A Golden Jubilee of Materials Science and Engineering

October 27 and 28, 2005
Hardin Hall, Rebecca Crown Center
633 Clark Street, Evanston

NORTHWESTERN
UNIVERSITY

Northwestern University
Cosponsored by the Robert R. McCormick School of Engineering and Applied Science
and the Office of the Provost of Northwestern University

Thursday, October 27

8:30–8:40 a.m. Welcome

Peter W. Voorhees, chair and Frank C. Engelhart Professor, Department of Materials Science and Engineering, Northwestern University

Lawrence B. Dumas, provost, Northwestern University

Session 1: Materials Science and Engineering Turns 50 — Past and Future Perspectives

8:45–9:25 a.m. Morris E. Fine, "Why Materials Science?"

Morris E. Fine is Walter P. Murphy Professor Emeritus in Northwestern's materials science and engineering department. He joined the department in its early days in 1954, was its first chair, and is currently principal or coinvestigator on several sponsored research projects. He is a member of the National Academy of Engineering and a fellow of the American Physical Society, the American Society for Metals (ASM), the Minerals, Metals, and Materials Society (TMS), the American Ceramic Society (ACerS), and the American Association for the Advancement of Science (AAAS). His awards include the Mathewson Gold Medal from the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), the Douglas Gold Medal from AIME, the ASM Gold Medal, and the TMS Educator Award. He has delivered the ASM Campbell Memorial Lecture and the Institute of Metals' Robert Mehl Lecture.

Fine will talk about the early history of materials science as a separate discipline, the establishment and first years of Northwestern's materials science department, and his thoughts on the field's future.

9:30–10:10 a.m. Jeffrey Wadsworth, "The Role of Materials Science in National Security: From Ancient Times to the Present and into the Future"

Jeffrey Wadsworth is director of Oak Ridge National Laboratory and former deputy director for science and technology at Lawrence Livermore National Laboratory. He earlier worked for Lockheed Martin. He is a member of the National Academy of Engineering and a fellow of ASM International, TMS, and AAAS. He has published more than 275 papers and one book and has been awarded four patents.

Materials science has been the driving force behind the development of revolutionary technologies for national security throughout human history, from the Stone Age to the Bronze Age to the Iron Age. The influence of Damascus steels on European steelmaking is a pre–Industrial Revolution example. In modern times advances in materials science guided the development of nuclear weapons from the Manhattan Project to their ultimate expression in the Trident missile system. Today our emerging capabilities for designing and engineering materials at the atomic level offer remarkable opportunities to improve national and global security. Materials science is essential to promoting nuclear nonproliferation, reducing the global danger from weapons of mass destruction, protecting warfighters and first responders, and extending our ability to combat asymmetric attacks.

10:15–10:45 a.m. Coffee break

Session 2: Metals: A Nanoscale View

10:45–11:25 a.m. Julia R. Weertman, "NANO Can Mean Strong"

Julia R. Weertman is Walter P. Murphy Professor Emerita in Northwestern's materials science and engineering department. She is a member of the National Academy of Engineering and AAAS and a fellow of TMS and ASM International. She received the Von Hippel Award from the Materials Research Society and the Achievement Award from the Society of Women Engineers.

As nano-sized features (e.g., grain size, precipitates, or layered structures) are introduced into a metal, large increases in strength can result. These benefits often, but not always, are accompanied by a devastating loss of toughness. This talk will present current knowledge about phenomena associated with deformation in nanocrystalline metals such as microstructural instabilities under stress and about plasticity mechanisms when dislocation activity is restricted. An understanding of such processes is needed to design useful nanocrystalline alloys.

11:30 a.m.–12:10 p.m. David N. Seidman, "From Atoms to Microstructures to the Properties of Modern High-Temperature Structural Alloys"

David N. Seidman is a Walter P. Murphy Professor in Northwestern's materials science and engineering department. He is a fellow of TMS, the American Physical Society, and ASM International. He received a Max Planck Research Prize (Max-Planck-Gesellschaft) and a Von Humboldt Stiftung Prize and was twice a John Simon Guggenheim Memorial Fellow.

To paraphrase Steven Chu, 1997 Nobel laureate in physics and director of the Lawrence Berkeley National Laboratory: "If 30 years from now we have *not* solved the energy problem, life as we know it will be changed." This critical observation is relevant to a presentation about research on metallic alloys for use at elevated temperatures. Carnot's famous cycle for the most efficient thermodynamic heat engine of any type (1820s) tells us that the higher the operating temperature with respect to ambient temperature, the greater its thermodynamic efficiency. It is imperative, therefore, that, using the basic concepts of materials science and engineering, we continue to improve the ability of metallic alloys to function at elevated temperatures in heat engines of all types, as well as the understanding of why they are capable of operating at elevated temperatures. With this as a preamble, this presentation will focus on why studying metallic alloys on an atomic scale, subnanometer, using radically new instrumentation, can yield insights into their behavior at considerably larger length scales, centimeters to meters. The local-electrode atom-probe (LEAP) tomograph provides an investigator with a three-dimensional picture of a reconstructed atomic lattice that contains both positional and chemical information that, in turn, yields the microstructure on length scales from the subnanoscale to mesoscale. Seidman will illustrate the above points with results from current research on model high-temperature nickel-aluminum-chromium base superalloys and aluminum-scandium-element X base alloys, where their microstructure on a subnanometer to mesoscale has a direct impact on their elevated temperature properties. Additionally, he will discuss what has to be accomplished to further improve these alloys to increase their maximum operating temperatures.

12:15–2 p.m. Lunch

Session 3: Ceramics — Novel Processing Routes and High-Tech Applications

2–2:40 p.m. Frederick F. Lange, "Making Advanced Ceramic Powders Behave Like Clay: Manipulating Interparticle Forces for New Shape-Forming Technologies"

Fredrick F. Lange is a professor and chair of the materials department at the University of California, Santa Barbara. He is a member of the National Academy of Engineering, was a Humbolt Senior Fellow, and has received the Max Planck Research Award.

Clay saturated with water was the first hand-molded material made by humankind. Nearly all ceramics are still made with powders. Advanced ceramic powders do not have the inherent plastic properties of clay. Recent research has shown that interparticle forces can be manipulated to produce clay-like behavior and new shape-forming technologies. Without repulsive shrouds, particles attract one another to form touching, cohesive networks because of their pervasive attractive van der Waals forces. Either the electrostatic double-layer method, which shrouds the particles with ions, or the steric method, which shrouds the particles with molecules, can be used to produce repulsive forces. Because the shrouds have a low atomic mass, they do not strongly contribute to the van der Waals attractive force. Repulsive forces arise when the shroud of one particle penetrates that of an approaching particle. The separation distance needed to produce repulsion can be controlled by the "thickness" of the shroud. Thus, when the shrouds strongly interact at large separation distances, the van der Waals force can be completely shielded, and the particles are strongly repulsive. When the interaction occurs at very short separation distances, the van der Waals force first causes the particle to be attractive but repulsive before they touch. For this case, the particles sit in a potential well and form a weakly attractive but nontouching network. Forces are required to pull attractive particles apart; these networks have a yield stress that is required for shape forming. The yield stress will depend on the interparticle force and the number of particles per unit volume. Rheological methods have been developed to measure the "strength" of a particle network. These methods are used not only to characterize the interparticle forces but also to judge the shape-forming ability of a consolidated slurry. These fundamental principles will be used for new forming applications that include crystallization of identical nanoparticles, crystallization of submicron spherical particles within much larger emulsion droplets, and rapid shape forming via isopressing at µm to cm component scales.

2:45–3:25 p.m. Scott A. Barnett, "Solid Oxide Fuel Cells and the Hydrogen Economy"

Scott A. Barnett is a professor in Northwestern's materials science and engineering department. He has published more than 150 papers in peer-reviewed journals and has 11 patents in the area of thin films and solid oxide fuel cells. He was awarded the Office of Naval Research Young Investigator Award and is a fellow of the American Vacuum Society. He is founder of Functional Coating Technology LLC in Evanston.

It is well known that solid oxide fuel cells (SOFCs) can play a role in a hydrogen economy by doing highly efficient conversion of hydrogen to electricity and efficient hydrogen production by steam electrolysis. Barnett will describe a few alternative approaches to clean, efficient energy afforded by the use of hydrocarbon or alcohol fuels in SOFCs. The current hydrogen economy strategy is to centrally produce hydrogen and distribute it for use in, for example, fuel-cell vehicles. In the near term (until sufficient renewable energy sources are available), hydrogen would be produced from hydrocarbons, with steam reforming being the leading contender. However, physical separation of the endothermic reforming process from the fuel cell (and the heat produced therein) results in significant cost and efficiency penalties. An alternative technology is a direct methane SOFC that can coproduce H_2+CO (syngas) and electricity; projections indicate that this can be a very cost-effective means of producing hydrogen from natural gas. Barnett also will describe recent results on direct internal reforming of gasoline in SOFCs, which makes efficient use of excess heat for the endothermic reforming reaction, potentially allowing substantially higher efficiency than a hydrogen fuel cell. Finally, he will describe a renewable energy alternative to the hydrogen economy that would work well with SOFCs and that avoids the difficult storage problems associated with hydrogen.

3:30–4 p.m. Coffee break

Session 4: Biomaterials — Current Practices and Future Promises

4–4:40 p.m. Samuel I. Stupp, "Expanding Frontiers in Biomaterials"

Samuel I. Stupp is Board of Trustees Professor of Materials Science and Engineering, Chemistry, and Medicine at Northwestern University, where he received his PhD degree. He is a member of the American Academy of Arts and Sciences and a fellow of numerous societies. He has received many awards, including the U.S. Department of Energy Prize for Outstanding Achievement in Materials Chemistry and the American Chemical Society Award in Polymer Chemistry.

The interface between materials science and biology had its genesis more than half a century ago, when known materials were first used to repair human tissues. These biomaterials, many still in use today, are basically inert but can repair the structure of tissues or restore the function of failed organs. The field is now expanding into the exciting realm of bottom-up molecular and supramolecular design of materials to interact directly with cells. Such “bioactive” materials could soon become the drivers of tissue and organ regeneration in humans. The new opportunities are emerging at the convergence of nanoscience and biology and are opening other frontiers that will have broad impact in science. The use of designed materials to learn biology, the design of materials that imitate biology, or the use of biology to make abiotic materials are all part of this exciting new field. The lecture will illustrate various aspects of the field, explaining the development of self-assembly codes for biomolecular materials and the functions that emerge.

4:45–5:25 p.m. Joshua J. Jacobs, “Corrosion of Orthopedic Implants — Who Cares?”

Joshua J. Jacobs is Crown Family Professor and associate chair for academic programs in the orthopedic surgery department at Rush Medical College. He is an alumnus of Northwestern University. His research focus is on the biocompatibility of permanent orthopedic implants, particularly joint replacement devices. He has received many honors, including the Ann Doner Vaughan Kappa Delta Award (American Academy of Orthopedic Surgeons) and Surgeon-In-Chief Pro-Tempore (Hospital for Special Surgery).

Permanent orthopedic implants are well tolerated in the vast majority of patients — i.e., they are biocompatible. However, they may be associated with adverse local and remote tissue responses in some people in the long term. These adverse effects are mediated by the degradation products of these implant materials, which may be present as particulate wear and corrosion debris, colloidal organometallic complexes (specifically or nonspecifically bound), free metallic ions, or inorganic metal salts/oxides and/or sequestered in an organic storage form such as hemosiderin. Much of the focus on the long-term biocompatibility of implant materials has centered on the metallic components because of their tendency to undergo electrochemical corrosion resulting in the formation, at least transiently, of chemically active degradation products. Concern about the release and distribution of metallic degradation products is justified by the known potential toxicities of the elements used in modern orthopedic implant alloys — titanium, aluminum, vanadium, cobalt, chromium, and nickel. Toxicity may result from metabolic alterations, alterations in host/parasite interactions, immunologic interactions of metal moieties by virtue of their ability to act as haptens (specific immunological activation), antichemotactic agents (nonspecific immunological suppression), or lymphocyte toxins and by chemical carcinogenesis. At this time, the association of metal release from orthopedic implants with any metabolic, bacteriologic, immunologic, or carcinogenic toxicity remains conjectural, since cause and effect have not been established in human subjects. Nonetheless, in a number of settings, corrosion of orthopedic implants has resulted in adverse clinical outcomes due to the local histological responses to corrosion products. Improved preclinical testing protocols are required in order to facilitate the development of corrosion-resistant metallic implant systems and mechanically accelerated electrochemical processes.

Banquet

6 p.m.   Cocktails

6:30 p.m.   Dinner

Welcome

Henry S. Bienen, president, Northwestern University

C. Bradley Moore, vice president for research, Northwestern University

After dinner   Stephen L. Sass, "The Substance of Civilization: Materials and Human History from the Stone Age to the Age of Silicon"

Stephen L. Sass is a professor of materials science and engineering at Cornell University. He received his PhD degree from Northwestern. He is a fellow of the American Physical Society and ASM and, at Cornell, a Stephen H. Weiss Presidential Fellow, a university-wide undergraduate teaching honor.

Materials have enabled revolutionary advances in how we live, work, fight, and travel; hence, the naming of eras after them: Stone, Bronze, and Iron Ages. By putting technology into a historical and human context and examining the advances made possible by innovations with materials, this talk will explore the role of materials in the development of modern Western industrial civilizations starting with the Stone Age. Connections between critical developments will be identified — for example, the relationships among materials, agriculture, and written languages in the fourth millennium B.C. and among the exodus of the Hebrews, the general tumult in the eastern Mediterranean, and the onset of the Iron Age as the second millennium B.C. ended. The roles of China and Islam in stimulating advances in technology will be explored. Early technologies will be illustrated with beautiful works of art.

Friday, October 28

8:30–8:45 a.m. Welcome

Peter W. Voorhees, department chair and Frank C. Engelhart Professor, Department of Materials Science and Engineering, Northwestern University

Julio M. Ottino, dean, McCormick School of Engineering and Applied Science, Northwestern University

Session 5: Polymers — Soft Materials Solve Hard Problems

8:45–9:25 a.m. Anne M. Mayes, MS&E Goes Soft: A Personal Vision for Polymeric Materials

Anne M. Mayes ,Toyota Professor in the materials science and engineering department at Massachusetts Institute of Technology, received her PhD from Northwestern. She has won numerous awards, including MRS Outstanding Young Investigator and the American Physical Society Dillon Medal for Polymer Physics. She is a fellow of the American Physical Society and a MacVicar Faculty Fellow at MIT.

It's an exciting time to be a materials scientist. Progress in fields as disparate as medicine, transportation, information processing, and defense go hand in hand with developments in materials chemistry and processing. Polymeric materials in particular have a defining role to play in addressing some key 21^{st}-century challenges. Advances in polymer synthesis and processing in the last decade have generated a bountiful toolbox for fabricating polymeric and organic/inorganic hybrid materials with properties tailor-made for a given application, in some cases taking cues from examples in nature. This talk will offer personal reflections about how recent innovations in polymer science could be put to use in coming decades to address national and global technology priorities.

9:30–10:10 a.m. Richard H. Friend, Polymer Electronics

Richard H. Friend is Cavendish Professor of Physics and chair of the School of Physical Sciences at Cambridge University. He has received numerous awards and honorary doctorates. He has started two successful companies focused on polymer electronics technology and is a fellow of the Royal Society.

Conjugated polymers provide a class of processable, film-forming semiconductors and metals. We have worked on the development of the semiconductor physics of these materials by using them as the active components in a range of semiconductor devices. Polymer light-emitting diodes show particular promise, providing full color range and high efficiency. Polymer heterojunctions can be exploited both in LEDs and in polymer photovoltaic cells. An important approach that can be exploited with solution-processed polymers is the formation of de-mixed polymer blends formed with electron- and hole-accepting polymers. This presentation will discuss conditions required for photo-induced charge transfer (as required for photovoltaic diode operation) or for energy transfer (as required for LEDs) and consider evidence for localization of excitons at the heterojunction in this regime. Patterned deposition using ink-jet printing techniques allows fabrication of full-color LED displays. Direct printing can also be used to fabricate submicron geometry polymer transistors and circuits. The talk will describe the use of such circuits for active-matrix display backplanes.

10:15–10:45 a.m.   Coffee break

Session 6: Electronic, Optical, and Magnetic Materials — Enabling the Information Revolution

10:45–11:25 a.m.   Teruaki Aoki, "Technological Innovation and New Lifestyles in the Broadband Network Era"

Teruaki Aoki is senior executive vice president at Sony Corporation. His PhD is from Northwestern. He became general manager of Sony' s semiconductor group in 1981 and went on to management positions in corporate planning, research and development strategy, recording media products, and consumer audio-video products. In 1998 he moved to New York to become president and chief operating officer of Sony Electronics, a U.S. subsidiary. He returned to Tokyo in 2000 to become Sony's senior executive vice president.

The commercial Internet has only 10 years' history, but it is said that the data traffic on the network increased 1,000 times in that period. Needless to say, the Internet has greatly changed business and lifestyles and created markets. So far, however, major applications of the Internet have been e-mails and web browsing on PCs because the bandwidth of the network is limited. This situation will drastically change on the global scale. The broadband networks — such as ADSL, digital cable, and optical fiber to the home — will be available to most of people at home. In addition, the wireless broadband networks such as wireless LAN and third- and fourth-generation cell phones will be available at a reasonable cost. Such broadband infrastructure will create another lifestyle, where people can enjoy rich content such as music and high-definition video anytime and anywhere. To realize this, we need to develop technologies including software and systems and new devices and materials.

11:30 a.m.–12:10 p.m.   Bruce W. Wessels, "New Frontiers in Electronic Materials: III-V Ferromagnetic Semiconductors and Spintronics"

Bruce W. Wessels is a Walter P. Murphy Professor in the materials science and engineering and electrical engineering and computer science departments at Northwestern, as well as chair of electrical engineering and computer science. He is fellow of ASMI and the American Physical Society and the author of 255 articles and coauthor of five books. He has been awarded 13 patents.

Recent developments in the synthesis of ferromagnetic semiconductors have led to the possibility of electronic devices that use both charge and spin. These materials can potentially enable semiconductor circuits that exhibit electronic, magnetic, and photonic functionalities. For example, injecting spin-polarized current into a semiconductor would enable qubit (quantum bit) operation for quantum computing. The ferromagnetic semiconductors are synthesized by doping nonmagnetic semiconductors with transition metals. To obtain ferromagnetism, the semiconductors must be doped to levels in excess of their equilibrium solubility limit. Using metal-organic vapor phase epitaxy, metastable semiconductor alloys have been formed with Curie temperatures above room temperature. The nature of the magnetic interaction has been studied using synchrotron radiation. The magnetic properties are attributed to the presence of atomic-scale magnetic ion clusters that interact via free carriers.

12:15–2 p.m.   Lunch

2–2:40 p.m.   Mark C. Hersam, "Hybrid Organic/Inorganic Materials at the Nanometer Scale"

Mark C. Hersam is an assistant professor in Northwestern's materials science and engineering department. He has been named an Arnold and Mabel Beckman Young Investigator, a National Science Foundation CAREER Award recipient, an Army Research Office Young Investigator, an Office of Naval Research Young Investigator, and an Alfred P. Sloan Research Fellow.

The Hersam Research Group develops nanofabrication and nanocharacterization techniques for hybrid organic/inorganic materials and devices. Ongoing research topics include silicon-based molecular electronics, organic light-emitting diodes, molecular rotors, nanopatterned sensors, encapsulated carbon nanotubes, and catalytic oxide surfaces. In all cases the interplay between the organic and the inorganic subcomponents influences the overall structure and properties of the hybrid nanomaterial. Consequently, nanoscale characterization of organic/inorganic interfaces is required to develop structure-property relationships in these systems. Furthermore, nanometer scale processing techniques enable optimization of the performance of hybrid organic/inorganic devices. As a case study of our research approach to nanomaterials science and engineering, this talk will focus on the application of the structure-property-processing paradigm to silicon-based molecular electronic materials and devices. A homebuilt ultrahigh vacuum scanning tunneling microscope allows individual molecules to be imaged, addressed, and manipulated on semiconducting surfaces with atomic resolution at room temperature. Specifically, three different molecules will be considered on the Si(100) surface: styrene, cyclopentene, and 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO). In all cases, STM spectroscopic characterization of individual molecules mounted on degenerately n-type Si(100) show multiple negative differential resistance (NDR) events at negative sample bias. On the other hand, at positive sample bias, the current-voltage characteristics do not show NDR, although a discontinuity in the differential conductance is observed. When the Si(100) substrate is changed to degenerate p-type doping, the charge transport behavior is qualitatively similar but at the opposite bias polarity. These empirical observations can be quantitatively explained using a capacitive equivalent circuit model and the energy band diagram for a semiconductor molecule-metal junction. In addition, using multistep feedback controlled lithography, heteromolecular nanostructures consisting of both styrene and TEMPO molecules have been fabricated on hydrogen passivated Si(100). Atomic-scale characterization of these structures will be discussed in the context of silicon-based molecular electronics.

Session 7: Computational Materials Science: from Simulation to Engineering Practice

2:45–3:25 p.m. Didier de Fontaine, "Gibbsian Thermodynamics for the Electronics Age"

Didier de Fontaine is a professor emeritus in the materials science and mineral engineering department at the University of California, Berkeley. He received his PhD from Northwestern. His many honors include being a fellow of the American Physical Society and the Materials Research Society Turnbull Lecturer.

In a monumental classic paper published 130 years ago, J. Willard Gibbs virtually single-handedly created the field of equilibrium thermodynamics, whose practical relevance has kept on increasing over the years. Gibbsian thermodynamics is one of the most complete and rigorous continuum macroscopic theories ever derived. That it is a "black-box" theory is its strength and its weakness in an age when materials science tends to have discrete, microscopic flavor. How is one to obtain the physical parameters needed to make classical thermodynamics "go"? From experiment? Yes, that is essential. But today, thanks to fairly recent theoretical advances, it is also possible to "do thermo" on a computer, to the delight of those who dislike messy lab work. De Fontaine will describe briefly the new "alloy theory" and illustrate its use by some examples, including applications to order-disorder reactions in high-Tc superconductors.

3:30–4 p.m. Coffee break

4–4:40 p.m. Lyle H. Schwartz, "Materials Engineering for Affordable New Systems"

Lyle H. Schwartz is retired director of the U.S. Air Force Office of Science Research. He is a former director of the Materials Science and Engineering Laboratory of the National Institute for Standards and Technology and former president of the Federation of Materials Societies. He received his PhD degree from Northwestern and for five years was on Northwestern's materials science and engineering faculty and directed the University's Materials Research Center. He is a member of the National Academy of Engineering and has received many awards and honors.

Academic departments focused on materials research have evolved over the last half-century and now, with some exceptions, are broadly focused and called departments of materials science and engineering. It will be the contention of this presentation that while the “science” part has evolved to extraordinary degrees, the “engineering” part is still in many ways in its infancy. To discuss this issue, it is first necessary to establish a definition of engineering in the modern day and then to examine the developments in our field and see how they match up against the definition. As most fields of engineering have evolved, computational methodology has been developed, enabling designers to integrate the combined knowledge of that field into convenient packages leading to improved designs, shortened design cycles, and more affordable systems. Materials selection remains a critical part of the design cycle, but our contribution to this process remains largely a body of empirically obtained property data that the designer feeds into the design software as a “given.” New materials, particularly structural materials, are developed using our knowledge base, but final properties are obtained only by costly empiricism. Several steps have been taken over the years to introduce appropriate computational capabilities to the materials development process, and in recent years the integration with design has been made in rudimentary ways. However, we still have a long way to go before the E can really be justified in MSE, and much of that road will be traveled only with the assistance of our colleagues in departments of mechanical, electrical, and chemical engineering.

4:45–5:25 p.m.   Gregory B. Olson, “Materials by Design”

Gregory B. Olson is Wilson-Cook Professor of Engineering Design in Northwestern’s materials science and engineering department. He is a founder of QuesTek Innovations LLC in Evanston and a fellow of ASM International and TMS.

Building on Northwestern’ s tradition of innovation, a systems approach to computational materials design pioneered at the University two decades ago has reached commercial success and redefined undergraduate materials education. The recent Defense Advanced Research Projects Agency (DARPA)-AIM initiative has broadened the methodology to span the full materials development and qualification cycle, while integration of graduate “scieneering” research with undergraduate “techmanities” education has applied a unified approach across metals, ceramics, polymers, composites, and processed foods and has exposed undergraduates to concurrent materials design in a multidisciplinary engineering setting. The new Office of Naval Research “D3D Consortium” initiative integrates multiscale 3D tomographic analysis and simulation to provide a new level of accelerated high-fidelity materials design. As an agent of “affordable change,” application of computational design to “green” materials now entering the marketplace is enabling a transformation to sustainable technology responsive to society’s broader needs.

5:30–5:40 p.m.   Final Comments

Peter W. Voorhees, department chair and Frank C. Engelhart Professor, Department of Materials Science and Engineering, Northwestern University

10-05/175/MG-KP/10454