Department of Chemical Engineering

In academic year 2007, the Department of Chemical Engineering at MIT enjoyed another good year, maintaining its leadership role in the profession, with high productivity and visibility in teaching and research. For the 18th consecutive year, our graduate and undergraduate programs garnered number one rankings among the nation's chemical engineering departments from *US News and World Report.* The Chemical Engineering faculty continues to run vigorous research programs, with sponsored research expenditures of more than $27 million for the fiscal year ending June 30, 2007.

There were some significant changes in the department this year. On February 1, 2007, Professor Klavs F. Jensen assumed the position of department head of the Department of Chemical Engineering, taking over from Professor Robert C. Armstrong, who had served the department well in that position since 1996. Professor Gregory C. Rutledge continues to serve as the executive officer of Chemical Engineering. Professor William M. Deen serves as the department's graduate officer, and Dr. Barry S. Johnston is undergraduate officer. Professor Paula Hammond wraps up 3 years as the graduate admissions officer and will be succeeded by Professor Arup Chakraborty in 2007–2008. Professors Daniel I. C. Wang and Robert S. Langer hold the honored position of Institute Professor. We are proud to announce the promotion of Professor William H. Green to full professor.

The department enjoyed a successful year of attracting young faculty to MIT. Professor Michael S. Strano and Professor J. Christopher Love both accepted positions in Chemical Engineering and will join the faculty in 2007. Professor Strano comes to the department from the University of Illinois at Urbana-Champaign, where he started his career as assistant professor nearly four years ago. Since then, he has authored or coauthored more than 36 articles and several book chapters and patents. Professor Strano's research focuses on carbon nanotubes. Professor Love received his BS in chemistry with highest distinction at the University of Virginia in 1999 and his PhD from Harvard University in 2004. Professor Love's future research plans integrate principles from materials science and chemistry to develop micro- and nanotechnologies that enable new, quantitative biological studies. As part of his position at MIT, Professor Love will also be affiliated with the Broad Institute.

The department welcomed one addition to our support staff, Katie Foster, assistant to Professor Gregory C. Rutledge. Liz Webb, former assistant to Professor Gregory McRae and Dr. Barry S. Johnson, retired in March after 23 years at MIT. Robin Elices, former director of the Administrative Services Organization (ASO) for Chemical Engineering and the Department of Materials Science and Engineering, accepted the position of executive director, MIT Energy Initiative (MITEI), in the Laboratory for Energy and the Environment. The department welcomes Su Chung, previously administrative officer of Center for Technology, Policy and Industrial Development as the new director of ASO.

In the news, the Department of Chemical Engineering was very prominent in the area of energy and the environment in 2006–2007. In January 2007, a national 18-member panel led by Professor Jefferson Tester released a study entitled "The Future of Geothermal Energy," sponsored by the US Department of Energy. This report assesses the feasibility, potential environmental impacts, and economic viability of using enhanced geothermal system technology to increase the fraction of the US geothermal resource that could be recovered commercially. Professor Gregory McRae and Professor Emeritus János Beér were members of an interdisciplinary MIT panel that issued a report, "The Future of Coal—Options for a Carbon Constrained World," in March 2007. Senior chemical engineering students also contributed to this report through a set of analyses they performed as part of their capstone design project in chemical engineering. Professor Paul Barton and graduate student Ajay Selot were in the news for developing a mathematical model that focuses on the "upstream supply chain," which could help energy companies ensure a more reliable supply of natural gas. Professor Gregory Stephanopoulos and postdoctoral associate Hal Alper engineered a yeast that can improve the efficiency of ethanol production by manipulating the yeast genome to create a strain that tolerates a high level of ethanol, which is ordinarily toxic to the yeast that ferments the plant material. Finally, chemical engineering junior Joe Roy-Mayhew was part of the team "Biodiesel@MIT," which won the GE mtvU Ecomagination Challenge. The national contest, sponsored by GE and MTV, encourages students to take initiative in sustainability and "greening" of their campuses.

Undergraduate Education

Since 2004, the Department of Chemical Engineering has offered bachelor of science degrees in both chemical engineering (Course 10) and chemical-biological engineering (Course 10-B). Department undergraduate enrollment continues to remain strong, increasing from 236 to 253 students this year. Chemical Engineering currently has the highest student-to-faculty ratio in the School of Engineering. The department advises students about career paths in chemical and chemical-biological engineering through active participation in freshman advising seminars, fall and spring term open houses, parents' weekend, and other activities. Overall, 81 SB degrees were conferred as of June 2007, with 63% awarded to women. Student quality remains excellent. The distribution of undergraduate students by class over the last 10 years is shown in Table 1.

Table 1. Undergraduate Enrollment over the Last 10 Years

Class Year	97–98	98–99	99–00	00–01	01–02	02–03	03–04	04–05	05–06	06–07
Sophomores	97	88	71	67	47	56	56	95	100	95
Juniors	90	90	85	76	66	49	43	55	83	75
Seniors	130	94	103	89	84	65	41	55	53	83
Total	**317**	**272**	**259**	**232**	**197**	**170**	**140**	**205**	**236**	**253**

The new program leading to the bachelor of science degree in chemical-biological engineering was introduced in 2004 in response to our students' demand for a focused and coherent educational curriculum in biological aspects of chemical engineering, with more in-depth training in advanced modern chemical and molecular biology. The new program embodies three primary components: (1) a core in advanced biology, comprising subjects in biochemistry, genetics, and cell biology; (2) a core in engineering science comprising subjects in mass and energy balances, thermodynamics, heat, mass and momentum transport, and chemical kinetics; and (3) a capstone design experience that emphasizes problems in chemical-biological engineering while teaching integration and synthesis of fundamental science principles for solving engineering problems and understanding complex systems. Student participation in Course 10-B has been very robust since the outset, with undergraduate enrollment rising from 27 students in 2004 to 105 in 2006 and 150 in 2007. Currently, students in the chemical-biological engineering program constitute 60% of the undergraduates in the Department of Chemical Engineering; 44 seniors graduated with degrees in chemical-biological engineering in the class of 2007, and 52 freshmen in the class of 2010 declared majors in chemical-biological engineering.

The average starting salary for graduates of the Department of Chemical Engineering is $62,000 (2007 senior survey), which is among the highest in the School of Engineering. This attests to the success of the graduates of the 10 and 10-B programs in the department and to the continued high demand for our students. The senior surveys indicate that, between 2001 and 2007, 50% to 70% of our students went on to graduate or professional school.

Undergraduates in the Department of Chemical Engineering maintain active student chapters of the American Institute of Chemical Engineers (AIChE) and the Society for Biological Engineers (SBE), with invited speakers, presentations at national meetings, and visits to company sites. The student officers of AIChE were Maxine Yang (president), Daphne Hao (vice president), Michael Zhang (secretary), Jamie Rubin (treasurer), Devan Kestel (class of 2007 representative), Amanda Lanza (class of 2008 representative), and Robert Jackson (class of 2009 representative). The student SBE chapter was founded last year. Its officers this year were Chris Tostado (president) and Ben Wasserman (vice president).

The department implemented its own mid-term course feedback system in 2007 to facilitate communication between students and instructors in the undergraduate programs. The system was tested in fall 2006 and fully deployed in spring 2007; it provides students with a convenient mechanism to give feedback to instructors while the subject is ongoing, so that instructors are better able to address the specific needs of a class in a given year.

Graduate Education

The graduate program in the Department of Chemical Engineering offers master of science degrees in chemical engineering (MS) and in chemical engineering practice (MSCEP), the doctor of philosophy (PhD) and doctor of science (ScD) degrees in chemical engineering, and the doctor of philosophy degree in chemical engineering practice (PhDCEP). The PhDCEP track was established in 2000 in collaboration with the Sloan School. The total graduate student enrollment is currently 235, with 217 in the doctoral program and 18 master's level degree candidates. In the doctoral program, 202 students are in the PhD/ScD track and 15 are in the PhDCEP track. In the master's level program, 14 are in the MSCEP track. Twenty-nine percent of our graduate students are women, and 3% are underrepresented minority students. Thirty-eight of our graduate students received outside fellowship awards, including those from the National Science Foundation, the National Institutes of Health (NIH), the Department of Defense, and others. The distribution of graduate students by degree is shown in Table 2 for the last 10 years. During the 2007 academic year, 46 doctoral degrees (44 PhD or ScD, 2 PhDCEP) were awarded, along with 28 master's level degrees (25 MSCEP, 3 MS) for a total of 74 advanced degrees conferred. Thirty-nine students passed the doctoral qualifying exams and were promoted to candidacy for the PhD/ScD or PhDCEP. The department received 279 applications for admission to the doctoral program, offered admission to 58 individuals, and received 47 acceptances of offers, for an acceptance percentage of 81%, the highest in recent history. Of 79 applications for master's level degrees, the department made 25 offers and received 18 acceptances of offers, for a yield of 72%. Among the incoming class for 2007, 21 are women and 8 are minority or Asian-American graduate students. The incoming graduate class held an undergraduate grade point average of 4.95 (out of 5.0).

Table 2. Graduate Enrollment over the Last 10 Years

Degree level	97–98	98–99	99–00	00–01	01–02	02–03	03–04	04–05	05–06	06–07
Master's	51	59	54	40	38	36	26	19	16	18
Doctoral	167	140	145	166	209	245	232	216	203	217
Total	**218**	**199**	**199**	**206**	**247**	**281**	**258**	**235**	**219**	**235**

The department introduced two new subjects at the graduate level this year: 10.546 Statistical Thermodynamics with Applications to Biological Systems, taught by Professor Arup Chakraborty and Professor John Deutch (Chemistry), develops classic equilibrium and time-dependent statistical mechanical concepts and supporting computer simulation methods for application to chemical and biological problems, and 10.393 Multiscale Analysis of Advanced Energy Processes, taught by Professor Jefferson Tester, Professor Mikael Golay (Nuclear Engineering), and Dr. Elisabeth Drake, uses case studies to introduce the motivation, approach, and specific options for achieving a more sustainable energy supply with lower environmental impact. Modules include nuclear power for electricity and hydrogen production, conventional and synthetic fossil fuels and carbon sequestration, conversion of biomass into transportation fuels and energy, and geothermal energy recovery and conversion to electricity. This subject is very timely, in light of developing initiatives in energy Institute-wide.

The Department of Chemical Engineering is actively involved and takes a leadership role in several MIT-wide education and research programs. A few of these are highlighted here.

The Department of Chemical Engineering's Singapore–MIT Alliance-2 program, called Chemical and Pharmaceutical Engineering (CPE), completed its first year on June 30, 2007. Professor Bernhardt Trout is the codirector of this program with Professor Raj Rajagopalan, head of department, National University of Singapore. There are currently 11 students in the program, six dual master's students, and five direct entry PhD students. The research part of CPE focuses on metabolic engineering, chemical catalysis, and downstream processing. The MIT faculty involved with CPE are Professors Stephen Buchwald (Chemistry), Patrick Doyle, Alan Hatton, Kenneth Smith, Gregory Stephanopoulos, Bernhardt Trout, and Daniel Wang.

As the DuPont MIT Alliance (DMA) continues to grow, it remains dedicated to the principles of novelty and excellence in the research program. There is a commitment at both DuPont and MIT to promote the basic principles of cutting-edge collaborative research that will have a significant impact on the long-term commercial goals of DuPont and the educational culture of MIT. The close relationship of DuPont and MIT is fostered through the multidisciplinary team effort in the alliance research program. Each funded project has one or two DuPont investigators as liaisons who work closely with MIT researchers. DMA supported two incoming graduate students in the 2007 group of first-year Chemical Engineering graduate students: Kevin Nagy and Jason Rich. The education thrust promotes participation at the investigator level as well. DMA sponsored a one-day tutorial given by Professor Daniel Blankschtein in Wilmington, Delaware, on multiscale modeling of surfactant solubilization. On the research activity side of the Alliance, there are seven principal investigators from the Chemical Engineering Department: Professors Paul Barton, Daniel Blankschtein, Paula Hammond, Alan Hatton, Gregory Rutledge, Jefferson Tester, and Bernhardt Trout. They received $1,540,000 in research funding in 2006 and $1,412,000 in 2007. Professor Klavs Jensen serves on the DMA Internal Advisory Committee. Professor Robert Cohen is the associate director of DMA for MIT.

After completing five successful years of operation, in May 2007 the Institute for Soldier Nanotechnologies (ISN) was selected by the Department of the Army to begin its first renewal contract. The ISN mission is to dramatically improve the survivability of the soldier through fundamental research to discover nanoscale and nano-enabled materials, devices, and systems. Industrial partners and Army laboratories transition promising outcomes of MIT basic research toward practical products for the soldier, other first responders, and civilian applications. Currently, the ISN involves more than 40 MIT faculty from 10 departments, 75 graduate students, and 25 postdocs in more than 30 projects focused on five strategic research areas: light-weight, multifunctional fibers and materials; injury intervention and autonomous medical treatment for the soldier; protection against bullets and explosions; detection of hazardous substances; and integration of nano-based components to create practical systems. The ISN also sponsors the annual Soldier Design Competition (SDC), which provides MIT and West Point undergraduate students with an engineering design opportunity to develop technologies to help today's soldiers. To date, the SDC has led to 10 start-up companies. Professor Karen Gleason is associate director of the ISN. Additionally, Professors Paula Hammond, Klavs Jensen, Robert Langer, and Gregory Rutledge from the Chemical Engineering Department all have active ISN research programs.

Faculty Notes

Professor Robert Armstrong stepped down as department head in February, after nearly 11 years of service. He became deputy director of the newly formed MITEI in the fall and is working with the director, Ernest Moniz, in launching the research, educational, campus, and outreach components of the initiative. He received the 2006 Bingham Medal of the Society of Rheology, the Society's highest honor, and presented the Bingham Lecture at the Society of Rheology's Annual Meeting in October. In November 2006, he received the AIChE Warren K. Lewis Award for contributions to chemical engineering education. During the past academic year he gave the Bernard Andes Hess

Lecture at the University of Virginia, the ConocoPhillips Lecture at Oklahoma State University, the Distinguished Lecture in Engineering at the University of Tennessee, and the Stanley Katz Memorial Lecture at the City College of New York. He serves on the advisory boards of chemical engineering departments at Georgia Tech, Northwestern University, Virginia Tech, the University of Washington, the University of Tennessee, and the University of Wisconsin.

Professor Emeritus János Beér participated in the MIT study "The Future of Coal." He continued his membership on the National Coal Council, Advisory Council to the U.S. Secretary of Energy, and served on its study work group that produced the Council's report to the secretary entitled "Coal: America's Energy Future." He also served on the National Academies NRC Panel on Integrated Gasification Combined Cycle Technology R&D, as part of the Prospective Evaluation of Applied Energy Research and Development at the Department of Energy.

Professor Daniel Blankschtein's research group conducts fundamental theoretical and experimental research in the area of colloid and interface science, with emphasis on industrially and biomedically relevant applications. His teaching responsibility included the interdisciplinary Course 10.55, Colloid and Surfactant Science, which draws students from across the Institute. Professor Blankschtein and his students delivered talks and presented posters at the 2006 AIChE Annual Meeting and at the 2006 20th European Colloid and Interface Society Conference held in Budapest, Hungary. As a member of the DMA, Professor Blankschtein delivered a tutorial, "Modeling the Bulk Solution Behavior of Surfactants in Aqueous Media," at the DuPont Experimental Station, which was very well attended by DuPont scientists and engineers. He continues to serve on the editorial board of Marcel Dekker's *Surfactant Science Series*.

Professor Robert E. Cohen spent the spring term of 2006 on sabbatical leave at Balliol College, University of Oxford, where he engaged in the research and educational activities of materials-centered colleagues in the Department of Engineering Science. In the fall of 2006, he presided over the technical program and social events at the 20th anniversary celebration of MIT's interdepartmental Program in Polymer Science and Technology, an enterprise that he founded and directed in the mid-to-late 1980s. In October of 2006, Professor Cohen was named the first recipient of the Capers and Marion McDonald Award, a prize administered by the School of Engineering to recognize excellence in mentoring and advising at MIT. He presented numerous research seminars including invited lectures at Georgia Tech, University of Massachusetts at Amherst, and University of Connecticut, and he served on the visiting committee of the Department of Chemical Engineering at Columbia University. Professor Cohen also continued to direct the research and educational activities of the DMA, a responsibility that he has maintained since January 2000.

Professor Charles L. Cooney continued as the faculty director of the Deshpande Center for Technological Innovation and chaired the Center's annual IdeaStream Symposium in April 2007. He continued to serve as the colead, representing the School of Engineering, in developing the MIT BP Projects academy in partnership with the Sloan School of Management. Professor Cooney completed a role as chair of the Food and Drug

Adminstration Advisory Committee for Pharmaceutical Sciences. He is a member of the MIT Community Service Fund Board, the Lemelson-MIT Screening Committee, the MIT Committee on Intellectual Property, the Faculty Committee on Staff and Administration, and the Sloan Dean Search Committee. Professor Cooney is also an overseer of the Boston Symphony Orchestra and a trustee of Boston Ballet.

Professor Arup Chakraborty continued his research on T cell activation and established a new consortium (funded by the NIH) called the Immune Response Consortium (IRC), which involves nine principal investigators from seven institutions. The purpose of the IRC is to bring together theory and computation (rooted in statistical physics and engineering analysis of chemical kinetics) with genetic, biochemical, and imaging experiments to understand the mechanisms underlying T cell activation. Chakraborty also initiated a major new research direction aimed at understanding the principles underlying T cell–mediated autoimmunity. He gave numerous plenary and invited lectures on his research. Chakraborty's research was recognized by three major awards in the past few months: (1) the NIH Director's Pioneer Award, (2) the E.O. Lawrence Memorial Award in the Life Sciences, and (3) election as Fellow of the American Academy of Arts and Sciences. Chakraborty also taught a new interdisciplinary subject (with John Deutch), called Statistical Mechanics with Applications to Chemical and Biological Systems, that was cross-listed by three departments. With Klavs Jensen, he also taught a mandatory subject on chemical reaction engineering for chemical engineering graduate students. Chakraborty is chairing a National Academies panel that is preparing a "Biomolecular Materials and Processes" report at the request of various government agencies. He has also served on the Visiting Committees of the Chemical Engineering Department at Lehigh University and the Chemical, Materials, and Petroleum Engineering Department at the University of Southern California.

Professor William Deen continued to serve as graduate officer and chair of the Graduate Committee, with oversight responsibility for graduate program policy and for the academic progress and well-being of the department's graduate students. He received the Outstanding Faculty Award for graduate-level teaching, as voted by the students. He gave several invited talks at universities and scientific meetings, including a presentation at a well-attended symposium at the annual meeting of the American Society of Nephrology. His work involves the fundamentals of molecular movement through spaces of molecular dimensions and the analysis of pathophysiological processes involved in kidney disease and in carcinogenesis.

Professor Patrick S. Doyle was promoted to associate professor without tenure this year. He was invited to give the Thiele Lecture at the University of Notre Dame. In addition, he delivered invited talks at several conferences and institutions including Proctor and Gamble and the University of California at Santa Barbara. He serves as the meeting program chair for the fluid dynamics section of the American Institute of Chemical Engineering. His research entails fundamental studies of complex fluids in microfluidic flows and fields.

Professor Karen K. Gleason became the first holder of the Alexander and I. Michael Kasser Chair in the department, continued in her second year as associate director of

MIT's ISN, and also continued on as chief scientific advisor to GVD Corporation, a start-up company she cofounded 6 years ago. In the past year, she presented the Debye Lecture in the Physics Department at the University of Utrecht, Netherlands, and also gave invited presentations on her group's research on chemical vapor deposition (CVD) technology at the American Chemical Society's Fluoropolymer 2006 Conference (Charleston, South Carolina), at the Materials Research Society Conference (San Francisco, California), and at the Fourth International Conference on Hot-Wire CVD in Takayama, Japan. Additionally, she was elected to chair the 5th International Conference on Hot-Wire CVD to be held in 2008.

Professor William H. Green presented new methodology for predicting chemical kinetics as a chapter in *Advances in Chemical Engineering* and in invited lectures at Princeton, Rice, University of New Hampshire, University of Pittsburgh, and at the national meeting of the American Chemical Society (ACS). His students set up the first experiment in the new Harrison Spectroscopy Laboratory space in Building 6, measuring reactions of unsaturated free radicals with an advanced laser apparatus. He reported detailed kinetics of several organic and inorganic chemical systems in several articles in the *Journal of Physical Chemistry* and other archival journals, and he continues to serve as associate editor of the *International Journal of Chemical Kinetics*. With Professor Barton, he developed a rigorous method for controlling the error introduced by neglecting less important chemical reactions in steady-state reacting flow simulations. Professor Green participated in the Department of Energy workshop assessing the nation's basic research needs in combustion, and this summer he will participate in a similar assessment of the nation's basic research needs in catalysis. He is currently serving on the Institute committee reviewing MIT's research and teaching programs on the environment.

Professor Paula Hammond was inducted as a Fellow of the American Physical Society in March 2007, through the American Physical Society Division of Polymer Physics; she was recognized for her research work in the assembly of liquid crystalline polymers and in functional polyelectrolyte multilayer assembly. Research developments in sequential multiagent drug release from polymer multilayers led to a new NIH grant on the development of release films for orthopedic implants. This project, originally funded by the Deshpande Center under an Ignition Grant, was also the basis of an entry in the MIT $100K Entrepreneurial Competition by graduate students Helen Chuang (Course 10), Lakshman Pernenkil (Course 10), Chris Bettinger (Course 3), Benoit Elichabe, Mara MacDonald (Course 10/HST), and Renee Smith (Course 5/HST); the team, called MAD Nanolayers, was among the seven finalists from an original group of more than 180 entries. Collaborative efforts on virus-based battery electrodes with Professor Angela Belcher of Materials Science and Biological Engineering and Professor Yet-Ming Chiang of Materials Science were recognized by *Popular Mechanics Magazine* with the Popular Mechanics Breakthrough Award in October 2006. These efforts are continued in new electrochemical energy investigations with the Belcher group as a part of the MITEI. Finally, Professor Hammond completed her final year as graduate admissions chair for the department and became a member of the National Academy Advisory Board on Chemical Sciences and Technology.

Professor T. Alan Hatton continued to serve as director of the David H. Koch School of Chemical Engineering Practice, where he has strived to maintain the international flavor of the program by placing student teams at host companies in the UK, Switzerland, and Germany as well as in the US. He is also an active participant in the SMA program on Chemical and Pharmaceutical Engineering. Professor Hatton was appointed an Honorary Fellow of the University of Melbourne in 2007, where he delivered The Occasional Address (the Commencement Speech) at the Engineering Degree Award Ceremony in March 2007 and the Tewkesbury Lecture in May 2007. Professor Hatton is a member of the Scientific Advisory Board of the Particle Fluids Processing Center at the University of Melbourne and a member of the Advisory Board of the Department of Chemical and Biological Engineering at Tufts University. Over the past year, he has given a number of invited lectures at ACS and AIChE meetings, including a Plenary Lecture in the Stine Award Symposium of the AIChE, and at the Magnetic Separation and Nanomagnets conference in Karlsruhe, Germany. Seminar invitations included those by the Indian Institutes of Technology in Kanpur, Kharagpur, Delhi, and Bombay; the University of Mumbai Institute of Chemical Technology; the Institute of Chemical Technology, Lodz, Poland; the University of Melbourne; and Novartis, Basel, Switzerland. Professor Hatton is chair of the conference on The Role of Structure in Chemical, Biological and Environmental Separations (Costa Rica, January 2008); on the Organizing Committee of the International Solvent Extraction Conference ISEC 2008 (Tucson 2008); and on International Advisory Committees for Polymer Networks (Cyprus 2008) and International Symposium on Colloids and Surface Science (Kolkata 2007). He has also coorganized symposia at the ACS meetings in Chicago and Boston. He is on the editorial board of the journal *Current Opinion in Colloid and Interface Science* and coeditor of the section "Applications."

Professor Klavs F. Jensen was appointed department head February 1, 2007. He continues his research on functional micro- and nano-structured materials and devices for chemical, optical, and electronic applications. With collaborations in chemistry and biology, he has explored a wide range of microfabricated systems for chemical and biological applications with particular emphasis on systems for which microfabrication provides unique process advantages. Physically-based simulations of reactive systems, specifically simulation across multiple lengths and time scales, complement the experimental studies and provide new insight into the underlying physical and chemical rate processes. During the past academic year, he gave invited/plenary lectures at the 20th International Symposium on Micro-Scale Bioseparations (Amsterdam, The Netherlands); NanoBioSymposium (Tokyo, Japan); PITTCON (Orlando, FL); ACHEMA (Frankfurt, Germany); International Symposium on Microchemistry and Microsystem (Hakone, Japan); 17th International Congress of Chemical and Process Engineering (Prague, Czech Republic); Workshop on New Avenues to Efficient Chemical Synthesis—Emerging Technologies—Schering Foundation (Berlin, Germany); Workshop on Microfluidics as a New Opportunity for Chemistry, l'Ecole Supérieure de Physique et de Chimie Industrielles (Paris, France); Engineering Foundation Endowed Lectureship at University of Texas, Danish Technical University (Lyngby); and Leermakers Symposium, Wesleyan University (CT). He continued to serve on the scientific advisory board for the Singapore A*STAR Institute for Nano and Biotechnology and on the steering committee for the International

Conference on Miniaturized Chemical and Biochemical Systems. He was awarded an honorary technical doctorate from the Technical University of Denmark.

Professor Robert Langer was elected in 2006 to the National Inventors Hall of Fame and received honorary doctorates from Northwestern University and Albany Medical College. He also received the American Institute of Chemical Engineer's James E. Bailey Award, was named the University of Pennsylvania School of Medicine Distinguished Lecturer and the Weiss Lecturer at Northeastern University. In 2007, he received an honorary doctorate from Yale University and was named the Alexander Rich Lecturer at MIT, the Shucart Lecturer at Tufts University, and the Ford Lecturer at Case Western Reserve University. He received the Herman F. Mark Polymer Chemistry Award and the Chemistry of Materials Award from the ACS.

Professor Kristala Jones Prather continued work in the area of synthetic biology, with a focus on the design of biosynthetic pathways for microbial production of organic chemicals. She became a principal investigator in the newly established interdisciplinary, multiuniversity "SynBERC: Synthetic Biology Engineering Research Center." SynBERC was initiated in summer 2006 and is supported by a five-year, $17 million grant from the National Science Foundation. Investigators in the center are drawn from the University of California, Berkeley (lead); University of California, San Francisco; Harvard University; and Prairie View A&M University, in addition to MIT.

Professor Gregory C. Rutledge continued his role as the executive officer of the Department of Chemical Engineering, and served on MIT's Computer Space Task Force and the School of Engineering Gender Equity Committee. He is a member of the editorial board of *Polymer* and is a founding editor of the *Journal of Engineered Fibers and Fabrics*. He serves on the Research Award Selection Committee of the Society of Plastics Engineers and coorganized the Materials Research Society Symposium on Structure, Processing and Properties of Polymer Nanofibers for Emerging Technologies. He delivered keynote lectures at the DECHEMA Conference on Chemical Nanotechnologies in Frankfurt, Germany; Electrostatics 2007 in Oxford, England; and the International Nanofiber Symposium 2007 in Tokyo, Japan. He also presented invited lectures at the University of Marburg (Germany), ITW Aachen (Germany), University of Washington, University of Oklahoma, University of Leeds (England), Rensselaer Polytechnic Institute (New York), and the Semenov Institute of the Russian Academy of Sciences (Moscow). His research involves the molecular engineering of soft matter through the development of molecular simulations, materials characterization, and electrospinning of polymer nanofibers.

Professor Gregory Stephanopoulos was named visiting professor of the Institute for Chemical and Bioengineering of ETH Zurich, where he spent his sabbatical leave. He also continued his service on the advisory boards of six academic institutions and the managing board of the SBE, which promotes the engineering applications of biology to industry and medicine. Professor Stephanopoulos also gave the Amundson Lectures at the University of Guadalajara, the McCabe Lectureship at North Carolina State University, and the 2007 Lowrie Lectures at Ohio State University. He continued to serve as editor-in-chief of the journal *Metabolic Engineering*, published by Elsevier and on the editorial boards of seven other scientific journals. Among numerous research presentations at professional society meetings (AIChE, ACS, American Society for Microbiology), he also delivered plenary and invited lectures at the Genomes to Systems Conference (Manchester, UK), the 1st Maga Circe Conference on Metabolic Systems Analysis (Monte Circeo, Italy), the 10th International Symposium on the Genetics of Industrial Microorganisms (Prague), the Annual Conference of the Society for Industrial Microbiology (SIM, Baltimore, MD), the 6th Metabolic Engineering Conference (Netherlands), the 1st International Conference on Biomolecular Engineering (San Diego, CA), and the 2nd ASM conference on Integrating Metabolism and Genomics (IMAGE2, Montreal). He continued his educational and research activity in bioinformatics and metabolic engineering that led to the publication of two seminal papers and four patents that received widespread coverage by the media and scientific press. These ideas provided the basis for a biotech start-up that won first prize at the MIT 100K competition and three other international contests.

Professor Jefferson W. Tester's research program focuses on clean chemical processing and renewable energy technologies with new research thrusts in biomass conversion in hydrothermal media and advanced drilling technology using spallation and fusion methods. This past year, he accepted cochair responsibilities for the energy education task force as a part of MIT's newly launched energy initiative (MITEI). Professor Tester continued to serve as chair of the National Advisory Council of the Department of Energy's National Renewable Energy Laboratory and as chair of the Governor's Advisory Committee of the Massachusetts Renewable Energy Trust. He also served on advisory boards for Los Alamos National Laboratory, Cornell University, American Council on Renewable Energy, and the Paul Scherrer Institute of the Swiss Federal Institute of Technology (ETH). He cochaired panels dealing with supercritical water oxidation technology and energy research and technology issues for the Army Research Office and the Defense Science Board. He gave invited lectures at Universities of Maryland, Nevada, Alberta, City College of New York, Amherst College, and the MIT Clubs of Boston, Hartford, and Milwaukee. He spent significant time writing, producing, and releasing a 400+-page MIT-led assessment of the role of geothermal energy in the United States. This report led to major international interviews and media coverage and an extensive lecture circuit in the United States, Iceland, and Australia as well as professional geothermal conferences and congressional briefings and testimony. Professor Tester is also the Institute for Geophysics and Planetary Physics Orson Anderson Fellow at Los Alamos National Laboratory for 2007–2008.

Professor Bernhardt L. Trout set up major new projects with biopharmaceutical companies, including the new Novartis-MIT Center for Continuous Manufacturing. He took over the leadership of the Singapore–MIT Alliance CPE program. He is a member of the Committee on the Undergraduate Program as well as multiple other Institute and departmental committees. He has been the invited or keynote speaker in various conferences on protein stabilization, in addition to being a freshman advisor and Fellow of Next House.

Professor Daniel I. C. Wang delivered the keynote address at the Bioprocess Engineering Conference at Hubei University, Wuhan, China, in 2006. He completed his third year in 2006 as a member of the Membership Policy Committee for the National Academy of Engineering. He continued as the chairman of the Scientific Advisory Board for the Bioprocessing Technology Institute, Singapore, in 2007. He delivered a lecture at the L.T. Fan Distinguished Lecture Series in 2007 at Kansas State University. He continued to hold the Temasek Distinguished Visiting Professor for the fourth year at the National University of Singapore. He was also invited to be the Distinguished Visiting Professor at Shanghai Jiao Tong University, China, in 2006. He delivered seminars in 2006–2007 at the University of Illinois, Rensselaer Polytechnic Institute, and Kansas State University. Lastly, his former students hosted a celebration and symposium in honor of his 70th birthday in 2006. The proceedings from the symposium were published as a special issue in the journal *Biotechnology and Bioengineering* in his honor in 2006.

Research Highlights

Surface Modification by Design via Vapor Deposition (Karen K. Gleason)

Surface properties include the ability to be wet more or less easily by water (hydrophilic and hydrophobic, respectively), to be antimicrobial or conducive to cell growth, and to be electrically conductive versus electrically insulating. Surface modification can provide these benefits with negligible weight gain, since the applied coatings can have thicknesses of less than 100 nanometers. Surface modification allows valuable surface properties like lubricity, biocompatibility, and chemical resistance to be imparted to inexpensive substrates having complementary bulk properties.

If the coating material has limited solubility or if the object to be coated degrades or swells upon exposure to solvent, the method of choice for surface modification becomes vapor-phase processing. Additionally, vapor-phase deposition can yield conformal coverage ("shrink-wrapping") of complex nano- and microstructures, thus avoiding difficulties due to surface tension effects and wettability issues that arise in liquid-phase processing.

New techniques for vapor deposition recently developed in Professor Karen Gleason's laboratory are low-energy ("gentle") cousins to methods currently employed by the semiconductor industry to produce high-purity thin films and interfaces (Figure 1). While these existing high-energy processes are excellent for inorganic materials, reduced energy processing is essential to allow delicate organic functionalities to be fully incorporated on the surface. Lower energy processing also reduces undesired cross-linking, resulting in flexible films. Flexibility is a key factor in enabling semicontinuous roll-to-roll operation, which provides a substantial cost benefit over batch operation. Low-energy, solvent-free methods are also compatible with delicate substrates, such as paper and plastics.

The first new method is initiated chemical vapor deposition (iCVD) in which vapors of an initiator species are introduced into a vacuum chamber (~0.1 to ~1.0 torr) along with vapors of one or more vinyl monomer species. The initiator decomposes to form free radical species under conditions in which the monomer is stable. The free radical fragments and monomers absorb and react onto a cooled (usually room temperature) substrate. This is an efficient process in which one free radical fragment can result in the

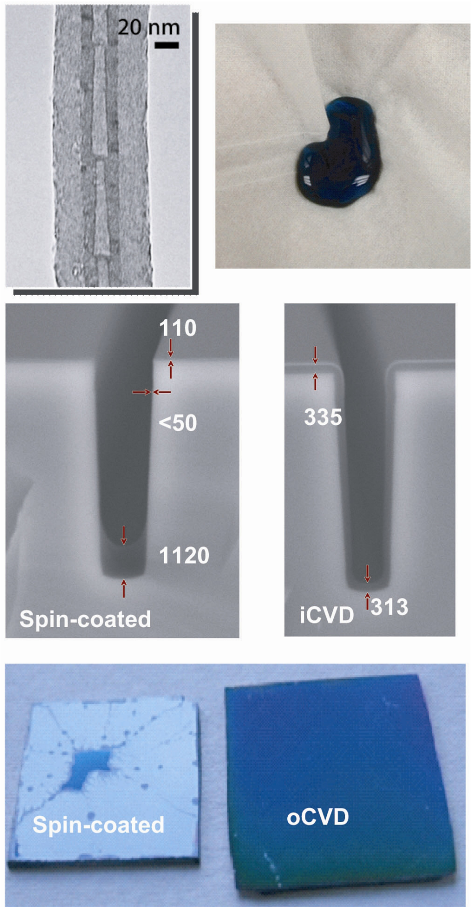

Figure 1. Top left: Conformal coverage of a multiwall carbon nanotube by ~20 nm thickness of a polymeric coating deposited by initiated Chemical Vapor Deposition (iCVD). Top right: Surface modification of tissue paper paper by iCVD polytetrafluoroethylene, causing dyed water to bead up rather than be absorbed. Middle: Comparison of solution processing (left) and iCVD (right) to achieve polymeric coverage of trench features etched in silicon, showing the greater uniformity in thickness over the entire structure is achieved by vapor deposition. Bottom: Comparison of solution processing (left) and oxidative Chemical Vapor Deposition (oCVD) to created coatings of conducting polymer on a silicon wafer, revealing that undesired wettability effects are absent in vapor deposition.

polymerization of hundreds of monomer units. Even though gas-phase concentrations are low, the surface concentrations of the absorbed species can approach that of a liquid, enabling rapid reaction. The surface reactions in iCVD polymerization are identical to the radical polymerization steps in a bulk liquid phase, albeit on a surface. Detailed kinetic modeling studies of iCVD have confirmed that the kinetic polymerization rate constants for many vinyl monomers at the surface match those for standard bulk polymerization in solution.

The use of a free radical initiating species is the key feature that greatly enhances the deposition rate while simultaneously decreasing the energy required to perform the iCVD deposition, typically <5 watts for an 8-inch-diameter substrate. For comparison, vapor-phase deposition of inorganic material over the same area would typically require hundreds or even thousands of watts. The gentle nature of the iCVD process derives both from this low-energy utilization rate as well as from an ability to work at low substrate temperatures.

The iCVD method is a platform technology that has produced more than 40 different homopolymers. Random copolymers, alternating copolymers, and grafted polymer chains have been demonstrated using the iCVD method. Surface properties achieved include nonleaching antimicrobial layers, flexible dielectrics with low leakage current, and coatings with specific ligand-binding capability on porous substrates and particles. Both superhydrophobic and superhydrophilic iCVD coatings have been developed.

Engineering of iCVD coatings has led to extremely stable and flexible biopassivation coatings for neural implants and enteric coatings of drug particles for pH-sensitive release.

A second robust vapor deposition technique has been developed for the family of conducting polymer thin films, which are synthesized by step growth rather than free radical polymerization. With a mechanistic approach, the oxidative chemical vapor deposition (oCVD) method involves gas-phase delivery of both an oxidant and a monomer to the growth surface. The reaction is spontaneous and the substrate temperature is low, resulting in the formation of high-conductivity coatings without damage to the underlying substrate. The solventless oCVD technique yielded poly(3,4-ethylenedioxythiophene) (PEDOT) thin films with 10 to 100 times higher conductivity than the PEDOT:poly(styrenesulfonate) films, which were cast from a commercially available aqueous suspension. The improved properties for the oCVD films stem from eliminating the need to use nonconductive poly(styrenesulfonate) component to achieve solubility.

Mechanistic understanding of growth mechanism led to the ability to propagate conductive polymer chains directly from the growth surface with the use of any additional linker molecules. The creation of durable covalent linkages between the substrate and the surface functionalization layer affords excellent adhesion and also enables high-resolution (60 nm) lithographic pattern formation. The demonstration of patterns in conducting polymer patterns grafted onto common plastic substrates is a potential breakthrough for integrated circuitry for flexible electronics where mechanical robustness is extremely important, requiring excellent interfacial properties and adhesion.

Each organic thin film synthesized by iCVD and oCVD displays a well-defined chemical structure as a result of selectively limiting the reaction pathways available during processing through a judicious choice of reactants and minimizing the energy input that drives the CVD chemistry. The exquisite control over composition and conformality achieved by these new vapor-phase methods enables precise organic functionality to be designed and applied to almost any type of substrate.

Predicting the Complex Chemistry of Energy (William H. Green)

The world is facing several major energy-related challenges: (1) providing the energy needed at an affordable price, so that all the people of the world can have an acceptable standard of living, (2) ensuring security and reliability of energy supply to all the nations of the world in the face of geopolitical and natural disasters, and (3) accomplishing all this without wrecking the world's climate or causing inordinate harm to public health or the local environment. A quick look at current economic, resource, and greenhouse gas models indicates that accomplishing these goals will require the introduction of new fuels and new energy-use technologies on a vast scale. Reliable predictions of the efficiency, performance, and life-cycle environmental impact of the many options are needed now to reduce the huge societal, environmental, and economic risks associated with huge investments in new energy sources and technologies (Figure 2).

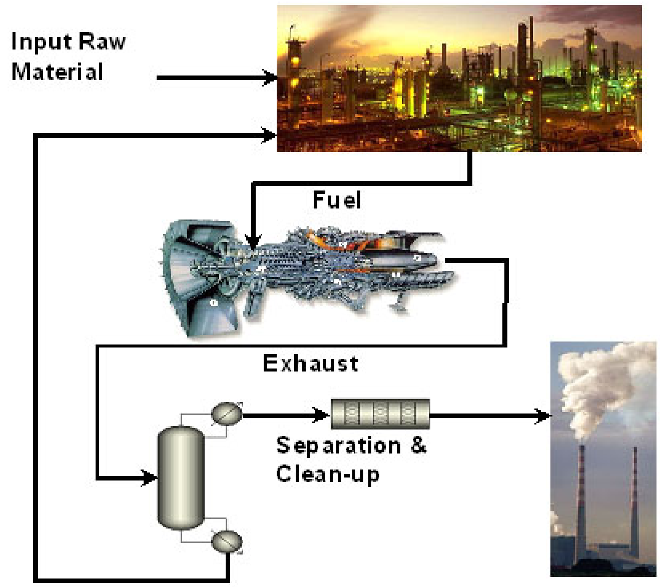

Figure 2. Illustration of the technology life cycle for a conventional energy source (petroleum).

Chemical engineers attempted to make these sorts of predictions some 30 years ago during the first energy crisis. At that time, it was very difficult to make reliable predictions for any process that involved multiple chemical reactions even if bench-scale data were available. So they proceeded by building large pilot and demonstration units. Data from these large-scale units could then be used to make predictions, but they were typically valid only over the relatively small range where data were available. This data-heavy approach made energy research and development slow and very expensive, and the restriction to interpolation biased research and development toward incremental rather than step-out improvements.

This time around, we have the benefit of computers, algorithms, quantum chemistry, and rate theories that were not available in the 1970s, so a very different approach is possible. We can now model the chemistry in many proposed energy systems at a fundamental level, allowing much more accurate extrapolations. This has the potential to allow reactive chemistry to be treated with rigorous process optimization approaches, as has already been done for most separation and flow processes.

Ideally, chemical kinetics should proceed as shown in Figure 3; present knowledge allows the predictions needed for engineering, innovation, and decision making. Some of these predictions are tested against experiment, and from that comparison the state of knowledge is improved, allowing more accurate predictions the next time.

All of this assumes that one can use the existing knowledge to make quantitative predictions, in particular to extrapolate from existing fuels and energy conversion devices to predict the behavior of proposed new fuels/devices. However, in practice it is very difficult to make accurate quantitative predictions for energy-related chemistry, because invariably the fuels are complex mixtures of many different molecules, all reacting simultaneously, often in a nontrivial heat and mass transport environment.

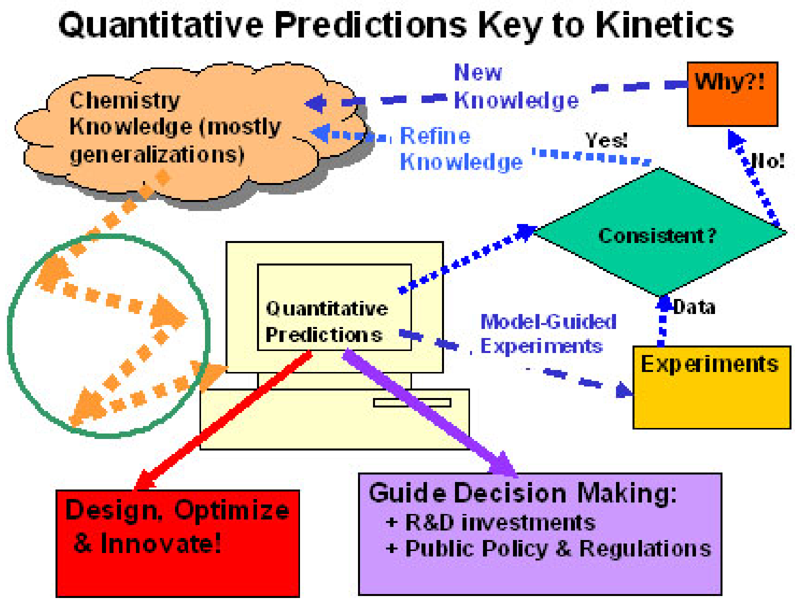

Figure 3. The real purpose of kinetics is to provide the quantitative predictions needed for rational design and for decision-making. Comparison of the predictions with experiment is a key step in improving our understanding of reactive chemistry. Despite their importance, it is still rather difficult to make quantitative predictions; more often in the literature one sees "postdictions" made after the experimental results are known. Professor Green's research group has been developing methods and software to automate and improve the accuracy of the predictions (circled arrows).

Professor Green's research group has been working to fill in the gaps in our ability to make quantitative predictions of reaction rates and product slates (i.e., he has been focusing on the steps in the circle in Figure 3). His group recently developed extensible open-source software that rapidly constructs the large chemistry models (typically about 1,000 reactions) needed to describe the thermal chemistry of liquid fuels (Figure 4). In the process, the software uses results from quantum chemistry to estimate all the needed rate constants and molecular thermochemistry. It is important that this software is extensible and widely distributed, so that the chemistry knowledge that underlies the model predictions can be easily updated by experts on each type of reaction and reactive intermediate.

The large chemical kinetic models constructed by the computer can be very difficult to solve. Professor Green and Professor Barton have collaborated to address many of the numerical issues that arise when solving these large chemical kinetic simulations and developed a numerical procedure for rigorously determining whether these predictions are consistent with experimental data (after considering all the uncertainties involved).

In 2006–2007 Professor Green published several journal articles, including a chapter in *Advances in Chemical Engineering*, demonstrating the quantitative accuracy of the new predictive chemical kinetics procedure for fuel pyrolysis and exploring how well present chemistry knowledge can predict other types of energy-related chemistry. The model predictions were compared with experimental data measured by several different research groups including Professor Tester's group at MIT, Professor Guy Marin's group

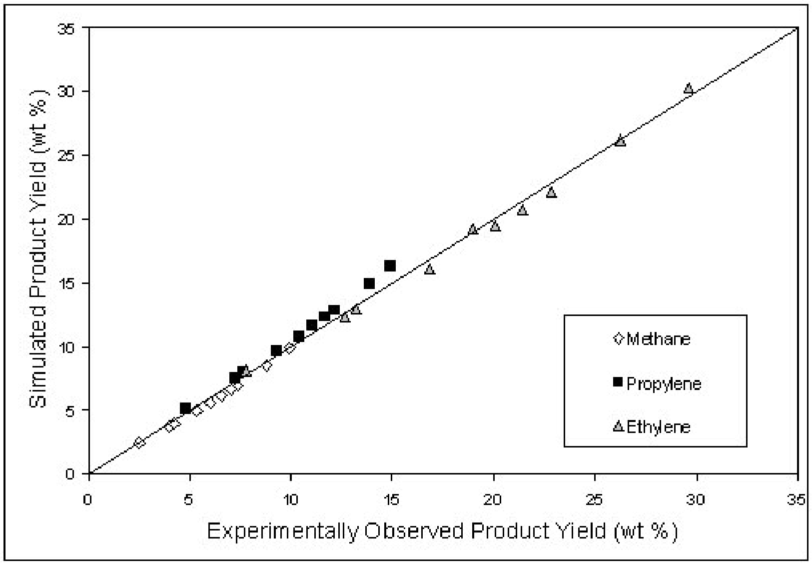

Figure 4. Comparison of the computer-generated model predictions with experimental data on the 1000 K pyrolysis of n-hexane. This is a pure prediction, no parameters were adjusted. For systems like the thermal decomposition of hydrocarbons, where the fundamental chemistry is well known, computer-generated a priori predictions can be as accurate as experimental data. Adapted from K. van Geem et al., A.I.Ch.E J.(2006).

at Ghent University, Professor Lisa Pfefferle's group at Yale, and direct measurements of reactive intermediates by Dr. Craig Taatjes's group at Sandia National Laboratory. This approach focuses attention on key gaps in the chemistry knowledge base and provides decision makers and designers with a measure of the reliability of the extrapolative predictions.

In the coming year, Professor Green's students will be working with chemical engineers around the globe to help them to become familiar with the new predictive tools and to enlist their aid in expanding and improving the chemistry knowledge base to make quantitative predictions feasible for an ever-expanding range of energy chemistries.

Multifunctional Hybrid Nanomaterials via Electrostatically Driven Polymer Assembly (Paula T. Hammond)

New materials developments in the Hammond group have focused on biomedical applications and on new approaches to the design of electrochemical energy devices. The alternating adsorption of oppositely charged molecular species, known as the electrostatic layer-by-layer process, is a simple and elegant method of constructing highly tailored ultrathin polymer and organic-inorganic composite thin films. We have utilized this method to develop a number of functional ultrathin film systems, including materials that can be tailored for biomaterials surfaces, cell templating, display, and sensor and delivery applications. A method of generating biodegradable, conformal thin films on a number of different surfaces with nanometer-scale control of the composition throughout the film thickness has allowed the design of multiple agent delivery thin films. Initial work led to Deshpande funding to launch the idea of these multidrug delivery release films for orthopedic implant coatings; the work has since been funded by an NIH grant, and the concept was entered into the $100K competition by MIT Chemical Engineering graduate students, where it reached the final round of competition. New explorations in the group have include the use of some of these controlled thin films as unique redox active nanoscale systems that systematically deconstruct to release proteins and biopolymers on application of small electrochemical potentials. Possible applications as electroresponsive remote-release drug delivery systems are currently under study.

These highly controlled thin films can also be designed to act as solid state electrolytes or polymer membranes for the transport of ions in ultrathin electrochemical devices, including fuel cells and batteries. New developments in fuel cells include multilayer membranes that can block fuel gases or liquids at the electrode but readily allow the passage of protons across the membrane. Such films could be used to modify existing Nafion membranes or as independent components of a composite thin film membrane. Finally, new developments in collaboration with the Angela Belcher research group and the Yet-Ming Chiang research group in Materials Science and Engineering led to a thin-film battery electrode based on the assembly of viruses with the solid state electrolyte polymer systems. The resulting films led to highly packed viruses with large surface areas; the viruses were genetically engineered to support biomineralization of cobalt and/or cobalt oxide and to bind gold nanoparticles. The resulting electrode exhibited 60% improvement in capacitance over standard Li ion-based batteries; this work was published in *Science* in 2006 and received a Popular Science Innovation Award this past November.

Annual Lectures, Seminars, and Symposia

The department once again hosted a very successful series of three annual major lectures: the 21st Hoyt C. Hottel Lecture, delivered by John Hofmeister, president of the Shell Oil Company; the 13th Alan S. Michaels Lecture, delivered by Professor David Tirrell of the California Institute of Technology; and the 29th Warren K. Lewis Lecture, delivered by Stefan Marcinowski, member of the Board of Executive Directors and research executive director of BASF.

Our departmental seminar series featured a distinguished group of academic and industry leaders from the Max-Planck Institute of Colloids and Interfaces, the CBR Institute for Biomedical Research, the University of Colorado at Boulder, Carnegie Mellon University, Rensselaer Polytechnic Institute, the University of California at Berkeley, the California Institute of Technology, Eidgenössische Technische Hochschule Zürich, Princeton University, Cornell University, Iowa State University, Epitome Biosystems, Raindance Technologies, and Genentech.

The department also hosted a symposium on Friday, October 13th, 2006 to celebrate the life and work of Professor Emeritus Robert C. Reid. His educational and research contributions to chemical engineering were highlighted in a series of invited presentations emphasizing applied thermodynamics and physical property estimation. Professor Reid is known throughout the chemical engineering community for his contributions to methods of teaching thermodynamics, estimating physical properties and the understanding of a variety of complex physical-chemical phenomena, including the phase behavior of supercritical fluids and boiling heat transfer at the interface between two immiscible liquids. Professor Reid was an active member of the MIT faculty for 31 years before retiring in 1985. His former students, many of whom have gone on to careers in teaching and research, remember him as an inspiring mentor. He was known to be humble and thoughtful in his approach to engineering problems, and all who remember him comment on his welcoming and friendly demeanor. In coordination with the symposium, a tree was planted in his memory in the courtyard by Building 66.

Departmental Awards

The department awards ceremony took place on May 14, 2007, in the Gilliland Auditorium of the Ralph Landau Building. We are pleased to recognize this year's recipients of the Outstanding Faculty Awards: Professor William M. Deen was the graduate students' choice and Jean-François Hamel was selected by the undergraduate students.

The Edward W. Merrill Outstanding Teaching Assistant Award was presented to graduate student Saurabh Tejwani for his work in 10.213 Chemical and Biological Engineering Thermodynamics. The Outstanding Graduate Teaching Assistant Award was presented to Brian Skinn for his service to 10.50 Analysis of Transport Phenomena and to Kurt Frey for his service to 10.551 Systems Engineering.

Chemical Engineering Special Service Awards were conferred to the members of the Graduate Student Council: Wayne Blaylock, Kelly Davis, Gary Chia, Amanda Engler, Kevin Fowler, Bo Gong, Michael Harper, Daniel Klein, Chris Marton, Jonathan McMullen, Neidi Negron Rodriguez, and Huan Zheng. In addition, Jordi Mata-Fink was awarded the Chemical Engineering Rock for outstanding athleticism and Maxine Yang was recognized for her year as president of the Student Chapter of the American Institute of Chemical Engineers. All third-year graduate students are required to present a seminar on the progress of their research, and the two recipients of the award for outstanding seminar were Kristin Mattern and Salmaan Baxamusa.

Our undergraduates also earned numerous accolades over the course of the year. The Merck Fellows Award was presented to Alexander Bagley in recognition of his scholastic excellence. The Henry Ford Scholar Award was given to Adam Madlinger, who has shown exceptional potential for leadership in engineering and society. Sravanti Kusuma was presented with the Cunningham Scholarship, which is given to promote women in engineering. The Robert T. Haslam Cup, which recognizes outstanding professional promise in chemical engineering, went to Shyam Raghavan. The department's oldest prize, the Roger de Friez Hunneman Prize, is awarded to the undergraduate who has demonstrated outstanding achievement in both scholarship and research; this year it went to Michael Zhang.

The department is quite pleased to recognize Iris Chang, the undergraduate coordinator, and Mary Wesolowski, graduate coordinator, as the department's outstanding employees of the year for their dedication and outstanding service to faculty, staff, and students. The School of Engineering Infinite Mile Award went to department member Alina Haverty from the Chemical Engineering Headquarters office. In addition, members of the Department of Chemical Engineering ASO received the Infinite Mile

Team Award. The team members presented with this award were Leia Amarra, Sara Darcy, Edith Jaehne, and Richard Lay.

The Department of Chemical Engineering at MIT has certainly had a very fruitful and rewarding year and is poised for even bigger and greater successes for the upcoming year.

Klavs F. Jensen
Department Head and Warren K. Lewis Professor of Chemical Engineering

Gregory C. Rutledge
Executive Officer and Lammot du Pont Professor of Chemical Engineering

More information about the Department of Chemical Engineering can be found at http://web.mit.edu/cheme/index.html.