Summary of the Power Systems Workshop on Nanotechnology for the Intelligence Community

Interim Report

October 9-10, 2003
Washington, D.C.

Greg Eyring,
Rapporteur

NATIONAL MATERIALS ADVISORY BOARD

NATIONAL RESEARCH COUNCIL
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This study was supported by Contract No. 2003-A442100-000 between the National Academy of Sciences and the Intelligence Technology Innovation Center (ITIC). Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

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Printed in the United States of America

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Acknowledgments

The committee appreciates the participation of all who attended the workshop and the following individuals who prepared presentations:

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Terry Lowe, Los Alamos National Laboratory (NMAB member)
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Daniel Steingart, University of California
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George Whitesides, Harvard University (committee member)

This summary has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review was to provide candid, critical comments to assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards of objectivity, evidence, and responsiveness. The content of the review comments and draft manuscript remain privileged to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this summary:

Aladar A. Csontos, U.S. Nuclear Regulatory Commission
Robert J. Dowding, U.S. Army Research Laboratory
David R. Forrest, Naval Surface Warfare Center
Robert Shull, National Institute of Standards and Technology

The review of this report was overseen by Robert A. Frosch, Harvard University. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. While the individuals listed above provided many constructive comments and suggestions, responsibility for the final content of the summary rests solely with the rapporteur and the NRC.

Contents

INTRODUCTION 1

TOPIC 1: Overview of Power Technologies 3

TOPIC 2: Nanoscale Properties of Energy Storage Materials 7

TOPIC 3: Device Experience 11

TOPIC 4: Manufacturing and Material Handling Considerations 15

TOPIC 5: Natural Power 17

TOPIC 6: Review of National Science Foundation Report 21

APPENDIXES

A Workshop Participants and Agenda, 23
B List of Attendees, 27
C Committee Biographies, 29
D Acronyms, 37

INTRODUCTION

The Power Systems Workshop on Nanotechnology for the Intelligence Community was organized by the staff at the National Materials Advisory Board (NMAB) of the National Research Council (NRC) and was conducted under the intelligence community Nano-Enabled-Technology Initiative (NETI), administered by the staff of the Intelligence Technology Innovation Center (ITIC). This interim report summarizes the highlights of the workshop, as directed by the statement of task for the project as a whole; the workshop agenda is given in Appendix A. A follow-on workshop will be conducted to explore sensing and locating technologies; summary notes from that second workshop will also be issued as an interim report. Authored by a single appointed rapporteur attending each workshop, these interim reports are subject to review for accuracy using normal National Academies' procedures prior to release. A third and final report will be prepared as a full consensus study by the Committee on Nanotechnology for the Intelligence Community, which was established to assist the intelligence community by exploring the potential for nanotechnology to address key intelligence community needs.

This is a summary of workshop proceedings, including the presentations made to the committee and the subsequent discussion. As such, it follows the interests and knowledge of the presenters and does not provide a comprehensive analysis of the topics discussed. Nor does this document contain any findings and recommendations of the committee. Rather, this summary, together with the summary of the following workshop on sensing and locating technologies, will provide useful input to the final report, in which the committee will offer its findings and recommendations.

The study sponsors provided the committee with classified background briefings on ITIC's interest in nanotechnology-enabled opportunities in both the energy/power field and the sensing/locating field, in order to provide context for the committee's deliberations. This interim report does not attempt to summarize in detail these classified presentations on intelligence community programs and activities. In general terms, the energy/power presentation focused on ITIC's view of opportunities for nanotechnology to improve the performance of rechargeable batteries.

The external data-gathering portion of the workshop was organized in five topic areas, with two or three speakers addressing each topic:

1. Overview of power technologies
2. Nanoscale properties of energy storage materials
3. Device experience

4. Manufacturing and material handling considerations
5. Natural power

Following the presentations for each topic, there was a brief panel discussion involving all of the presenters for that topic. The workshop summary below follows this same organizational scheme: for each topic area, the main points of each speaker's presentation are highlighted, followed by a recapitulation of the general discussion.

At the end of the workshop, Debra Rolison, a committee member from the Naval Research Laboratory, presented the main results of a November 2002 National Science Foundation (NSF) workshop entitled "Approaches to Combat Terrorism: Opportunities for Basic Research in Energy/Power Sources," which featured a subgroup focusing on opportunities for basic research in energy and power sources. A brief summary of her presentation is also included here. Appendix B lists the workshop attendees, and a short biography for each speaker is given in Appendix C.

TOPIC 1: OVERVIEW OF POWER TECHNOLOGIES

Three presentations were made on this topic, by George Blomgren of Blomgren Consulting Services, Ltd., John Miller of JME, Inc., and Daniel Steingart, a Ph.D. student at the University of California, Berkeley. Their papers are summarized below.

THE INFLUENCE OF NANO MATERIALS ON ENERGY STORAGE DEVICES

George Blomgren focused on the near- to medium-term opportunities to improve high-energy rechargeable batteries such as lithium-ion (Li-ion) and nickel metal hydride (NiMH), though he briefly addressed the long-term potential of biofuel cells at the end of his talk. NiMH batteries are currently the standard battery used in hybrid electric vehicles; they offer a specific energy capacity (energy capacity per unit weight) of about 50 Wh/kg and specific power (power per unit weight) up to 1,100 W/kg. The technology is relatively mature, though modest near- to medium-term increases in discharge rate capability are likely, mainly through improvements to engineering design rather than new materials or nanostructures.

Li-ion batteries, already widely used in electronics, have specific energies of around 160 Wh/kg and are expected to show more substantial near- and mid-term increases in capacity, rate capability, and stability. Discontinuous improvements in performance are expected to result from the introduction of new materials, including negative electrode materials (especially metals that alloy with Li), positive electrode materials (including materials that are more chemically stable than Co^{+4} materials with higher capacity), and new electrolyte salts. Chemical stability is critical not only for safety but also for reliability and service life as one proceeds to smaller and smaller particle sizes.

Li-ion microbatteries are already well advanced in the lab, and printed batteries using vapor-deposited materials are becoming of interest for small or flexible cells. In the long term, nanoscale Li-ion batteries could be integrated with devices using templated materials—etched substrates and various deposition methods—or cells utilizing colloidal-scale self-organization of components.

Also in the long term, biofuel cells powered by sugar solutions—for example, using one enzyme-coated electrode to oxidize glucose and another enzyme-coated electrode to reduce oxygen—could have a revolutionary effect on small, integrated power sources.

ELECTROCHEMICAL CAPACITOR TECHNOLOGY

John Miller discussed electrochemical capacitors (ECs), often called “supercapacitors” or “ultracapacitors.” These have the highest energy density of all capacitor types, approaching 20 Wh/kg. So far, memory backup has been the most common application, but new applications include communications, transportation (they are ideal for regenerative braking in electric vehicles), and power quality. They rely on double-layer charge storage at the electrode/electrolyte interface.

The most promising ECs are “asymmetric” ECs that feature one battery electrode and one charge storage electrode. This asymmetric arrangement results in approximately a twofold increase in capacitance and higher cell voltages. For many engineering applications, the best solution may be a combination of a battery and an EC; this enables one to exploit the high energy capacity of a battery and the high power density of an EC.

ECs use porous electrodes that maximize charge storage, such as activated carbon. This gives them a different frequency response from other types of capacitors. Multiwall carbon nanotubes (MWNT) show great promise as an electrode material, and preliminary experiments indicate that MWNT electrodes have the fastest frequency response of any material yet tested. Among other benefits, use of MWNT allows enhanced charge storage, and the electrode pore volume and surface area can be decoupled (as is not the case for activated carbon), which enables greater control over performance characteristics.

In the near term (<3 years), asymmetric ECs such as the $PbO_2/H_2SO_4/C$ system should be able to achieve 20 Wh/kg with significant cost reductions. In the long term (>3 years), improved design as well as new materials such as MWNT should enable energy densities of 28 Wh/kg and optimization for many different power levels/profiles.

MICRO POWER SYSTEMS OVERVIEW

Dan Steingart noted that current wireless two-way sensors/transceivers have dimensions on the order of cubic centimeters and that batteries take up 90 percent of this volume. Primary batteries are not practical given the application area of most sensor systems. Steingart reviewed a variety of energy reservoir options (batteries, fuel cells, capacitors, etc.) and energy-scavenging options (solar, temperature gradients, human power, vibrations, etc.) for supplying power to sensor networks. The most appropriate power source depends upon the nature of the task and the area of deployment.

There are two main paradigms for wireless architectures: modular and monolithic. In modular systems, off-the-shelf technology components are fabricated together on one small printed circuit board; this provides software flexibility at the cost of higher energy consumption. An example of where a modular design would be most appropriate is a sensor net intended to gather audio and/or visual information with 10-100 nodes, some fixed and some moving, with variable assignments that may change during the time of interest. In this case, the power source might be a micro fuel cell or micro heat engine, since audiovisual applications require much energy and a high-bandwidth transmitter.

Monolithic systems feature an integrated design based only on the specific functionality of the device; this results in less flexibility but lower energy consumption. An example of where a monolithic design would be most appropriate is a sensor network intended for low-frequency measurement of simple quantities (light levels, temperature, etc.) over long durations with thousands of fixed and piggybacked mobile nodes. In this case, the extra design time for a monolithic architecture is worth the extra durability in the field, and the power source might be an energy scavenger coupled with an ultracapacitor or microbattery. The scavenging system can be chosen based on the relevant environments, and the energy storage system can be matched to the amount of energy scavenging available.

TOPIC 1 DISCUSSION

The first topic of discussion was the relationship between the structure and properties of carbon nanotubes used for electrodes. Only the external surface of the nanotubes is available for exploitation; the internal surface is not in contact with the electrolyte and is therefore unreactive. A MWNT structure containing about five concentric walls appears to offer optimum properties because one can etch the surface to get two, three, and four-wall edges that yield a high external surface area with access to stored energy at very short times. For MWNT, a capacitance of approximately 15 $\mu F/cm^2$ can be achieved. Capacitance results for single-wall carbon nanotubes (SWNT) have been published recently.

The discussion then turned to the question of what is likely to come next after the Li-ion battery system. It was noted that there are no lighter metals than lithium, and the eventual fruit of work on Mg systems is hard to predict. The Li-FeS_2 system has been studied for 40 years and is not yet viable; one must achieve reasonable power and energy densities simultaneously. The NRC has a parallel committee working on “soldier power,” where developments in Zn-air and Mn-air are being examined (potentially useful in soldier applications because air is free). Indeed the next battery may be a fuel cell. It was noted that some failed battery chemistries might turn out to be viable in hybrid capacitor systems.

One panel member commented that the energy density of batteries is one or two orders of magnitude less than that of liquid fuels such as kerosene. The reason for this is that most batteries include the weight of metal casings and electrolyte; also, batteries can be made reversible, a feature not offered by liquid fuels. A more global response is that this is not a valid comparison, because if the goal is to produce electricity, as batteries do, one must look at the entire system. Conversion of liquid fuels to electricity involves several inefficient steps that would have to be accounted for in any valid comparison.

The discussion then turned to the commercialization of battery technology. The commercial marketplace drives most investment in new battery technologies; the government invests a comparatively small amount. Most new battery ideas break down in the implementation stages of engineering and manufacturing—areas that are not typically funded by the government. In the case of capacitors, major government development funding was provided by the National Institute of Standards and Technology (NIST), though much of the manufacturing has moved offshore to China and Mexico. In industry, applications always drive the R&D.

If one did not have to manufacture a battery system for industry but was willing to invest significant government money in a specialty application because of the benefits to the nation, one could be more creative.

To the question of where the biggest improvement might come from in battery technologies, it was replied that no rechargeable battery currently uses more than about 25 percent of its volume as active materials. In theory, one could build a battery in which between 50 and 75 percent of the theoretical maximum could be utilized if one could simultaneously achieve high surface area and high space-filling. It was believed that achieving a two- or threefold improvement in performance did not depend so much on the amount of R&D money as it did on the formation of interdisciplinary teams of researchers.

TOPIC 2: NANOSCALE PROPERTIES OF ENERGY STORAGE MATERIALS

Three presentations were made on this topic, by Dane Morgan of the Massachusetts Institute of Technology, Dan Scherson of Case Western Reserve University, and Ann Marie Sastry of the University of Michigan. Their papers are summarized below.

AB INITIO METHODS IN POWER TECHNOLOGIES: BATTERIES AND NANOSCALE MATERIALS

Dane Morgan made the case for rational materials design based on ab initio calculations involving well-characterized systems having a small number of atoms (calculations with 100-150 atoms are average; 1,000 atoms would be a maximum). When such calculations are combined with empirical potentials, it is possible to treat a billion atoms. The calculations can be used to predict energy-related properties such as structural stability, lattice parameters, voltages, and reaction rates, as well as charge-density-related properties such as band structure, optical properties, and electrical conductivity. Compared with experimentation, calculations offer a fast and inexpensive way to explore many possibilities. However, Morgan stressed that it is essential to have experimental knowledge of structures in order to use calculations effectively.

He presented results for Li intercalation oxides such as Li_xCoO_2 in batteries as a substitute for Co in order to decrease price and increase energy density. Calculations were also performed to understand the strains induced in Li_xCoO_2 during battery cycling as a result of Li transport. These strains can cause the particles to fracture and reduce battery performance.

Such calculations are expected to be more accurate and useful at the nanoscale, where fewer atoms are involved. For example, one could compare the properties of carbon nanotube bundles with those of graphite or catalytic oxidation processes on 10-atom gold nanoparticles. Morgan noted that ab initio calculations have become a standard tool of materials science and should be a part of nanoscience research, complementary to experimentation.

ELECTROCHEMICAL CHARGE STORAGE DYNAMICS

Dan Scherson presented research aimed at characterizing the in situ dynamics of battery electrode changes during charge/discharge cycles. The objective is to monitor the extent of Li^+ intercalation within various Li^+ battery constituents so as to provide a rational basis for improving battery performance. The experimental approach is to use Raman spectroscopy, which is a vibrational probe that reflects local forces and small volumes in a time-resolved fashion (but provides only indirect structural information), and correlate Raman spectral changes observed on charging and discharging with data obtained using x-ray diffraction (XRD), a structural probe that provides information on long-range order in bulk materials. If one can establish a direct and unique link between the vibrational and the structural information, one can use Raman microscopy as a quantitative time- and space-resolved probe of dynamic events in the material.

Scherson described Raman spectra of model materials: single, micrometer-sized particles of $LiMn_2O_4$ (Li^+ intercalation cathode for Li^+ batteries) and graphite (Li^+ intercalation anode for Li^+ batteries) while recording cyclic voltammetry. He showed that specific Raman peak heights varied according to the extent of Li^+ intercalated, and that these variations could be quantitatively related to phase changes observed in XRD spectra on the same material. Scherson then performed the experiment on an operating graphite-Li_xCoO_2 Li-ion battery and obtained encouraging results on the anode, allowing time-resolved line maps of lithiated graphite as a function of the state of charge. Further experiments across the entire cross-sectional edge of the battery will enable assessment of models describing the Li^+ dynamics in real devices.

NANOSTRUCTURED MATERIALS FOR POWER SUPPLIES: DESIGN OF MATERIALS

Ann Marie Sastry began by noting that designing smaller power supplies means making better use of volume. How can we model the more stochastic nature of performance properties as we move to smaller length scales? Small is good, but we have to strategize about the architectural arrangement of materials. In particular, both the electron and ion pathways must be percolated (connected in a continuous path through the space of interest) to facilitate the electrochemical reaction. Active particles usually suffer phase and volume changes during electrochemical processes, so conduction and mechanics are linked at all scales. Conduction physics is critical, and this points to the need for more work on synthesis/property modeling. Is two-dimensional ideal, or three-dimensional, or something intermediate? The creation of designed properties in surface layers/films depends on the dispersion of particles on the surface.

Sastry discussed models of the percolation probability as a function of the volume fraction and aspect ratio of particles. For the constant area/volume fraction, there is a greater probability of percolation in three dimensions than in two dimensions. Particles with higher aspect ratios are superior for achieving percolation at any given volume fraction, but processing is critical. Utilization of nanostructured materials as coatings can inhibit unwanted chemical reactions without sacrificing the electron conductivity. In the design of materials, there needs to be a greater emphasis on the internal mechanics of heterogeneous systems, continued focus on percolative phenomena, and development of optimal multiphase blends.

TOPIC 2 DISCUSSION

The panel discussion focused on the extent to which major advances in power device properties are still possible with known chemistries as opposed to new chemistries. By using higher aspect ratio particles to reduce electrode mass, it appears possible to get 20 to 30 percent higher specific properties. By investing a lot of energy to achieve optimal self organization[1] of components, it was felt that perhaps a twofold improvement was possible. However, the primary interest of the committee was in opportunities to improve properties by more than an order of magnitude.

It was pointed out that in capacitors, one could improve capacity by an order of magnitude from the increased packing fraction enabled by nanoparticles. Furthermore, asymmetric EC capacitors had increased energy capacity an order of magnitude by better design rather than by different materials. A further twofold increase can be obtained by cycling deeper (e.g., 20 percent discharge as opposed to the current typical discharge of 10 percent).

Regarding the development of new materials for power devices, it was pointed out that a small number of researchers—for example, John Goodenough at the University of Texas—had identified the bulk of the new cathode materials that have been tested. It was suggested that expert system software incorporating the analysis used by Goodenough would be useful for developing a list of promising new materials to explore.

[1] In this report, the term "self-organization" refers to construction of a regular array such as a CVD diamond film or Langmuir-Blodgett film, with relatively high levels of associated defects. The term "self-assembly" refers to construction of complex three-dimensional structures via selective pattern matching and sticking of complementary surfaces. An example would be T4 phage parts self-assembling in solution. This process is associated with a relatively low level of defects by comparison.

TOPIC 3: DEVICE EXPERIENCE

Three presentations were made in this session, by Esther Takeuchi of Wilson Greatbach Technologies, Inc., Nancy Dudney of Oak Ridge National Laboratory, and Robert Nowak, a consultant formerly with DARPA. Their papers are summarized below.

POWER SOURCES USED FOR HUMAN IMPLANTS

Esther Takeuchi discussed power sources for human implants, microbatteries, opportunities for nanomaterials, and alternative energy-harvesting approaches. Power sources for implantable biomedical devices must have 5+ years longevity (10-12 years is desirable); they must be small; and they must be capable of providing information on their status in response to an external query. All implantable batteries in use today are Li-based primary systems, with the vast majority being $Li\text{-}I_2$. For some applications, the battery must deliver more than 1 Ah over 5 years. If one could recharge the battery (e.g., via external RF power through the skin), batteries could be smaller (microbatteries) and device lifetimes of 10-20 years might be achievable. However, there are operational and psychological advantages to implantable batteries that do not need to be recharged. A solid state Li-ion battery based on Oak Ridge technology is being commercialized. It achieves a cycle life greater than 50,000 cycles, an energy density of 200 Wh/kg, and a capacity up to 0.2 mAh/cm^2.

In principle, the use of nanomaterials in conventional battery systems could enhance power and discharge rate capability. This could be useful in applications such as heart defibrillators, which require infrequent pulses of high power. To test this approach, a coin battery cell was prepared with a nanoparticle-sized silver vanadium oxide (SVO) cathode that resulted in a two- to fivefold lower tap density and an order of magnitude (or more) improvement in surface area compared with a conventional SVO cell. In tests, the nano-SVO system actually produced a lower gravimetric and volumetric energy density than the conventional system. While the nano SVO cathode may not have been optimized, this raises the awareness that one cannot simply insert nanomaterials into conventional designs and expect performance to improve.

Takeuchi went on to discuss a number of energy-harvesting possibilities, broken out into Category 1 (systems that could be coupled with a rechargeable cell or capacitor, such as solar cells or self-winding-watch-type mechanical energy) and Category 2 (systems with self-sustaining power levels, that is, those that use pH or thermal gradients, biofuel cells, or implantable nuclear devices). She concluded that any new power system for implantable devices has to compete with existing battery sources in cost, size, reliability, and predictability. One has somewhat more flexibility (e.g., to use rechargeable systems) in applications that are not life-critical. For all options, achieving a balance of high power and high energy density presents a significant challenge. For medical applications, the system management requirements of the patient and physician are key considerations.

MICRO- AND NANOSCALE RECHARGEABLE BATTERIES: STATE OF THE ART AND CURRENT RESEARCH

Nancy Dudney discussed recent and projected developments in miniaturized batteries. In the near term (<3 years), the action will continue to focus on thin-film, solid-state batteries made by vapor deposited layers of electrodes and electrolyte on a substrate (overall battery widths not including substrate of about 15 µm). The Li-Li_xCoO_2 system appears optimal and provides both low trickle current and high pulse power for applications such as data transfer. Since these batteries must be integrated into the device, the substrate is not counted in calculation of the performance metrics. For the best cells, capacity at 25°C for a 4-µm-thick $LiCoO_2$ cathode is around 250 µAh/cm^2, energy density is >1 mWh/cm^2, and power densities (short duration) are around 30 mW/cm^2. These battery materials are proven, have uniform current densities, and can meet the needs of MEMS devices. Known challenges include (1) battery development on thinner, more flexible substrates, (2) stacking for creation of three-dimensional batteries, (3) improving yield (currently only 10 percent), and (4) packaging. At present, there is insufficient market pull to drive low-cost solutions to these problems.

Over the medium term (3-5 years), Dudney foresees development of thin-film batteries on very high surface area substrates (e.g., fibers) achieving a 5- to 10-fold increase in substrate surface/volume. One application would be fibers with a battery coating that could be woven into textiles, e.g., for soldier power. Prototype fiber batteries ("powerfibers") embedded in a polymeric matrix have been demonstrated that are robust under flexing, and an 18-ft fiber today can provide 1 mWh of energy and 90 mW peak power. By 2004, an order of magnitude improvement is expected: a 500 x 500 array of fibers is expected to be able to deliver 3 A at 3 V, with a capacity of 100 mWh. Current work includes depositing thin-film batteries (crystalline $LiCoO_2$-based) on carbon fiber tows for use in composites. Anticipated challenges include the stability of new materials for high surface areas, the uniformity of current (with attendant concerns about stability and utilization after many cycles) and flaws in connectivity caused either by fabrication or stresses from cycling. Costs of the fibers remain uncertain.

Over the long term (more than 5 years), batteries constructed from nanomaterials (nanofibers and nanoporous structures) will be possible. Fabrication concepts include construction of three-dimensional nanoarchitectures by concentric tube template synthesis to form electrode fibers, individual cells fabricated within micromachined wells, and self-organized nanoarchitectures using block copolymers with oxides or disordered, mesoporous active materials. In Dudney's view, the biggest potential for revolutionary change will come from these self-organized nanostructures, especially if they can be made substrateless. These also have the greatest potential for cost savings. Challenges include those mentioned above as well as the difficulty of incorporating a current collector into the architecture.

COMMITTEE ON SOLDIER POWER/ENERGY SYSTEMS AND PORTABLE/COMPACT POWER SYSTEMS

Robert Nowack reviewed recent work by a parallel NRC committee looking at soldier power issues (he is a member of that committee). He noted that the Pentagon has a $100 million Objective Force Warrior (OFW) program under way, now in Phase II, which is funded at $40 million. The aim of OFW is to enable soldiers to gather and process information more readily on the battlefield. However, soldiers are already overloaded with equipment (some special operations soldiers carry 120-140 pounds of gear), even without the electronics, batteries, and computers that OFW wants to add on. Therefore, lightweight, compact systems are at a premium, and nanotechnology could help reduce the weight carried into the field. With the first OFW advanced technology demonstration scheduled for FY06, the power source must be "on the shelf" today. The Army is interested in a hybrid of Zn-air and Li-ion batteries, which together can extend a mission by about 4 hours compared with the sum of the operating times (18.5 hours) for the two individual batteries.

For units that require very high power loads, such as a radio reconnaissance team, portable, lightweight devices that convert logistic fuels to electrical power are preferable to batteries. Both fuel cells and heat engines are being considered here that use fuels such as methanol, hydrocarbons, and bottled hydrogen. For fuel cells, a logistic fuel preprocessor and reformer that converts fuels to hydrogen is being developed for 3- and 10-day missions. The most appropriate power supply depends on the mission—for durations of less than a day, it is hard to match the performance of a battery. For longer times, battery weight becomes prohibitive, and energy conversion devices such as direct methanol fuel cells make more sense. One can also reduce the demand for power by utilizing more efficient chips, displays, and so on. Small two-chamber diesel engines and generators have relatively low efficiency (~15 percent) but can operate on the impure diesel fuels that are likely to be available.

There are 20 or 30 programs on power from microelectromechanical systems (MEMS) devices in the United States, including miniaturized Wankel, turbine, and linear engines and micro fuel reformers for fuel cells.

Nowak concluded with a warning that all useful soldier power systems contain enough energy to cause serious damage in the event of an accident or the impact of a bullet. Standard battery systems can be improved in various ways, but no more than a twofold increase in energy density is foreseen. Lightweight, high-efficiency energy conversion devices that can use air as the oxidizer are the key to making use of high-energy-density, convenient liquid fuels; however, these systems need to be designed for tactical robustness—for example, to withstand immersion in water. The relatively advanced state of hydrogen/air fuel cells and the very high energy density of hydrogen justify the significant DoD effort to find new ways of delivering hydrogen to the soldier. Hybrid energy systems are likely in the future, and management of power demands is essential.

TOPIC 3 DISCUSSION

Once again, the discussion following this panel began with the question, What comes next after Li-ion cells? The Army is enthusiastic about C-air cells for soldier power, although these involve a molten carbonate electrolyte at high temperature. The possibility of Be-air was mentioned, but the general feeling was that the toxicity of Be would make this unlikely, except perhaps for specialized applications. Manufacturers would be unlikely to consider making Be batteries because of Environmental Protection Agency (EPA) regulations, environmental health and safety issues, and cleanup costs. The Army wants to get rid of nuclear materials for energy generation, though it was noted that the most efficient way to go from nuclear to electric is by way of a Stirling engine.

There does not appear to be commercial demand for energy harvesting. In medical applications, Li batteries can provide 5-7 years of service, and given the rapid advances in the field, few patients or doctors want to use a device more than 7 years. For the military, everything depends on the mission: how long the device needs to function, total energy, power, and duty cycle. For doing telemetry, a lot of power is needed, and this might need to be supplied externally. DARPA has funded an exploration of energy-harvesting options; biofuel cells were rated high for current density but raised sustainability concerns. For most missions, it is hard to beat a battery; for others with low power requirements, the few watts one could obtain by harvesting heel-strike energy might be enough. Nonhuman sources of bioenergy might be useful for missions lasting longer than about 30 days.

There were mixed views about whether having a commercial market for a particular power source is essential. One view was that the power source almost has to be commercial to survive. Another view was that if the government determines that the goal is worth it (e.g., the satellite programs), it can sustain the necessary infrastructures and vendors. One must find the value that justifies the investment.

It was noted that there is much to be learned from biological processes, particularly in regard to self-organization in fabricating nanostructures. Bone is formed by collagen that self-organizes, leaving holes that line up, and minerals intercalate into the aligned structures. One can take advantage of such thermodynamically favorable processes in nanostructured materials.

TOPIC 4: MANUFACTURING AND MATERIAL HANDLING CONSIDERATIONS

Two presentations were made in this session, by Terry Lowe of Los Alamos National Laboratory and Kevin Hemker of Johns Hopkins University. Their papers are summarized below.

CHALLENGES FOR NANOSCALE MANUFACTURING

Terry Lowe stressed that manufacturing is likely to be the biggest challenge in commercializing nanodevices and must be embraced, along with R&D, in a comprehensive systems approach. The semiconductor industry is already facing nanoscale issues as complementary metal oxide silicon (CMOS) feature sizes continue to be reduced, although new nano methods of making transistors (e.g., using silicon or carbon nanotubes) are thought to be 10 years in the future. Lowe said that 198 companies worldwide are producing nanoparticles for various applications. One of the major advantages is the huge increase in surface area possible. For example, a 100-gram golf ball has a surface area equivalent to a Post-It note, whereas 100 grams of 40-nm particles have a surface area greater than a soccer field. Nanoscale optical properties also differ significantly from micrometer-scale optical properties; for example, 30-μm Al particles are silver in color, whereas 30-nm Al particles are black.

Companies making nanoparticles have found it necessary to perform nanoscale characterization of their products at various stages of the production process in order to obtain adequate process control. The best processes today have a variation in particle size of about 4 nm (for an average diameter of 28 nm) over a week of production. Today's plants can produce between 1 and 3 pounds per day; they need to get to hundreds of pounds to be economically viable. Building such a plant is estimated to require an investment of $2.5 million for every 100 pounds produced and about 4 years to fully understand and control the process.

Removal of barriers to commercialization will require nano-savvy product and process engineers. In addition, potential regulatory, environmental, health, and safety issues need immediate attention. (Debra Rolison, a committee member, said that a book would soon be published on these topics.)

RESILIENCE OF MICRO/NANO MATERIALS—EFFECTS OF VIBRATION, STRESS, TEMPERATURE, TIME, ETC.

Kevin Hemker noted that the mechanical, electrical, optical, magnetic, and chemical properties of materials change at the nanoscale; one exception may be tensile modulus, which appears to be independent of length scale. Smaller is stronger, up to a point. For example, the fact that flaws are much smaller in MEMS materials makes it possible to use silicon as a structural material. A 300-fold increase in strength can be attained by changing the current density during deposition, which results in the formation of nanocrystals. However, the grain boundaries of nanostructures will increase with extended exposure to elevated temperatures, increasing flaw sizes and thereby reducing strength The increased surface area of nanomaterials means increased reactivity and susceptibility to environmental conditions. Electrodes in Li-ion batteries can swell 300 percent with Li^+ ion intercalation, raising all sorts of issues having to do with stress, fatigue, and so on. Porous battery materials may best be modeled as cellular solids.

TOPIC 4 DISCUSSION

The panel discussion started with a question about the feasibility of using live organisms—including engineered organisms—to make the desired small particles. One response was that biosynthesis is slow and one then has to separate the product from the organisms, with attendant concerns about purity, etc.

There was a question about how long one would have to wait for biomaterials to evolve to a point that they could be used reliably in applications. It was pointed out that structural materials used today in aerospace needed 20+ years to move from laboratory to production. (Note, however, that DARPA has the Accelerated Insertion of Materials program, which tries to accelerate the transition of advanced materials into applications.) Nanomaterials are perceived as evolving more rapidly. However, it was pointed out that as nanomanufacturing processes evolve, the properties of the product change and it is important to continue to characterize them carefully. Many current microstructure devices—e.g., MEMS—are overdesigned; there is much room to reduce thicknesses and the like without affecting performance. We will not have that luxury as we move to smaller length scales. We also do not know how atoms jumping around as a result of thermal fluctuations—caused, for example, by changes in current—will affect the lifetime of nanostructures.

It was noted that for some purposes, e.g., dense crystal microstructures, it is desirable to have a wide dispersion of starting particle sizes rather than the narrow dispersions discussed by Lowe. There has been some research on nanoscale composites, but the difficulty is that these particles have a tendency to agglomerate. Some superalloy composites have been fabricated successfully on the micrometer scale.

One person wanted to know whether there are any catalogs of currently available nanomaterials for use by designers. The answer was that, in general, there are not, although some companies put out brochures listing their products. There is an organization for MEMS that puts foundries in contact with potential users. It was pointed out that after 40 years of polymer composite material development, we still do not have a composites design manual for aerospace engineers, so we are far from having one for nanomaterials. There has been some progress in compiling the mechanical properties (though not strain measurements) of materials for micrometer-scale devices; however, in microdevices, the test of material performance is, in effect, the performance of the device.

TOPIC 5: NATURAL POWER

Two presentations were made in this session, by George Whitesides of Harvard University (a committee member) and Michael Heller of the University of California, San Diego. Their papers are summarized below.

BIO-BASED NANO SYSTEMS

George Whitesides began with the admonition that we should focus not on technologies that are commercially viable but rather on where there is intelligence value. Examples include the following:

1. Obtaining better human intelligence,
2. Detecting and tracking weapons of mass destruction (WMD),
3. Better surveillance, and
4. Exfiltration—getting information in and out of a sensor system.

On item 1, it will be important to invent a new technology base as opponents become more adept at shielding their activities from overhead assets. One key area could be modifying humans or animals to harvest natural internal chemical gradients to produce biobatteries ("a goat with an electric socket on its side"). Energy harvesting from natural sources could be the best solution for powering sensors or exfiltrating information.. Examples might include harnessing the sodium and potassium gradients across cell membranes; oxygen gradients within the body; or light-harvesting implants based on mitochondrial chylomicrons, the very efficient photosynthetic organelles in green plants.

On item 2, the question is how we look for WMD. One approach might be to develop ubiquitous sensors that are cheap and disposable—an example of which might use all-organic electronics. While such materials have poor properties as semiconductors, if we move to transistor gate sizes of 50 nm the performance might be adequate.

On items 3 and 4, a major issue in surveillance is refueling of the sensor system. A laser might be used remotely to recharge a battery, for example. Instead of having a solar cell that converts light to electricity, one could use the cell to store energy in chemicals or to charge a battery. Retroreflectors on the sensor system might also be powered by interrogating laser light. For some applications that require higher power, nuclear materials might be a good solution for some batteries, in spite of the political issues. Another option might be to genetically engineer *E. coli* bacteria to make sensors that detect chemical weapons or even changing light levels. These bacteria would feature nanometer-sized components, be self-replicating, and be cheap once the research has been done.

Nanotechnology brings three things to the problem of power sensors:

1. New materials,
2. Better use of existing materials, and
3. New forms of catalysis.

On item 1, new battery materials such as carbon, silicon, and titanium offer favorable thermodynamics but terrible kinetics. They form self-passivating layers that slow down the process. This can be solved by raising the temperature—for example, by using a nuclear material as a fuel source.

Nanotechnology may offer a solution to the generic membrane problem. In the past, the kinds of pores one could obtain were determined by how materials precipitate. The field of engineered nanoscale pores is a key R&D area.

On item 2, carbon nanotubes look promising as current collectors. These materials were first patented in 1982, but the field has been in stasis for the past 20 years because of the "60 million dollar chicken-or-egg problem." That is, potential users want a manufacturing line to produce large quantities of cheap material, but before building such a line, producers want some assurance that markets will be forthcoming. Whitesides believes that Japanese companies will solve this problem: Carbon nanotubes can provide high electrical conductivity when loaded into a polymer matrix at low volume fractions, and the market for conducting polymers is very large—about 10 million pounds per year.

Multiwalled nanotubes are so stiff that they cannot be stuffed into a small space, but an oriented forest of tubes can be grown instead. The virtue of the polywall structure is that only the outside wall interacts with the environment; the inside walls do not, so these materials are self-insulating.

On item 3, vapor-liquid-solid (VLS) catalysis can be used to make carbon nanotubes from iron nanoparticle melts. The carbon diffuses along the surface of the iron and precipitates as nanotubes on the back side. Silicon tubes form in a more perfect structure than carbon tubes. New forms of catalysis are needed.

BIO-BASED NANO SYSTEMS: CHALLENGES IN DEVELOPMENT OF BIOMIMETIC NANOMECHANICAL SYSTEMS FOR ENERGY CONVERSION

Michael Heller presented an overview of the 2002 NRC report on the National Nanotechnology Initiative, *Small Wonders, Endless Frontiers*. In his view, the development of nanotechnology thus far has been evolutionary rather than revolutionary. He is concerned about the growing technophobia surrounding nanotechnology, as expressed in recent books and magazine articles. We need better micro-nano manufacturing methods, particularly for making integrated devices. Heller discussed the potential of nanotechnology in composites and advanced materials, microelectronics, computing, and energy conversion. A largely unexplored area is bionanotechnology.

Biological systems do things very differently. They use uniquely organized, highly efficient nanoscale structures (one such biological process is photosynthesis). Heller described experiments aimed at developing an efficient nanomachine for converting chemical energy into mechanical motion using kinesin and dynein nanomotor proteins with ATP synthase. In living organisms, enzymes are the dynamic catalytic nanomachines that run all synthetic, energy conversion, and animation processes. People can make some pieces of these systems, but they cannot bring them together. Heller's message was that chemomechanical nanostructures and their catalytic, dynamic, and mechanistic properties are the business end of living systems and have the most potential for leading to a truly new generation of biomimetic animation and energy transduction nanodevices.

TOPIC 5 DISCUSSION

The discussion for this session began with a series of comments. If one wants to look for widely dispersed "bad stuff"—chemical agents or explosives—one should consider using insects, e.g., lightning bugs (or something in between *E. coli* and goats). Power is a major issue. If one wants to use a laser to refuel a sensor system, it would have to be weapons-class in size. On the other hand, natural systems have a low energy density, and this requires equally low-power methods of analysis—e.g., by biological processing.

DARPA has studied engineered bugs, the virtue being that they are small and their breeding time is short. In fact, the government has spent enormous amounts on the development of bio-nano. If one uses dragonflies or hummingbirds, their "batteries" must be refueled very often. Humans are "100 watt objects." Bees have also been considered as detectors for explosives.

Biological organisms use some 20 amino acids and DNA uses 4 different bases in its structure. One cannot mimic biological function without using amalgams of comparable complexity—that is, one cannot just use nanotubes. One view was that rather than creating synthetic mimics of biological function, it would be better to use biological structures already in place. Pound for pound, insect flight muscles are equivalent in power to a jet engine, but they run more efficiently and on a lower-grade fuel.

Whitesides's view is that it is desirable to use the whole organism rather than remove pieces and use those; living organisms often provide enormous amplification of signals. The immune response system is a gold mine of information; by reading the immune system, one can obtain a history of exposures for the organism. One can use cell machinery to make more robust biological molecules, but it is important to remember that while some cells remain stable at 100°C, the individual components may not be stable when taken out of the organism. One should not pick apart the sensor and the power source—they should ideally be integrated together.

TOPIC 6: REVIEW OF THE NATIONAL SCIENCE FOUNDATION REPORT *APPROACHES TO COMBAT TERRORISM: OPPORTUNITIES FOR BASIC RESEARCH IN ENERGY/POWER SOURCES*

Debra Rolison, a member of this committee and of the committee that wrote the NSF report, *Approaches to Combat Terrorism: Opportunities for Basic Research in Energy/Power Sources* summarized the November 2002 meeting at which the report had been presented. That report set forth the current options for portable/mobile/leave-behind power sources for integrated circuits. To get improved performance, we need improved materials. A key opportunity is to create multifunctional architectures using nanoscopic components that produce power. Particularly promising are porous, disordered materials that can be synthesized by soft methods such as self-organization.

In batteries, we want to achieve higher capacities by transferring more electrons per metal center. We also want to maximize charge transfer by reducing cathode/electrolyte/anode separation dimensions to the nanoscale. By synthesizing an open, intercalated V_2O_5 aerogel for Li-ion batteries, one can increase the Li ion uptake by a factor of 4 compared with the best dense V_2O_5, creating a capacity of 1,600 Wh/kg. In batteries made from nanoscale materials, one sees a blurring of the properties usually ascribed to discrete components; for example, on discharge, batteries show voltage changes more commonly associated with capacitors. This introduces a degree of multifunctionality to these architectures—e.g., the battery power supply does not require a separate capacitor.

As an example of a three-dimentional nanostructured battery architecture, Rolison showed an all-solid-state battery with a sol-gel-derived MnO_2 ambigel cathode coated with an electrodeposited polymer electrolyte separator, and the remaining mesoporous volume filled with Li metal anode. This integrated, interpenetrating architecture maximizes the interface between anode and cathode (and minimizes the distance between them), more effectively utilizes the available volume, and results in a battery with both high energy and high power density. Using a similar approach, high-quality nanowire and superior ultracapacitors featuring polymer-modified carbon nanofoams can be produced. In these microporous structures, it is important to realize that the walls of the micropores cannot be wetted with liquid electrolyte on any practical time scale—one must rely on solid-state charge transfer. This has huge implications for nanotubes and other ultra-high-surface-area materials.

In fuel cells, we need better electrocatalysts that are not poisoned by less-than-pristine fuels and would like to get rid of proton-conducting membranes altogether. Disordered Pt/Ru blacks can be used as catalysts in direct methanol fuel cells, which can be made carbon-free and membrane-free through a nanowired architecture design. The key is to design multifunctional disordered electrode architectures rather than using a "masonry" (layer-on-layer) approach.

Similarly, in thermoelectric, photovoltaic, and thermionic power sources, nanostructured materials/processing approaches may break the historical limitations of low efficiency and high-temperature requirements.

In energy-harvesting applications, one typically needs to tap into low-power, low-temperature distributed sources. Pulsed power is possible if one could use the low-power continuous source to trickle charge a capacitor or fill the "fuel tank" of a leave-behind, direct methanol fuel cell. Ultraporous nanoarchitectures may find uses as catalysts or capacitor materials in these systems. For instance, it is possible to generate an aerogel of nanosized gold particles and cytochrome C that is stable at room temperature for 6 weeks. This suggests that it may be possible to self-assemble an artificial energy transport chain that mimics biological energy transport chains. In another example, state-of-the-art CO oxidation catalysts can be created by using sol-gel chemistry to generate gold-titanium oxide composite aerogels in which 6-nm gold particles intermingle with 10-nm titania particles. This like-sized neighbor architecture enables catalytic activity that is not available in the older architectures in which a 3-nm gold particle rides on a 40-nm titania particle.

Rolison concluded by noting that if disorder is good in nanoarchitectures, almost all of our analytical/characterization tools that depend on order (e.g., x-ray diffraction, EXAFS) are inadequate. Thus, new characterization methods will have to be developed. Also, a key goal for the future is to understand how these disordered structures can be chemically and physically stabilized.

TOPIC 6 DISCUSSION

It was remarked earlier (see Topic 1 discussion) that no rechargeable battery uses more than 25 percent of its volume actively. How, it was asked, should we think about the percentage volume that is unused? The response was that if one charges and recharges slowly, one can "talk" to most of the battery volume. The issue is how much of the active material one can utilize in fast charging and discharging. If one is smart in the architectural design and uses electrode materials that can withstand the mechanical strains associated with ion movement, one can get more battery capacity. However, as we move to smaller and smaller length scales, we begin to smear the definitions of battery, capacitor, and the like.

The best present batteries have power densities of 25-30 W/g. How much better can we expect batteries to get, and when? According to Rolison, with MnO_2 porous architectures, one can double the C rate, since one can "talk" to nearly all of the surface area. If the electrode/electrolyte structures are thin, one can get around many of the problems faced by standard batteries. An important area for future study is hydrogen storage, either in hydrides or butadiene. Rolison concluded by saying that in the future, power for integrated circuits will be "all-nano all the time."

Appendix A
Workshop Participants and Agenda

PARTICIPANTS

Topic 1: Overview of Power Technologies
Presenters:
George Blomgren, Blomgren Consulting, Lakewood, Ohio
John Miller, consultant, JME Inc.
Daniel Steingart, University of California, Berkeley

Topic 2: Nanoscale Properties of Energy Storage Materials
Presenters:
Dane Morgan, Massachusetts Institute of Technology, Cambridge
Dan Scherson, Case Western Reserve University, Cleveland, Ohio
Ann Marie Sastry, University of Michigan, Ann Arbor

Topic 3: Device Experience
Presenters:
Esther Takeuchi, Wilson Greatbatch Technologies, Inc., Clarence, New York
Nancy Dudney, Oak Ridge National Laboratory, Knoxville, Tennessee
Robert Nowack, Consultant, Silver Spring, Maryland

Topic 4: Manufacturing and Material Handling Consideration
Presenters:
Terry Lowe, Los Alamos National Laboratory
Kevin Hemker, Johns Hopkins University, Baltimore, Maryland

Topic 5: Natural Power
Presenters:
George Whitesides, Harvard University
Michael Heller, University of California, San Diego

Topic 6: Review of the National Science Foundation Report *Approaches to Combat Terrorism: Opportunities for Basic Research in Energy/Power Sources*

AGENDA

Thursday, October 9, 2003

7:30 a.m.	*Continental Breakfast*	
8:00	Call to order and review of meeting objectives	Robert Hermann, Chair
8:05	Composition and balance discussion	Dennis Chamot, DEPS
8:45	*Break*	
8:55	Overview of NETI program ITIC videotape	Martin Carr
9:40	Survey of power systems/programs for the intelligence community	Enoch Wang
10:10	Discussion	
10:40	*Break*	

Topic 1: Overview of Power Technologies

10:50	Discussion items: • Battery systems • Supercapacitors • Energy harvesting	Outside participants: George Blomgren, John Miller, and Daniel Steingart
12:20 p.m.	*Lunch*	

Topic 2: Nanoscale Properties of Energy Storage Materials

1:00	Discussion Items: • Ab initio considerations • Laboratory observations and modeling — Surface science perspective — Chemistry perspective • Mechanical and physical property Perspective	Outside participants: Dane Morgan, Dan Scherson, Ann Marie Sastry

2:50	*Break*	

Topic 3: Device Experience

3:00	Discussion Items: • Implantable and biomedical power sources • Micro power sources for MEMS and NEMS devices • Soldier power energy systems	Outside participants: Esther Takeuchi, Nancy Dudney, Robert Nowak
4:40	Chairman's time	Robert Hermann
5:00	Adjourn	

Friday, October 10, 2003

7:30 a.m.	*Continental Breakfast*	

Topic 4: Manufacturing and Material Handling Considerations

8:00	Discussion items: • Considerations for the handling, compounding of nanosize materials • Resilence of micro/nano mateials for energy storage and power sources	Outside participants: Terry Lowe, Kevin Hemker

Topic 5: Natural Power

9:10	Discussion items: • Bio-based nano systems • The nature of power	Outside participants: George Whitesides, Michael Heller

Topic 6: Review of the National Science Foundation Report

10:00	Recent NSF nanotechnology study	
10:20	*Break*	
10:30	Chairman's time	Robert Hermann
10:50	*Break*	
11:00	Sponsor discussion of positioning and	Martin Carr/Jerry Walsh

	locating	
12:00 p.m.	*Lunch*	
1:00	Committee discussions	
3:00	*Break*	
3:15	Continue committee discussions	
4:30	Chairman's time	Robert Hermann, Chair
5:00	*Adjourn*	

Appendix B
List of Attendees

George Atkinson, NETI Technical Working Group
Antonio Cantu, U.S. Secret Service
Martin Carr, ITIC
Kenneth Crelling, Department of Defense
Aladar Csontos, Nuclear Regulatory Commission
James De Yoreo, Lawrence Livermore National Laboratory
Daniel Doughty, Sandia National Laboratories
Lawrence Dubois, SRI International
James Ellenbogen, MITRE Corporation
Alan Epstein, Massachusetts Institute of Technology
Wilhelm H. Gauster, Sandia National Laboratories
Hollis Helms, NETI Technical Working Group
Robert Hermann, Global Technology Partners
Shirley Jackson, Rensselaer Polytechnic Institute
Siegfried Janson, The Aerospace Corporation
Anthony Laviano, Raytheon
Ronald Lucas, Department of Defense
Brigitte Rolfe, MITRE Corporation
Debra Rolison, Naval Research Laboratory
R. Paul Schaudies, Science Applications International Corporation
Richard Silberglitt, RAND Corporation
Diane Snyder, Rand Corporation
Joseph Stockel, Power Systems Center
Bill Vanderlinde, University of Maryland, Laboratory for Physical Sciences
Cung Vu, Department of Defense
Gerald Walsh, NETI Technical Working Group
Julia Weertman, Northwestern University
George Whitesides, Harvard University
Ellen Williams, University of Maryland
Mary Young, HRL Laboratories

Appendix C
Committee Biographies

Robert J. Hermann, **NAE**, *Chair*, is currently a senior partner at Global Technology Partners, LLC, a Boston-based firm specializing in investments in technology, defense, aerospace, and related businesses worldwide. In 1998, Dr. Hermann retired from United Technologies Corporation, where he was senior vice president, science and technology. Prior to joining UTC in 1982, Dr. Hermann served 20 years with the National Security Agency, with assignments in research and development, operations, and the North Atlantic Treaty Organization (NATO). In 1977, he was appointed principal deputy assistant secretary of defense for communications, command, control, and intelligence. In 1979, he was named Assistant Secretary of the Air Force for research, development, and logistics and in parallel was director of the National Reconnaissance Office. He received B.S., M.S., and Ph.D. degrees in electrical engineering from Iowa State University. He was a member of the President's Foreign Intelligence Advisory Board from 1993 to 2001 and a chairman of the board of directors of the American National Standards Institute from 1998 to 2000. Dr. Hermann was also chair of the board of directors of Draper Laboratory. He is currently a member of the board of directors of Condor Systems, a member of NAE, and a member of the Defense Science Board.

Antonio A. Cantu is the chief research scientist of the Forensic Services Division of the United States Secret Service. His forensic interests include the chemical analysis of inks and paper on documents for determining their date and origin; the visualization of latent fingerprints using chemical, optical, and physical methods; and the optical and chemical tagging of targets for tracking and locating them. He has assisted in developing countermeasures against threats involving chemical, biological, radiological, nuclear, and explosive (CBRNE) materials. The latter includes technology for point detection and standoff detection of explosives. He co-chairs the Investigative Support and Forensic Subgroup of the Technical Support Working Group (the technical arm of the Interagency Working Group on Counter Terrorism). He has held positions at the U.S. Department of Justice, the Bureau of Alcohol, Tobacco and Firearms, and the FBI. Since 1986, he has been with the U.S. Secret Service. Dr. Cantu received a B.Sc. (1963) and a Ph.D. (1967) in chemical physics from the University of Texas, Austin. He was a postdoctoral fellow at the University of Alberta, Edmonton, and an OAS visiting fellow at the University of Mexico (1970).

James J. De Yoreo is currently acting director, Bio-Security and Nanosciences Laboratory of the Lawrence Livermore National Laboratory's Chemistry and Materials Science Directorate. His research interests include scanned probe nanolithography, nanoscale surface patterning, nucleation templates, physics of crystal surfaces in solutions, macromolecular crystallization, biomineralization, interaction of organic molecules with inorganic crystal surfaces, assembly of supramolecular motifs, high-resolution imaging, physics and chemistry of crystalline defects, and characterization of optical crystals. Dr. De Yoreo is a member of the Materials Research Society and vice president of the American Association for Crystal Growth. In 1994 he was presented the R&D 100 award—Development of rapid growth process for KDP, and in 2001 he received the Lawrence Livermore National Laboratory Science and Technology Award. Dr. De Yoreo earned a B.A in physics from Colby College and an M.S. and Ph.D. in experimental physics from Cornell University.

Daniel H. Doughty received his Ph.D. in inorganic chemistry from the University of Minnesota in 1979. His thesis work explored the synthesis, characterization, and mechanistic study of organometallic complexes used as homogeneous decarbonylation catalysis. He studied various compounds, primarily in the family of rhodium phosphine complexes. He also studied at the Catholic University of America and the University of New Mexico, where he obtained a B.S. in chemistry and an M.S. in inorganic chemistry. Dr. Doughty currently is the manager of the Lithium Battery Research and Development Department, Sandia National Laboratories. This group has responsibility for developing advanced power sources, typically batteries and electrochemical cells based on lithium. Areas of expertise include various lithium chemistries (e.g., lithium-ion rechargeable batteries and lithium thionyl chloride cells and batteries). The group works on cutting-edge electrochemistry as well as advanced batteries and battery materials for defense and commercial applications. Prior to taking this assignment in 1992, he led the Inorganic Materials Chemistry Division for 7 years. This group has responsibility for advanced ceramic and glass materials as well as general inorganic chemistry. Specifically, the preparation of preceramic materials was a major effort that used sol-gel chemistry and other solution routes to ceramic and glass materials. Previous projects at Sandia National Laboratories involved organometallic chemistry, inorganic chemistry, nanostructured gold colloids, and the kinetics of gas-solid reactions. Prior to joining Sandia, Dr. Doughty worked for 3 years at 3M Company as a research chemist developing advanced inorganic photoconductors. Other areas of interest are general materials chemistry and processing, including colloid chemistry, superconducting ceramics, intercalation compounds, and oxide surface chemistry. Dr. Doughty received the DOE Award of Excellence in 1989 and is a member of the American Chemical Society, the Materials Research Society, ECS, and Phi Kappa Phi honorary fraternity. He has over 80 publications, holds three patents, and has co-edited four technical proceedings volumes.

Lawrence H. Dubois received an S.B. degree in chemistry from the Massachusetts Institute of Technology in 1976 and a Ph.D. in physical chemistry from the University of California, Berkeley, in 1980. Dr. Dubois then joined AT&T Bell Laboratories to pursue studies of the chemistry and physics of metal, semiconductor, and insulator surfaces; chemisorption and catalysis by materials formed at the metal-semiconductor interface; and novel methods of materials growth and preparation. In 1987, he was promoted to distinguished member of the technical staff and technical manager. His efforts broadened to include projects on polymer-surface interactions; adhesion promotion; corrosion protection; chemical vapor deposition and thin-film growth; optical fiber coating; synthesis, structure, and reactivity of model organic surfaces; and time-resolved surface vibrational spectroscopy. In 1993, Dr. Dubois moved to MIT Lincoln Laboratory as a senior staff scientist and was assigned to the Defense Advanced Research Projects Agency (DARPA). In that capacity, he established the Advanced Energy and Environmental Technologies Program and managed projects on the development and manufacturing of rechargeable batteries; high-performance, direct-methanol, and logistic-fuel-powered fuel cells; and the development of new, more environmentally sound manufacturing processes, environmental sensors, and waste destruction/reclamation procedures. In 1995, Dr. Dubois was promoted to deputy director and in 1996 to director of the Defense Sciences Office at DARPA. This office is responsible for an annual investment of approximately $300 million for the development of technologies for biological warfare defense, biology, defense applications of advanced mathematics and materials, and devices for new military capabilities. In March 2000, Dr. Dubois joined SRI International as corporate vice president and head of the Physical Sciences Division, a group of over 150 scientists and engineers focusing on the development and commercialization of advanced materials, microfabrication technologies, power sources, biological warfare defense, medical diagnostics, molecular and optical physics, explosives and propellants, catalysts, coatings, and environmentally benign processing. Dr. Dubois is the author of over 130 publications and holds four U.S. patents and several foreign patents. His numerous honors include the prestigious IR100 and Alpha Chi Sigma awards as well as the Office of the Secretary of Defense Award for Outstanding Achievement and the Secretary of Defense Medal for Outstanding Public Service. He sits on the board of directors of two spin-off companies from SRI: Polyfuel and CYANCE.

Alan H. Epstein, NAE, is currently R.C. Maclaurin Professor at the Massachusetts Institute of Technology, Department of Aeronautics and Astronautics. He is also the head of the Division of Fluids, Propulsion and Energy Conversion. He is responsible for teaching gas turbine and rocket engine design at the undergraduate and graduate level; coordinating teaching, graduate admissions, and faculty staffing for fluid mechanics, propulsion, and energy conversion; directing the 80-person MIT Gas Turbine Laboratory; serving as principle investigator and director of the 50-person MIT MicroEngine Project; and conducting research on advanced propulsion and energy conversion technologies. His interests include teaching and research in the areas of compressor and turbine aerodynamics, compressor stability, turbine engine controls, turbine heat transfer, engine instrumentation and measurement, turbomachinery noise, and microengines and MEMS. Dr. Epstein's consulting activities include gas turbine engine design and design practice; engineering management and organization; and signature analysis of air-breathing vehicles. In addition to being a member of the National Academy of Engineering, Dr. Epstein also holds membership in the American Association for the Advancement of Science and the American Society of Mechanical Engineers, as well as being a fellow at the American Institute of Aeronautics and Astronautics. He has been a liaison, chair, and member of numerous National Research Council committees and boards, including Review of ONR’s Aircraft Technology Program, Implications of Micro and Nanotechnology for the U.S. Air Force, Review of Effectiveness of U.S. Air Force S&T Changes, and the Board on Army Science and Technology. Dr. Epstein received his B.S., M.S., and Ph.D. degrees from the Massachusetts Institute of Technology and has over 90 publications in the fields of gas turbine technology, air vehicle observables, instrumentation development, and MEMS.

Wilhelm B. Gauster is currently deputy director of the Physical and Chemical Sciences Center at Sandia National Laboratories, where he manages nanoscience activities for defense program applications. His own research has covered a wide range of topics in solid-state physics and nuclear technology, including thermomechanics, optical properties of semiconductors, neutron and electron irradiation effects, positron annihilation, muon spin rotation, plasma-materials interactions, and high-heat-flux components for fusion devices. He has managed a variety of programs in basic and applied research, fission and fusion technology, and energy policy. Dr. Gauster received an A.B. in applied physics from Harvard College and a Ph.D. in physics from the University of Tennessee. He has served as a member of numerous editorial boards and advisory panels, as an adjunct professor at the University of New Mexico, visiting scientist at the Jülich Research Center, and deputy head of site at the International Thermonuclear Experimental Reactor Joint Work Site in Garching (Germany). He was a member of the Department of Energy Magnetic Fusion Advisory Committee in 1988 and 1989 and received the Department of Energy Distinguished Associate Award in 1993.

Shirley A. Jackson, NAE, is currently the president of Rensselaer Polytechnic Institute. Her career prior to becoming Rensselaer’s president encompassed senior positions in government, as chairman of the U.S. Nuclear Regulatory Commission; in industry and research, as a theoretical physicist at the former AT&T Bell Laboratories; and in academe, as a professor of theoretical physics at Rutgers University. Dr. Jackson holds a Ph.D. in theoretical elementary particle physics from MIT and an S.B. in physics from MIT. Her research specialty is in theoretical condensed-matter physics, especially layered systems, and the physics of opto-electronic materials. In 1995 President Clinton appointed Dr. Jackson to serve as chair of the U.S. Nuclear Regulatory Commission (NRC), which position she occupied from 1995 to 1999. As chair, she was the principal executive officer of and the official spokesman for the NRC. She had ultimate authority for all NRC functions pertaining to an emergency involving an NRC licensee. The NRC is charged with the protection of the public health and safety, the environment, and the common defense and security by licensing, regulating, and safeguarding the use of reactor by-product material in the United States. This includes power reactors; research, test, and training reactors; fuel cycle facilities; reactor by-product use in medicine, industry, and research; the transportation, storage, and disposal of high-level and low-level radioactive waste; and the licensing of nuclear exports for peaceful uses. From 1991 to 1995, Dr. Jackson was professor of physics at Rutgers University, where she taught undergraduate and graduate students, conducted research on the electronic and optical properties of two-dimensional systems, and supervised Ph.D.candidates. She concurrently served as a consultant in semiconductor theory to AT&T Bell Laboratories. Dr. Jackson will become president of the American Association for the Advancement of Science (AAAS) in February 2004. She will serve as president-elect in 2003, as president in 2004, and will chair the AAAS board in 2005. Dr. Jackson is a member of the National Academy of Engineering and a fellow of the American Academy of Arts and Sciences and the American Physical Society. Dr. Jackson holds 21 honorary doctoral degrees. She is a member of the National Advisory Council for Biomedical Imaging and Bioengineering of the National Institutes of Health (NIH), serves on the Advisory Committee for the Department of Energy National Nuclear Security Administration (NNSA), and is a member of the U.S. Comptroller-General's Advisory Committee for the Government Accounting Office (GAO). She also has served on a number of committees of the National Research Council of the National Academy of Sciences.

Siegfried W. Janson is a senior scientist at the Aerospace Corporation. He obtained a Ph.D. in aerospace engineering from Cornell University in 1984. He was a postdoctoral associate at Cornell from 1984 to 1987, at which time he joined the Aerospace Corporation to pursue experimental research in electric thrusters and advanced laser-based propulsion diagnostics. Dr. Janson's current research interests are micropropulsion, micro/nanotechnology for space systems, formation flying, and distributed space systems. He has worked in the MEMS field for 13 years and authored or co-authored over 20 papers on microthrusters, micro/nanotechnology for space applications, and silicon satellites. He managed and co-managed two DARPA-sponsored MEMS programs (Digital Thrusters and Micro Power Generator) and participated in MEMS flight experiments on the shuttle and the International Space Station. Dr. Janson has given invited presentations on micro/nanotechnology for spacecraft to the National Academy of Engineering, the European Space Agency, and the International Space University. He was co-chair (2001) and chair (2003) of the SPIE conference MEMS Components and Applications for Industry, Automobiles, Aerospace, and Communications. Dr. Janson has served on several NRC panels for the review of Air Force Office of Scientific Research propulsion proposals and on the NRC Committee on Implications of Emerging Micro and Nano Technologies. He is a member of the IEEE and a senior member of the American Institute of Aeronautics and Astronautics (AIAA).

Anthony F. Laviano is a member of Raytheon Space and Airborne Engineering staff in El Segundo, California. He is a member of the Patent Committee and is program manager for Advanced Technical Programs. His focus is advanced technologies and products, which include power electronics; sensor, processor and antenna technologies; and dual-use applications—that is, he identifies, organizes, and transitions technology into both military and commercial application. He established and is the leader of the Nano Engineering and Science Technology Interest Group. He led and facilitated the Power Electronics Technology Interest Group; represents engineering in industry endeavors such as the Open Systems Joint Task Force for Power Electronics through the U.S. Air Force; is Power Sources Manufacturer's Association chairperson for the Industry Government Committee; and is co-leader of Electronic Power Specification Standardization Industry Working Group, which writes power electronics standards under IEEE auspices. He is past chairman of the IEEE Power Electronics Society for Southern California, a member of the IEEE Standards Association, the IEEE Los Angeles Council, the IEEE Wescon, and the Academy of Management, and is on the editorial board of the *Journal of Public Administration*. He is a certified contracts manager and a National Contract Association fellow. He received a Ph.D. in business administration from Nova Southeastern University, Florida, an M.B.A. from Pepperdine University, a B.A. from St. Charles College, Pennsylvania, and graduated from the U.S. Army Language School as a Chinese linguist. He is a former member of the National Faculty of Nova Southeastern University Graduate School of Business and Entrepreneurship, as well as the Hughes Aircraft Company technology staff. His technical involvement includes nanotechnology, antenna development, data and mission processors, power electronics, radar systems, software development, system architecture, terrestrial communication systems, and satellite communication systems.

Debra R. Rolison is currently the section head of Advanced Electrochemical Materials at the Naval Research Laboratory. Before this postion, Dr. Rolison was a research chemist at the Naval Research Laboratory. She is also an adjunct professor of chemistry at the University of Utah. Her research interests include synthesis and characterization of nanostructured materials, including research into processes occurring at the electrified interfaces of nanostructured materials with emphasis on (1) aerogels; (2) supported electrocatalysts and nanoscale electrodes; (3) zeolites; (4) colloids; (5) dispersions of catalytically active solids; and (6) chemically modified and dimensionally structured electrode surfaces. A recent research focus has been nanoarchitectures for catalytic chemistries, energy storage and conversion, biomolecular composites, porous magnets, and sensors. Principal inventions include (1) electrified microheterogeneous catalysis; (2) using silica sol as a nanoglue to synthesize composite gels and aerogels; (3) electrodesulfurization of solid carbon; (4) creating a three-dimensional nanowired mesoporous architecture; and (5) infrared-emitting materials. Dr. Rolison also writes and lectures widely on issues affecting women in science. Her ideas with respect to using Title IX to evaluate academic science and engineering departments recently led to a hearing on Title IX and the sciences before the U. S. Senate Subcommittee on Science, Technology, and Space. Dr. Rolison is a member of the American Chemical Society, the Materials Research Society, and the Society for Electroanalytical Chemistry; she was elected a fellow of the AAAS in 2001. She coauthored *Ultramicroelectrodes*, the first text on this active area, with M. Fleischmann, S. Pons, and P. Schmidt. She guest edited an issue of *Langmuir* devoted to the electrochemistry of nanostructured materials and recently served as a guest editor of a *Journal of Physical Chemistry* Festschrift in honor of Royce Murray. Her past and present editorial advisory board service includes *Analytical Chemistry*, *Langmuir*, *Journal of Electroanalytical Chemistry*, *Nano Letters*, and the *Encyclopedia of Nanoscience and Nanotechnology*. She was a member of the board of directors of SEAC and served as editor of *SEAC Communications*. Dr. Rolison was named the 2003 Woman of Excellence by the University of Delaware. She chaired the 2001 Gordon Research Conference on Electrochemistry and chairs the 2003 International Symposium on Aerogels. She received a Ph.D. from the University of North Carolina. She has published over 60 papers and holds 14 patents.

R. Paul Schaudies is a nationally recognized expert in the fields of biological and chemical warfare defense. He has served on numerous national-level advisory panels for the Defense Intelligence Agency, the Defense Advanced Research Projects Agency, and the Department of Energy. He has 14 years bench research experience managing laboratories at Walter Reed Hospital and Walter Reed Army Institute of Research, and was a Visiting Scientist at the National Cancer Institute. He served for 13 years on active duty with the Army Medical Service Corps, and separated from service at the rank of Lieutenant Colonel-select. Dr. Schaudies spent 4 years with the Defense Intelligence Agency as collections manager for biological and chemical defense technologies. As such, he initiated numerous intra-agency collaborations that resulted in accelerated product development in the area of biological warfare agent detection and identification. Dr. Schaudies is currently an assistant vice president and division manager of the Biological and Chemical Defense Division at SAIC. His division focuses on three major business areas: contract biomedical research, technology assessments, and scientific studies. Since joining SAIC, Dr. Schaudies has served on and chaired numerous technology review and advisory panels for U.S. government agencies. Dr. Schaudies received his bachelor's degree in chemistry from Wake Forest University and his doctoral degree from Temple University School of Medicine in the Department of Biochemistry. He has authored 27 scientific manuscripts in the peer-reviewed literature, as well as three book chapters. Dr. Schaudies is active in both government and academic circles.

Julia R. Weertman, NAE, has conducted research on the mechanical behavior of metals and alloys and the underlying phenomena that give rise to the observed behavior. Her research currently focuses on determining the mechanical properties of a variety of nanocrystalline materials, characterizing their structure, and studying deformation mechanisms in this small-grain-size regime. She also continues interest in the high-temperature behavior of metals. Her research has demonstrated the value of smallangle neutron scattering for detection and quantification of such features as voids and pores and for following the nucleation and growth kinetics of second-phase particles. Dr. Weertman is a member of the National Academy of Engineering and the American Academy of Arts and Sciences. She is past member of the Committee on Women in Science and Engineering and of the Committee on Human Rights of the National Academies and has served on several NRC panels. Currently she is a member of the NRC National Materials Advisory Board. She has served on advisory panels for DOE and NSF and for several national laboratories. She is on the board of review editors for *Science*. She is a fellow of the Materials Society and ASM International, received Special Creativity Awards for Research from NSF in 1981 and 1986, a Guggenheim Fellowship in 1986-1987, the Achievement Award from the Society of Women Engineers in 1991, and the Leadership Award from the Materials Society in 1997.

George M. Whitesides, NAS, received an A.B. degree from Harvard University in 1960 and a Ph.D. from the California Institute of Technology (with J.D. Roberts) in 1964. He was a member of the faculty of the Massachusetts Institute of Technology from 1963 to 1982. He joined the Department of Chemistry of Harvard University in 1982, and was department chairman from 1986 to 1989. He is now Mallinckrodt Professor of Chemistry at Harvard University. He received an Alfred P. Sloan Fellowship in 1968; the American Chemical Society (ACS) Award in Pure Chemistry in 1975; the Harrison Howe Award (Rochester Section of the ACS) in 1979; an Alumni Distinguished Service Award (California Institute of Technology) in 1980; the Remsen Award (ACS, Maryland Section) in 1983, an Arthur C. Cope Scholar Award (ACS) in 1989; the James Flack Norris Award (ACS, New England Section) in 1994; the Arthur C. Cope Award (ACS) in 1995; the Defense Advanced Research Projects Agency Award for Significant Technical Achievement in 1996; the Madison Marshall Award (ACS) in 1996; the National Medal of Science in 1998; the Sierra Nevada Distinguished Chemist Award (Sierra Nevada Section of the ACS), the Wallac Oy Innovation Award in High Throughput Screening (the Society for Biomolecular Screening) in 1999; the Award for Excellence in Surface Science (Surfaces in Biomaterials Foundation) in 1999; and the Von Hippel award (Materials Research Society) in 2000. He is a member of the American Academy of Arts and Sciences, the National Academy of Sciences, and the American Philosophical Society. He is also a fellow of the American Association for the Advancement of Science and the New York Academy of Science, a foreign fellow of the Indian National Science Academy, and an honorary fellow of the Chemical Research Society of India.

Ellen D. Williams is currently a professor in the Department of Physics and the Institute for Physical Science and Technology at the University of Maryland, as well as the director of the Materials Research Science and Engineering Center. Dr. Williams is a fellow of the American Academy of Arts and Sciences. In 2001 she was the recipient of the American Physical Society's David Adler Lectureship Award, and in 1998-1999, she was their centennial speaker. Dr. Williams serves on the National Security Panel of the University of California President's Council and is also on the editorial board of *Nano Letters* (ACS). Dr. Williams received a B.S. in chemistry from Michigan State University, a Ph.D. in chemistry from the California Institute of Technology, and did postdoctoral research in physics at the University of Maryland.

Mary H. Young is the director of the Sensors and Materials Laboratory of Hughes Research Laboratories, a research company that is jointly owned by Boeing, General Motors, and Raytheon Company. Dr. Young manages an organization with research emphasis in microelectromechanical (MEM) and nanofabrication technologies, energy technologies, electro-optical sensor materials and process technologies, materials engineering, and nanoelectronics. Dr. Young received her B.S. in physics at Wake Forest University, her M.S. in physics at the University of Maryland, and her Ph.D. at UCLA in electrical engineering. Since joining Hughes Research Laboratories in 1974, Dr. Young has conducted research on the development of ultrapure silicon, extrinsic semiconductors for use in IR detector programs, GaAs for a variety of electronic and optical device applications, superconductors for microelectronics, and superlattice materials for novel device concepts. Currently, she is engaged in directing the development of novel processes for materials, including semiconductors, active materials, materials for thermal management, and materials for energy and power, and in exploring innovative sensor types and designs, including MEMS devices, chemical and biological threat/environmental sensors, electromagnetic sensors, and multisensor control methodologies. Major application programs in energy storage and conversion, materials for automotive/aerospace sensors and power systems, semiconductor nanoelectronics, MEMS-based sensor and communications systems, and IR sensor-based systems are among the programs currently being conducted under the direction of Dr. Young. Dr. Young has contributed original work in electronic transport physics in semiconductors and in the physics of IR sensitive materials and IR devices and managed a number of IR sensor development programs. From 1971 to 1974 she was manager of an analytic facility for the Materials Research Laboratory at the University of Maryland. Dr. Young is a member of Phi Beta Kappa and of the American Physical Society and the Materials Research Society. She has more than two dozen publications on semiconductor materials, infrared detectors, impurity hopping electronic transport, neutron transmutation in semiconductors, and superlattice materials and devices.

Appendix D
Acronyms

CMOS	complementary metal oxide semiconductor
DARPA	Defense Advanced Research Projects Agency
EC	electrochemical capacitor
EPA	Environmental Protection Agency
EV	electric vehicle
ITIC	Intelligence Technology Innovation Center
Li-ION	Lithium-ion
MEMS	Microelectromechanical Systems
MWNT	Multiwall Carbon Nanotubes
NEMS	nanoelectromechanical system
NETI	Nano-Enabled Technology Initiative
NiMH	Nickle Metal Hydrid
NIST	National Institute of Standards and Technology
NMAB	National Materials Advisory Board
NRC	National Research Council
OFW	Objective Force Warrior
WMD	weapons of mass destruction