Hill is how difficult it is to attract resources to districts that don't already have a strong science and technology base. If they don't have it, they can't get it, and they can't get it because they don't have it. We have to make sure that funds are well and wisely spent, but on occasion there are valid reasons for earmarks, too.

Comment: There's always a reason why any particular earmark is the greatest project ever. But for a funding agency, it is very hard to go through an agonizing process of organizing and optimizing the limited funds available, only to have that process disrupted at the last minute by earmarks.

Freedhoff: Let me put a question to the audience, though. Would the professional societies you belong to ever issue a statement condemning a specific earmark, as opposed to condemning earmarks in general? I doubt it. So it's not just on us. It's on you, too.

Comment: I heard a talk by Representative Tom Davis a year ago, and he made two interesting points. First, most members do not want to be on the Science Committee, and second, scientists and engineers are difficult constituents because we make ourselves heard only when we have something negative to say.

Seraphin: Everyone likes positive feedback. Scientists do have a reputation of whining and complaining about funding all the time. Instead, why not make it clear how a member's vote helped his district? Or you could create a media opportunity for him.

Lockledge: It's true that a seat on the Science Committee is not a highly sought after position. When you come to the Congress as a new member, your first job is to get reelected. Being on the Science Committee doesn't help with fundraising, so members don't seek it out unless they have a particular interest or background.

Q: Would it seem self-serving if universities with materials programs— and that would cover most congressional districts—offered to serve as resources to their representatives and held forums on technology for them and their staffs in their districts?

Seraphin: I'm not sure it should be the universities. You would have a better chance going through local officials. Most states have a technology promotion office, for example.

Freedhoff: Or your local Chamber of Commerce.

Lockledge: Don't worry about promoting yourself. Other groups are not shy about mentioning that they voted for or gave money to an elected official. Make your existence known.

Q: With membership dropping and finances being what they are, it can be hard to sell professional societies on the importance of sponsoring congressional fellowships. Some of us are enlightened, but others don't see the value. Who pays your salaries and how important is it to have people like you?

Seraphin: We get stipends from our sponsoring societies. In my case, I also get a little money from my company, and I am expected to go back there when my fellowship ends. If you're looking for people to help make the case that the fellows program is important, I would be glad to help put together a stack of letters from legislative directors, senators, and so on, explaining how valuable fellows are and what role they play.

Freedhoff: You might also invite some fellows to come and talk in person to your society's board. Regarding the cost, societies can share the cost of a fellowship. The Materials Research Society and the Optical Society of America do this, for example.

Lockledge: Let me give an example of what a fellow can actually do. As part of the education initiative that I mentioned earlier, we have instituted a series of monthly lectures on Capitol Hill about science and math education. The series now has sponsors in both parties and in both the House and the Senate. I'm hopeful that it will be quite a big deal. I don't think this would have happened if I hadn't been here.

# The Role of Materials in National Security

*The third topical session examined the role of materials in national security. The overview talk in this session was presented by* ***David O. Swain*** *of the Boeing Company. Dr. Swain is president of Phantom Works, Boeing's research and development organization. Before the merger of Boeing and McDonnell Douglas, he held a variety of positions at McDonnell Douglas, starting in 1964 as an engineer on the manned Gemini project. His goal for Phantom Works is to advance Boeing's competitiveness through technology development, process improvement, and new product development, with a special focus on making products more affordable and more capable.*

***C. Paul Robinson*** *presented next. Dr. Robinson is president of Sandia Corporation and laboratory director of Sandia National Laboratories. He spent most of his early career as a physicist at Los Alamos National Laboratory, where he led the laboratory's defense programs. From 1988 to 1990, he served as the chief negotiator and head of the U.S. delegation to the U.S.-U.S.S.R. nuclear testing talks in Geneva. Dr. Robinson is a member of the National Academy of Engineering.*

***Maxine Savitz*** *of Honeywell was the next speaker. Dr. Savitz joined Honeywell (previously AlliedSignal) in 1985. From 1987 until June 1999, she was general manager of AlliedSignal Ceramics Components, the only U.S.-owned manufacturer of silicon-nitride structural ceramic for gas turbine applications. She is currently general manager for technology/partnerships. Prior to joining Honeywell, Dr. Savitz was with the Department of Energy and its predecessors, where she was deputy assistant secretary for conservation for four years. She is a member of the National Academy of Engineering and a former member of the National Materials Advisory Board.*

***Lewis E. Sloter II*** *of the U.S. Department of Defense gave the view from the Pentagon. Dr. Sloter is the Department of Defense staff specialist for materials and structures and is currently assigned to the Office of the Deputy Under Secretary (Science and Technology). He is responsible for technical oversight of Defense Department science and technology activities in materials, processes, and structures and for technical assessments associated with materials manufacturing and engineering applications.*

*The session ended with a panel discussion. The following are summaries prepared by the editors who adapted them from the remarks made by the individual presenters.*

## MEETING THE CHALLENGES OF AEROSPACE

The aerospace industry is a giant. Boeing has more than 6,000 military planes in the field, and more than 10,000 commercial craft. Each day 3 million people fly on 43,000 flights on these planes. Over the past 50 years, the challenges facing the aerospace industry have changed significantly. Initially, performance was the focus of both customers and manufacturers. Beginning in about 1982, the focus of customers changed to value— obtaining the same or better value at reduced cost—but until 1987, the industry stayed focused exclusively on performance, resulting in an imbalance between customer and supplier. Since 1997, customer and supplier have converged again, this time aiming for reduced cost, equal or better performance and quality, and shorter cycle time.

To reduce cycle time and cost, the aerospace industry has relied on innovative technologies, such as three-dimensional modeling and simulation and integrated tool sets. One example is the Delta IV launch vehicle, the first new U.S. rocket in 25 years. During the development of this rocket, various trade-offs were carefully considered, including trade-offs among requirements and between cost and performance. The result of paying so much attention to these issues was a shorter than historical development time, half the historical development cost, and a reduction in the parts count by 70 to 80 percent. The launch vehicle makes extensive use of technology that was previously demonstrated on other platforms, such as friction stir welding (which ultimately resulted in inspection-free joints) and cast titanium (which reduced cycle time and cost).

Another example is the C-17 transport plane, for which McDonnell Douglas originally won the contract in 1981. The secrets of this project's success include the use of fiber-reinforced composites and high-speed machining. Particular attention was paid to designing the tail section for affordability, leading to a new horizontal tail made of composite and metal, with a 20 percent weight reduction and an 80 to 85 percent part reduction. Paying extremely close attention to cost, especially in the high-cost areas, led to other improvements. For example, the aircraft contains more than 43,000 fasteners, each of which originally required wetting before installation. The introduction of prewetting saved $2 million.

On a cautionary note, the aerospace industry is reaping the rewards of 10 to 20 years of technology development. At present, only incremental improvements are being pursued vigorously because of the perception that technology leads only to improved performance, which is not currently in as much demand as are reduced cost and cycle time. We must remember that science and technology are also key to lower cost and cycle time for both defense and commercial aviation. For this reason, we need continued investment in the science and technology base. Science and technology make products more affordable.

## MATERIALS NEEDS FOR NATIONAL SECURITY

Our national security concerns have changed profoundly in recent years. The Cold War has ended, and we find ourselves in a multipolar, rather than bipolar, world. Rogue states and groups have appeared. New threats, such as chemical and biological agents, are of great concern. The terrorist chemical attack on the Tokyo subway in 1995 sounded a warning of this change. Had the temperature been a few degrees different, several thousand people could have died, with no prior warning or appropriate emergency response.

Meanwhile, the arsenal we rely on for our national security continues to age. New capabilities are being added in some areas, but other parts of our defense are slated to remain in service many decades past their original design lives. The nuclear stockpile is one example. Another is the aging of our aircraft, both military and commercial, as illustrated dramatically by the Aloha Airlines disaster in 1988.

To address these issues, we need new approaches to detecting, identifying, and neutralizing new threats and to certifying the continued performance of the aging components of our national defense system. New materials and processes will be critical to these tasks. For example, detection and identification will require systems that are smaller, more highly integrated, and more complex than have ever before been fielded. Here are some examples of materials and processing needs:

- New materials, such as amorphous diamond, with the wear resistance of crystalline diamond as well as tailorable stress characteristics. This material may be useful in ultrareliable microsystems that perform either mechanical or sensing functions.
- New ways to process materials that, for example, result in entirely new surface properties through new ion beam processing techniques or that allow incorporation of motion into silicon devices to enable microelectromechanical systems (MEMS) with the same reliability, low cost, and high functionality that we take for granted in silicon-based microelectronics.
- New ways to integrate materials into a component or system such as a chemistry laboratory on a chip. An example is a gas analysis capability in a few-square-centimeter area which includes a preconcentrator, a 1-meter separation column, and an output sensor that can perform a chemical analysis in a matter of a few seconds.
- Fabrication of structures at smaller dimensions than we thought possible not so very long ago. A new form of silicon, the photonic crystal, has the potential to dramatically increase the functionality of this ubiquitous material by introducing the ability to control photons.
- Understanding of materials and processes throughout their life cycle through modeling and simulation. The phenomena of interest occur at multiple length scales, requiring a sophistication in the approach to modeling and simulation that is just beginning to be possible.
- Application of materials science and engineering approaches and techniques to new areas such as detecting and responding to biological threats.

These materials needs are not unique to national security. They have been reiterated in much of what we have heard at this forum. In fact, they are echoed in a recent study, *Condensed Matter and Materials Physics: Basic*

*Research for Tomorrow's Technology* (National Academy Press, 1999). Some of the strategic research themes identified in that study are the very materials research and engineering needs outlined here:

- the synthesis and processing of new materials
- the drive to reduced dimensionality and nanofabrication
- the inexorable march toward increasing complexity
- the foray of materials research approaches and techniques into soft condensed matter and biological arenas
- the move from empiricism toward predictability in the simulation of materials properties and processes

## THE ROLE OF MATERIALS IN NATIONAL SECURITY: THE PAST, THE PRESENT, THE FUTURE

More than 20 years of ceramic materials technology development for gas turbines has led to improved high-temperature ceramic materials, component manufacturing technology, design and life prediction methodologies, and ceramic integration experience for a variety of applications. Honeywell's ceramic development programs have accelerated commercialization of ceramics for industrial engines, aerospace applications, and hybrid vehicles.

Ceramics exceed the capabilities of metallic components. Because they have one-third the density of superalloys, they offer significant weight savings, improved metallic disk life, faster rotor response, and reduced containment requirements. They can operate uncooled at up to 2500 °F, leading to increased power and lower specific fuel consumption, as well as lower emissions. They also have five to ten times higher resistance to wear and erosion/corrosion and at least twice the thermal low-cycle fatigue life.

Today's ceramics are very different from their predecessors. They have in-situ reinforced microstructure, giving high strength, high fracture toughness, and excellent thermal shock resistance. Their high Weibull modulus gives low variability and high predictability. Advanced computer design tools produce robust designs. High volume can drive the costs into a competitive regime, and production parts are now in commercial service.

Microelectromechanical systems (MEMS) are based on three principles combined on an integrated chip or single substrate: miniaturization of mechanical structures, microelectronics, and massively parallel architectures. These allow sensing, computation, actuation, and control to be merged in a single device. Features can include thin-film sensors and materials, optical detectors and emitters, and monolithic integrated microstructures. Applications under current study and development include fluid flow sensors, fluid property sensors, flame detection and combustion controls, ultraviolet detectors, gas analyzers, biological sensors, low-cost infrared sensors, and infrared sensor testing.

New materials on the horizon may have a significant impact on future devices. One class of promising new materials is single-wall carbon nanotubes that may be used as actuator materials. The properties of these materials are truly extraordinary: modulus of 6 million kg/cm$^2$; surface area of 1,500 m$^2$/g; strength of 0.3 million kg/cm$^2$; conductivity of 5,000 S/cm. An actuator has been fabricated that operates at about 1 volt in seawater or blood, suggesting possible marine and medical applications.

Materials developed in the twentieth century are slowly entering military systems when they can solve a problem that conventional materials cannot. The challenge for the future is to accelerate their insertion into production hardware so that it takes less than the current 15 to 20 years. Tools must be developed that will lead to more rapid acceptance by designers. There are many exciting materials for the new millennium with potential roles in national security, including piezo materials, such as aluminum silicates and other smart materials, and catalytic systems for remediating environmental hazards. It will be critical to search for materials that can play a dual role— materials with both military and commercial applications.

## GOVERNMENT PERSPECTIVE

Although there is support for science and technology (S&T) at the highest levels of the Department of Defense, the S&T budget is raided rather regularly to pay for other matters that arise, such as operations in Kosovo.

We live in an increasingly complex world. Revolutionary capabilities have entered the defense arena, including stealth, night vision, global positioning systems, adaptive optics and lasers, and phased-array radar. These technologies originated in the basic research program of the DOD. In fiscal year 2000, the DOD S&T budget is $7.4 billion: $1.1 billion for basic research (6.1), $3.0 billion for applied research (6.2), and $3.3 billion for advanced technology development (6.3). The total DOD budget for research, development, testing, and evaluation (6.1 through 6.7) is $34.4 billion. About $340 million of this is for materials and processes, not including some contributions from environmental research and development and compliance and about $100 million of materials-related work in the SBIR program.

It is critical for materials scientists and engineers to remember that materials are chosen for the function they provide. There has been a dramatic change in the use of materials over time. Particularly impressive changes have taken place in the use of aluminum (reduced from 49 percent in older aircraft to 31 percent in newer ones), titanium (increased from 13 percent to 21 percent), and carbon/epoxy-based materials (increased from 10 percent to 19 percent). The F-22 aircraft now in development contains 40 percent titanium, 15 percent aluminum, and a large proportion of thermoset materials. The V-22 aircraft is slated to contain 33 percent graphite/epoxy materials by weight. These changes were made to reduce weight and cost while improving strength and reliability.

Advanced materials play a critical role in our national security and will continue to do so.

## PANEL DISCUSSION

Question: What about rapid prototyping at Sandia?

Robinson: Interconnectedness is increasingly important in the design and development of systems. A particularly vivid example is the work on extreme ultraviolet lithography, which involves staff at both Sandia locations (New Mexico and California), at Lawrence Livermore National Laboratory and Lawrence Berkeley National Laboratory, and at several companies and universities. The interconnectedness of these locations has advanced to the point that location is no longer important. The work can be done equally well at a distance.

Q: Is there a way to commercialize developments in the national laboratories quickly?

Robinson: Sandia has many industrial partners and in fact has completed about 500 cooperative research and development agreements (CRADAs). Sandia also has an active licensing program.

Savitz: The gel-casting technology used by Honeywell (formerly AlliedSignal) was originally developed at Oak Ridge National Laboratory. A senior scientist at Oak Ridge came to AlliedSignal for two years to transfer the technology.

Q: Is U.S. dependence on foreign sources of critical raw materials a national security issue?

Sloter: The base for defense acquisition and the vulnerability of critical supplies are matters of concern, but we must remember that we are now living in a global economy.

Savitz: Honeywell’s supply of silicon nitride comes from Japan and Germany. The technical capability exists in the United States, but there is no economic incentive to manufacture it in this country.

Q: What is the relationship between the drive to reduce costs and the resulting quality?

Swain: We never settle for lower quality. In fact, the quality often goes up.

Q: What about life prediction?

Swain: One must view quality in the context of functionality. One should not substitute materials or processes if one is not sure that the quality will remain at least as high. It is imperative to go slowly.

Robinson: It is impossible to inspect out defects. Instead, one must design quality in, using such things as in-process sensors and controls and designing with operational models that include processing and the full life cycle of the system or component.

Q: Are MEMS reliable enough for use in national security applications?

Robinson: We have a long way to go. We must move slowly and do our homework to make sure we do it right. Some new materials, such as amorphous diamond, are very interesting because they offer the promise of extremely high reliability.

Q: Are you considering the environmental effects on materials, for example the pronounced effect of fog in the Los Angeles basin on the fatigue life of some materials?

Sloter: Yes. The Navy in particular is extremely concerned about such effects. Remember that a carrier deck in the middle of the Indian Ocean is exposed to one of the most corrosive environments one encounters.

Q: The cause of the Aloha Airlines disaster was determined to be holes drilled through the aluminum structure that were not properly passivated. This resulted in exposure of the substrate.

Robinson: At the time, the military was using an epoxy for passivation that would have prevented the problem, but it had not yet been approved by the Federal Aviation Administration for use on commercial aircraft. That epoxy has subsequently been approved.

# Materials, Jobs, and the Economy

*Duncan Moore presented an analysis of technology and workforce issues. Dr. Moore is the associate director for technology in the White House Office of Science and Technology Policy. An expert in gradient-index optics, computer-aided design, and the manufacture of optical systems, he is on leave from his position as the Rudolf and Hilda Kingslake Professor of Optical Engineering at the University of Rochester. He is a member of the National Academy of Engineering.*

There are two ways to increase federal support for science and technology: raise the baseline for all fields (usually by an amount comparable to the inflation rate) or establish an initiative in a specific field. In fiscal year 2000, the information technology initiative produced a 32 percent budget increase for that field. A further 35 percent increase for information technology is in the president's budget for fiscal year 2001. The nanotechnology initiative this year proposes an 84 percent budget increase. A successful technology initiative must have a clear societal benefit and a good answer for those who ask, "If it is so important, why isn't industry doing it?"

The budget process starts with submission of the president's budget to the Congress on the first Monday in February. The House and Senate budget committees allocate funds to each of the appropriations subcommittees, whose chairs are known as appropriations "cardinals." The cardinals then allocate funds to the various agencies under their purview. Science and technology funding is spread among several subcommittees, all of which have other responsibilities also. Subcommittee jurisdictions are thus significant in the budget negotiations: NSF and NASA compete with housing and veterans, DOE research competes with dams, DOD research competes with ships and aircraft.

The "middle game" includes appropriations hearings during March, April, and May, followed by floor action starting in June.

The "end game" comes as October approaches (the new fiscal year starts on October 1 each year). Key congressional players include the party leaders in both houses, the chairs and ranking minority members of the two appropriations committees, and some of the cardinals (which ones depends on which appropriations bills have passed already). Key players in the administration are the president's chief of staff, top officials of the Office of Management and Budget, and others who depend on the topics at issue. In theory the 13 appropriations bills are passed separately; in practice several are often combined. For example, in fiscal year 1999, 9 of the 13 were merged into a single omnibus bill.

When is the best time for scientists and engineers to get involved? That depends. In the case of the nanotechnology initiative, the materials community should stay engaged throughout the process.

Some areas of concern for this year's budget include earmarks, riders, DOD 6.1 and 6.2 funding, the conflict between the end game and the pressure to get out of Washington early to campaign for the November elections, the complacency of the science and technology community, and workforce issues.

The workforce issues are particularly troubling. In today's economy, when college graduates in any field can look forward to an unemployment rate of only 1.8 percent, fewer students are choosing to study "hard" subjects like engineering and the physical sciences—despite the fact that the overall number of degrees awarded is rising. Almost half of engineering doctorates go to nonresidents. Only 12 percent go to women.

# The Role of Materials in Energy and the Environment

*The final topical session examined the role of materials in energy and the environment. The overview talk in this session was presented by* ***Robert C. Pfahl, Jr.,*** *of Motorola. Dr. Pfahl is director of international and environmental research and development at Motorola Laboratories. In 1991 he received the Stratospheric Ozone Protection Award from the U.S. Environmental Protection Agency for his efforts to eliminate the use of chlorofluorocarbons in the electronics industry. He is a member of the National Materials Advisory Board.*

***Robert A. Frosch*** *of Harvard University spoke next. Dr. Frosch is an associate in the Robert and Renee Belfer Center for Science and International Affairs at the University's John F.Kennedy School of Government. A theoretical physicist by education, he has held senior positions at Columbia University, the Department of Defense, the United Nations Environment Program, the Woods Hole Oceanographic Institution, the National Aeronautics and Space Administration, and General Motors Corporation. He is a member of the National Academy of Engineering.*

***John Ehrenfeld*** *of the Massachusetts Institute of Technology was the next speaker. Dr. Ehrenfeld directs the MIT Program on Technology, Business, and Environment, an interdisciplinary educational, research, and policy program. A chemical engineer by training, he investigates how businesses manage environmental concerns and seeks organizational and technological changes to improve their practices.*

***Denise F. Swink*** *presented the view from the Department of Energy (DOE). Ms. Swink is the deputy assistant secretary for industrial technologies at DOE. The mission of her office is to improve resource efficiency and fuel flexibility in the industrial sector and thereby reduce overall production costs. She has also held positions in the DOE Office of Fossil Energy and at the Environmental Protection Agency.*

*The session ended with a panel discussion. The following are summaries prepared by the editors who adapted them from the remarks made by the individual presenters.*

## MATERIALS, ENERGY, AND ENVIRONMENT: AN OVERVIEW

Environmental concerns, such as pollution, global warming, and sustainability, have produced a variety of societal responses. These include public policy measures —such as the Geneva and Rio Conventions, the U.S.

Clean Air Act, the European Waste Electrical and Electronic Equipment Directive, and the Japanese Home Electronics Recycling Law—as well as consumer action on several levels. In recent polls, 50 percent of consumers reported having switched brands after learning of harm to the environment, and 76 percent said they would switch brands for environmental reasons if price and quality were equal.

Interestingly, significant regional differences affect this. In the United States, action on the environment is driven by regulation and focused on industry. Compared with other developed countries, the U.S. devotes less R&D to the development of environmentally preferred materials and products, instead emphasizing industrial processes, such reducing the use of lead or eliminating chlorofluorocarbons. Europe is driven by a combination of regulations and customer pressure and focuses on products, rather than the industries that produce them. For example, R&D in Europe emphasizes models for environmental design and analysis. Japan is driven partly by government and partly by industry itself. The Japanese focus is on markets, and R&D there is concentrated on the development of environmentally preferred new products, such as hybrid engines and halogen-free plastics.

Despite these differences, the ultimate consequences for the materials community are the same worldwide: societal concerns and consumer preferences are becoming part of the materials selection process. The addition of environmental criteria—minimized energy use, minimized matter use, recyclability, nonhazardousness—increases the difficulty of selecting the “best” material but offers economic rewards to the successful.

Several steps can be taken to improve progress in this area. More research is needed on scientific methodologies for evaluating options during the materials R&D process. Materials researchers and system designers must become better educated about the environmental properties of materials. And the business community must learn to understand not only the economic and societal benefits of addressing environmental issues but also the risks of not addressing them.

## MATERIALS AS ILLUSIONS (ALMOST)

I am a confirmed realist, but this talk will take the somewhat Buddhist view that materials are mere illusions. The only materials that are really forever are the elements of the periodic table. Everything else is just a collection of chemical bonds, a transient embodiment of chemical and mechanical assembly processes.

In nature, the waste of one organism becomes the food of another. Animal wastes become fertilizer for plants. Oxygen, a by-product of plant photosynthesis, allows animals to breathe. Everything is linked, and true waste is rare. By analogy, industrial ecology takes a systems approach to the materials life cycle, viewing it as a complex network of interconnected loops.

Taking this systems approach, we interviewed firms in the copper-based metals industry in New England. Every time a firm bought metal from a supplier, sent metal to a scrap dealer, or threw metal out, we recorded that transaction. Then to show the connections between firms, we made what we call a spaghetti diagram, a very tangled diagram even though it ignores what happens outside the 35 or 40 firms we studied. We found that copper is used with more than 98 percent efficiency. Some goes to landfills, but most of it simply goes round and round the loops of spaghetti.

How can such an efficient industrial ecosystem work for other materials? For copper-based metals, we found that scrap dealers are the key. Their business is to collect junk, break it apart, and sell sorted metal. Their part of the spaghetti diagram works only because they can do this. To make a similar system work for other materials, two kinds of technology are needed: disassembly technology (to take products apart in selective ways) and what I call “negentropy” technology (to sort mixtures into bins of things people actually want).

Much of the technology discussed here seems to be making disassembly and sorting more difficult than they were before. New engineered materials tend to be chemically or mechanically complex. On the other hand, the same kind of technological thinking that created these materials should also be amenable to figuring out how to take them apart and sort them.

## TECHNICAL PERSPECTIVE

Leading firms with good environmental reputations have shifted their approach to the environment. Where once they focused on cost reduction and compliance with regulations, they now think strategically about redesigning products and how to sell them. A consequence is that many companies now try to sell consumer satisfaction, function, and service rather than “stuff.”

Materials are central to most of these strategies. For the materials scientist and engineer they imply the following challenges:

- reduce material intensity
- reduce energy intensity
- enhance material recyclability
- reduce dispersion of toxic substances
- maximize sustainable use of renewable resources
- extend product durability

## GOVERNMENT PERSPECTIVE

Why is there an Office of Industrial Technology at the U.S. Department of Energy? Because the industrial sector accounts for more than one-third of U.S. energy consumption. Following the oil-price shocks in the 1970s, industrial energy efficiency improved by about 40 percent—20 percent through technology, and 20 percent because the mix of industries changed— but since the mid-1980s there has been little change. At the same time, environmental costs have been climbing as regulatory standards are strengthened. Incremental changes will not be enough to keep our industries globally competitive.

The Industries of the Future program seeks to improve this picture through R&D. Its focus is on the most energy-intensive industries, namely the materials extraction and processing industries, such as steel, forest products, and chemicals. These industries are responsible for 80 percent of U.S. industry's energy use and 90 percent of its waste production. Energy typically represents 15 to 40 percent of their production cost, and pollution and waste abatement typically represent another 10 to 25 percent. Yet R&D spending has been falling relative to sales in these industries, in part because of the many recent mergers.

The Industries of the Future process is based on road mapping. We work with each industry to develop a business-sense vision of the next 20 years, and based on that vision we develop a road map of technology R&D. Some of the resulting R&D projects are conducted by industry, and some by the Department of Energy. A key to the success of these road maps has been to start with a goal 20 years hence and work back from it, rather than start with a list of ideas for projects today. The program has had excellent success in getting its R&D results implemented in actual industrial practice.

In meetings like this, my hardest challenge is that people often say, "These are the old smokestack industries." That impression is wrong. High technology is key to their survival, and materials science in particular will play an essential role.

## PANEL DISCUSSION

*For the panel discussion, Ms. Swink was replaced by Dr.* ***Toni Maréchaux,*** *also of the Office of Industrial Technologies of the Department of Energy. Dr. Maréchaux previously held positions at National Steel and the NASA Glenn Research Center and has since become director of the National Materials Advisory Board.*

Q: Improved durability and reduced material intensity may mean a high up-front cost. An example of this is the use of stainless steel rather than carbon steel in steam generators.

Ehrenfeld: It's not always clear which strategy is best. This does indeed complicate the dematerialization challenges I mentioned. Every answer has to be specific to an individual product.

Q: In energy and environmental issues, will we in the United States act on our own based on public policy considerations, or will we be driven to action by pressure from the rest of the world?

Pfahl: Other countries are important markets for most companies these days, so U.S. regulations are not the only driver for change. And even more important than any country's regulations are the concerns of consumers, who often drive business decisions on the environment in advance of regulation or other public policy.

Maréchaux: The world is becoming an ever more global marketplace. If the United States doesn't fit its public policies to this fact of life, some industries may be driven out of the country.

Frosch: We have changed from thinking that quality costs money to realizing that bad quality costs money. A similar change is under way in our thinking about reuse and recycling. Why pay for something, put labor and energy and capital into it, and then throw it away?

Pfahl: Environmental cost accounting is an important development here.

Ehrenfeld: Public policy action is still important, though, for companies that haven't started to look at this yet.

Maréchaux: For example, the Industries of the Future program makes a point of funding projects on by-product utilization but not on waste treatment.

Q: What about the energy industry itself?

Maréchaux: To give just one example, there has been a lot of work on uses for fly ash, a by-product of burning coal.

Ehrenfeld: One can follow resources in the energy industry just as in any other. Coal is a material resource; greenhouse gases are a by-product. Energy is the same as any other case.

Frosch: Shifts in attitude may help. For example, instead of just burning a fuel to get thermal energy, think of it as a complex chemical feedstock. With some additional chemical processing, there may be interesting opportunities to turn that feedstock into energy and valuable chemical products at the same time.

# Agenda

## Day One: Tuesday, February 8, 2000

| | | |
|---|---|---|
| 7:00 | REGISTRATION BEGINS | |
| **Setting the Scene** | | Chair: Edgar A.Starke, Jr. |
| 8:00 | Welcome, *Edgar A.Starke, Jr., University of Virginia, NMAB Chair* | |
| 8:15 | Keynote Address, *Senator Pete Domenici (R-New Mexico)* | |
| 9:00 | Why Materials?, *Thomas W.Eagar, Massachusetts Institute of Technology* | |
| 9:15 | The Timeline of Materials Development, *Arden L.Bement, Jr., Purdue University* | |
| 9:45 | BREAK | |
| **Overview of the Issues** | | Chair: Julia M.Phillips |
| 10:00 | Structural Materials, *James C.Williams, Ohio State University* | |
| 10:15 | Functional Materials, *James W.Mitchell, Lucent Technologies* | |
| 10:30 | The Role of Government, *Thomas A.Weber, National Science Foundation* | |
| 10:45 | Panel Discussion | |
| 11:45 | LUNCH | |
| **Recent Studies and Symposia** | | Chair: Thomas W.Eagar |
| 1:00 | Materials Science and Engineering: Forging Stronger Links to Users, *Dale F.Stein, Michigan Technological University* | |
| 1:45 | Materials XXI, *R.G.“Gil” Gilliland, Oak Ridge National Laboratory* | |
| **Materials in Information Technology** | | Chair: Robert C.Pfahl, Jr. |
| 2:00 | Materials and Electronic Interconnects, *Andrew E.Lietz, HADCO Corporation* | |
| 2:30 | Materials Research for Computing and Communication, *Paul S.Peercy, University of Wisconsin* | |
| 2:45 | Materials, Materials Processing, and the Future of Information Technology, *Lawrence Dubois, Defense Advanced Research Projects Agency* | |
| 3:00 | Panel Discussion | |
| 3:30 | BREAK | |
| **Materials in Health and Biotechnology** | | Chair: Michael Jaffe |
| 3:45 | Overview, *Robert Z.Gussin, Johnson & Johnson* | |

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| 4:15 | Technical Perspective 1, *Galen D.Stucky, University of California, Santa Barbara* |
| 4:30 | Technical Perspective 2, *Robert Langer, Massachusetts Institute of Technology* |
| 4:45 | Government Perspective: Materials for a Healthy Life, *John T. Watson, National Institutes of Health* |
| 5:00 | Panel Discussion |
| 5:30 | RECEPTION |

## Day Two: Wednesday, February 9, 2000

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| **Congressional Perspectives** | | Chair: Sylvia M. Johnson |
| 8:00 | Panel Discussion by Congressional Staff, *Arun Seraphin, Office of Senator Joseph Lieberman; Scott Lockledge, Office of Representative Vernon Ehlers; Michal Freedhoff, House Science Committee, Energy and Environment Subcommittee* | |
| 9:30 | BREAK | |
| **The Role of Materials in National Security** | | Chair: Alan G. Miller |
| 9:45 | Meeting the Challenges of Aerospace, *David O. Swain, The Boeing Company* | |
| 10:15 | The Role of Materials in National Security, *C. Paul Robinson, Sandia National Laboratories* | |
| 10:30 | The Role of Materials in National Security: The Past, the Present, the Future, *Maxine Savitz, Honeywell* | |
| 10:45 | Government Perspective, *Lewis E. Sloter II, U.S. Department of Defense* | |
| 11:00 | Panel Discussion | |
| **Materials, Jobs, and the Economy** | | Chair: Sylvia M. Johnson |
| 11:30 | Materials, Jobs, and the Economy, *Duncan Moore, White House Office of Science and Technology Policy* | |
| 12:15 | LUNCH | |
| **Materials and Energy and the Environment** | | Chair: Lisa Klein |
| 1:15 | Overview, *Robert C. Pfahl, Jr., Motorola* | |
| 1:45 | Materials as Illusions (Almost), *Robert A. Frosch, Harvard University* | |
| 2:00 | Technical Perspective, *John Ehrenfeld, Massachusetts Institute of Technology* | |
| 2:15 | Government Perspective, *Denise Swink, U.S. Department of Energy* | |
| 2:30 | Panel Discussion | |
| **Conclusion** | | Chair: Edgar A. Starke, Jr. |
| 3:00 | Wrap-up Discussion | |
| 3:15 | ADJOURN | |

# Exhibits

In addition to the invited talks and discussion sessions, the forum included an area for exhibits, consisting of text and graphical displays and numerous hands-on examples. The exhibits highlighted the wide range of materials types and applications and their importance to modern life. Exhibitors included the following:

- The Aluminum Association
  Contact: Becky Snedeker
- The Boeing Company
  Contact: Lorin Bliss
- Honeywell
  Contacts: Phillip A.Craig, Honeywell Advanced Composites, Inc., and Hans Friedericy, Honeywell Aerospace Corporation
- NASA Langley Research Center
  Contacts: Jeffrey A.Hinkley, Advanced Materials and Processing Branch, and W.Keats Wilkie, Aeroelasticity Branch
- Department of Defense Reliance Group
  Contacts: Carol Hambric, Naval Research Laboratory, and Julie Christodoulou, Office of Naval Research

# Participants

Reza Abbaschian, University of Florida
Vijendra Agarwal, White House Office of Science and Technology Policy
Peter Angelini, Oak Ridge National Laboratory
Douglas Bauer, National Research Council, Commission on Engineering and Technical Systems
Robert Bayuzick, Vanderbilt University
Arden L.Bement, Jr., Purdue University
Stephen Benka, *Physics Today*
Arthur Bienenstock, White House Office of Science and Technology Policy
Norbert Bikales, National Science Foundation (retired)
Lorin Bliss, The Boeing Company
Rajendra Bordia, University of Washington
Leonard Brillson, Ohio State University
John Browne, Los Alamos National Laboratory
Dick Chait, National Research Council, National Materials Advisory Board
Dennis Chamot, National Research Council, Commission on Engineering and Technical Systems
C.I.(Jim) Chang, Army Research Office
Uma Chowdhry, Dupont
Julie Christodoulou, Office of Naval Research
Leo Christodoulou, Defense Advanced Research Projects Agency
Phillip A.Craig, Honeywell
Michael DeHaemer, ASM International
Patricia Dehmer, U.S. Department of Energy
Vincent Desajico, International Trade Commission
George Dieter, University of Maryland
Sara Dillich, U.S. Department of Energy
Arthur Diness, Institute for Defense Analyses
Pete Domenici, United States Senate
Earl H.Dowell, Duke University
Patrick Doyle, National Research Council, Board on Manufacturing and Engineering Design
Alan Dragou, U.S. Department of Energy
Lawrence Drzal, Michigan State University
Lawrence Dubois, Defense Advanced Research Projects Agency
Thomas W.Eagar, Massachusetts Institute of Technology
John Ehrenfeld, Massachusetts Institute of Technology
Chang-Beom Eom, Duke University
Arthur Epstein, Ohio State University
Nicholas Eror, University of Pittsburgh
James Evans, University of California, Berkeley
Gary Fischman, University of Illinois, Chicago

Tim Fitzsimmons, Senate Energy and Natural Resources Committee
Dan Foley, Honeywell Ceramics Components
Hans Frederikse, National Institute of Standards and Technology
Michal Freedhoff, House Science Committee, Energy and Environment Subcommittee
Doug Freitag, Bayside Materials Technology
Hans Friedericy, Honeywell
Robert A.Frosch, Harvard University
Ephrahim Garcia, Defense Advanced Research Projects Agency
John Garnier, Honeywell Advanced Composites
Nancy Gaston-Festa, SRI Consulting
Tom Gates, NASA Langley Research Center
Rosario Gerhardt, Georgia Institute of Technology
R.G.(Gil) Gilliland, Oak Ridge National Laboratory
Alastair M.Glass, Lucent Technologies
Henry Glyde, University of Delaware
John A.S.Green, The Aluminum Association
Robert Green, Johns Hopkins University
Robert Z.Gussin, Johnson & Johnson
Charles Hach, National Research Council, National Materials Advisory Board
Serge Hagege, Embassy of France
John Halkyard, Deep Oil Technology, Inc.
Dale Hall, National Institute of Standards and Technology
Carol Hambric, Naval Research Laboratory
Craig Hartley, U.S. Department of Energy
Julius Harwood, Harwood Consultants
Ken Hatten, Honeywell
Jeffrey A.Hinkley, NASA Langley Research Center
William Hong, Institute for Defense Analyses
John H.Hopps, Jr., Morehouse College
Emanuel Horowitz, Johns Hopkins University
Betsy Houston, Federation of Materials Societies
Anthony Hyder, University of Notre Dame
Kenneth Jackson, University of Arizona
Michael Jaffe, Rutgers University
Gerry Janacki, The Boeing Company
Purusottam Jena, Virginia Commonwealth University
Sylvia M.Johnson, SRI International
Julene Joy, National Academy Press
Wilkie Keats, NASA Langley Research Center
Ronald Kelley, Strategic Partners, Inc.
James Key, Idaho National Engineering and Environmental Laboratory
Sheila F.Kia, General Motors
James Killian, National Research Council, Division on Military Science and Technology
Kelly Kirkpatrick, White House Office of Science and Technology Policy

Lisa Klein, Rutgers University
Robert Langer, Massachusetts Institute of Technology
Rebecca Lankey, Environmental Protection Agency
Stephen Larkin, The Aluminum Association
Jorn Larsen-Basse, National Science Foundation
Richard Lehman, Rutgers University
Andrew E.Lietz, HADCO Corporation
Tony Liu, U.S. Army Corps of Engineers
Richard Livingston, Federal Highway Administration
Scott Lockledge, Office of Representative Vernon Ehlers, U.S. House of Representatives
David Luippold, Northrop Grumman
Pete Lyons, Office of Senator Pete Domenici, U.S. Senate
Christian Mailhoit, U.S. Department of Energy
Harris Marcus, University of Connecticut
Toni Maréchaux, U.S. Department of Energy
Stanley Margolin, Network Consulting, Inc.
John Marra, Savannah River Technology Center
Paul Maxwell, University of Texas
Jim McCauley, Army Research Laboratory
Jim McElroy, National Electronics Manufacturing Initiative, Inc.
Thomas McGee, Iowa State University
Carl McHargue, University of Tennessee
Denis McWhan, Brookhaven National Laboratory
Alan G.Miller, The Boeing Company
Daniel Miracle, Air Force Office of Scientific Research
James W.Mitchell, Lucent Technologies
Duncan Moore, White House Office of Science and Technology Policy
Daniel Morgan, National Research Council, National Materials Advisory Board
Arul Mozhi, National Research Council, National Materials Advisory Board
John Mundy, Oak Ridge National Laboratory
Dale Niesz, Rutgers University
Carlo Pantano, Materials Research Institute
Arvid Pasto, Oak Ridge National Laboratory
Paul S.Peercy, University of Wisconsin
Chris Peterson, SRI International
Robert C.Pfahl, Jr., Motorola
Julia M.Phillips, Sandia National Laboratories
Joseph Piche, Eikos, Inc.
Gordon Pike, U.S. Department of Energy
Robert Pohanka, Office of Naval Research
Janice Prisco, National Research Council, National Materials Advisory Board
David Pye, Alfred University
Patrick Quinlan, White House Office of Science and Technology Policy
Henry Rack, Clemson University

Robert Rapson, United States Air Force

John Rasmussen, National Research Council, Board on Manufacturing and Engineering Design

Bhakta Rath, Naval Research Laboratory

Michael Rigdon, Institute for Defense Analyses

C.Paul Robinson, Sandia National Laboratories

Thomas Robinson, U.S. Department of Energy

Angus Rockett, U.S. Department of Energy

Michael Rooney, Johns Hopkins University

Millard Franklin Rose, NASA Marshall Space Flight Center

James Salsgiver, Allegheny Ludlum Steel Company

Maxine Savitz, Honeywell

Ashok Saxena, Georgia Institute of Technology

Robert Schafrik, GE Aircraft Engines

Michael Schen, National Institute of Standards and Technology

Erland Schulson, Dartmouth College

Lyle Schwartz, Air Force Office of Scientific Research

Willard Searle, Jr., Searle & Associates, Ltd.

Arun Seraphin, Office of Senator Joseph Lieberman, U.S. Senate

Donald Shapero, National Research Council, Board on Physics and Astronomy

Jeffrey Shield, University of Utah

Massoud Simnad, University of California, San Diego

M.Jay Singh, NASA Glenn Research Center

Lewis E.Sloter II, U.S. Department of Defense

Leslie Smith, National Institute of Standards and Technology

Becky Snedeker, The Aluminum Association

Edgar A.Starke, Jr., University of Virginia

Dale F.Stein, Michigan Technological University (emeritus)

Roger Storm, Advanced Refractory Technologies, Inc.

Galen D.Stucky, University of California, Santa Barbara

David O.Swain, The Boeing Company

Denise F.Swink, U.S. Department of Energy

Steve Taulbee, Army Research Laboratory

Stephen Teitsworth, Duke University

Louis Terminello, Lawrence Livermore National Laboratory

Malcolm Thomas, Rolls-Royce, Allison Engine Company

Teri Thorowgood, National Research Council, National Materials Advisory Board

Joseph Tribendis, Alcoa Technical Center

Arvind Varma, University of Notre Dame

Mat Varma, U.S. Department of Energy

Cung Vu, National Research Council, Board on Manufacturing and Engineering Design

James W.Wagner, Case Western Reserve University

Charles Walker, Dow Corning Corporation

Michael Wargo, National Aeronautics and Space Administration

John T.Watson, National Institutes of Health
Stephen Wax, Defense Advanced Research Projects Agency
Thomas A.Weber, National Science Foundation
Harold Weinstock, Air Force Office of Scientific Research
Joseph Wells, Army Research Laboratory
Calvin White, Michigan Technological University
David Williams, Lehigh University
James C.Williams, Ohio State Univesity
Joseph Wirth, Raychem Corporation (retired)
Albert Yee, University of Michigan
Bill G.W.Yee, Pratt & Whitney
Sharon Yeung, National Research Council, National Materials Advisory Board
Michael Zehner, Office of Representative Virgil Goode, U.S. House of Representatives