## Laboratory for Energy and the Environment

The Laboratory for Energy and the Environment (LFEE) brings together collaborating faculty and staff from 14 departments to address the complex, long-term, multifaceted problems of energy supply and use and of sustainable development. LFEE multidisciplinary teams work not only on technological solutions but also on the economic, political, and social aspects associated with their realization. LFEE aims to foster constructive relationships between industry, governments, academia, and the public to understand and seek solutions to long-range energy and environment issues. LFEE works to build better understanding of the many issues between and among developed and developing nations that arise in the context of meeting global energy supply and environmental challenges. A central theme running through all of LFEE's initiatives is the role of science and technology in shaping better energy and environmental policy at all levels in both the public and private sectors. The education program of LFEE is committed to educating the next generation of energy and environmental leaders worldwide via joint projects locally and nationally, and through participation in international education programs with our partners around the world.

LFEE is codirected by Professor David H. Marks, of the Engineering Systems Division (ESD) and the Department of Civil and Environmental Engineering (CEE), and Professor Ernest Moniz, also of ESD and the Department of Physics. They are supported by Professor Jeffrey Steinfeld (Department of Chemistry), director of the LFEE Education Program; Stephen Connors, coordinator of multidisciplinary research; Dr. Teresa Hill, assistant director for communications and programs; and administrative officer John O'Brien. Professors Marks and Steinfeld coordinate the research activities at MIT affiliated with the Alliance for Global Sustainability (MIT/AGS).

### Highlights

In March 2005, the Institute hosted the annual meeting of the Alliance for Global Sustainability, which attracted scholars and stakeholders from industry, government, and nongovernmental organizations (NGOs) from around the world as the Alliance celebrated its first decade of collaboration. Internationally, LFEE continues to oversee MIT's participation in AGS. At this meeting, AGS launched a new flagship initiative, Near-term Pathways to a Sustainable Energy Future. The flagship program will focus regional energy research through each of the AGS member universities on energy issues of universal concern.

In May 2005, MIT's new president, Dr. Susan Hockfield, in her inaugural address, pledged Institute support to a coordinated, campus-wide initiative on energy. Within a few weeks, the Energy Research Council (ERC), headed by Professor Robert Armstrong (Department of Chemical Engineering) and Professor Moniz was formed. The ERC was charged with recommending multidisciplinary, multi-investigator, multiyear research programs that address important energy supply and use issues and that build on MIT's strengths in science, engineering, and policy. The ERC will also make organizational recommendations that facilitate effective implementation of the energy research programs. Having served for two years as director of MIT Energy Studies based at

LFEE, Professor Moniz was named codirector of the lab in June 2005. He will focus on expanding energy research and energy education for the MIT community through seminars, workshops, and other activities.

The appointment of Professor Moniz as LFEE codirector, the establishment of the ERC, and the organization of the AGS Pathways program reflect MIT's new focus on growing international concerns about the sources and uses of energy to meet increased demand while protecting the environment. LFEE-affiliated scholars in a variety of disciplines have been at work on the complex interrelationships between energy and the environment as well as other global environmental challenges to sustainable development since the lab's founding in 2001. They are looking at single technologies in depth and also across technologies to see how their use and improvement might lead to better management and policy formation.

LFEE's research volume for FY2005 was over $6 million, including sponsored research and fund accounts. LFEE research programs engage over 50 MIT faculty members and over 100 students annually. The lab occupies the 4th floor of Building E40, along with the Center for Energy and Environmental Policy Research (CEEPR), the Joint Program on the Science and Policy of Global Change, and work space for 57 graduate students. In AY2005, LFEE attracted new faculty and additional resources to support multidisciplinary research programs and expanded its educational initiatives both locally and internationally.

Building synergy across the Institute, LFEE director Professor Marks co-chairs the Council on the Environment with MIT's chancellor Professor Phillip L. Clay. The lab's weekly seminar series on global environment and sustainability issues draws participants from many research groups. The seminar series includes presentations of work in progress on environmental challenges and technology options as well as discussions of timely issues by invited guests. LFEE faculty helped the Industrial Liaison Program (ILP) structure and present the December 2004 conference on energy.

Professors Moniz and John Deutch (Department of Chemistry), with colleagues from the Scowcroft Group, have carried out work on how the nuclear fuel cycle should develop globally while addressing nuclear weapons proliferation concerns within the nonproliferation treaty framework. The key nuclear fuel services approach was presented in interdisciplinary MIT study, The Future of Nuclear Power (2003), while the new work explores practical implementation. At present, Professor Moniz is co-chairing with Professor Deutch a new study group addressing the future of coal in a greenhouse-gas–constrained world. Their report is anticipated in spring 2006.

Professors Marks and Moniz are also working to advance a partnership between LFEE and a developing research center on energy, water, and environment in Cyprus. The center is intended to be part of a larger research and educational institution that will serve as a bridge between the EU and the Eastern Mediterranean/Middle East region.

LFEE is home to the jointly listed graduate subject Sustainable Energy (22.811J/10.391J/ESD.166J/11.371J/1.818J/2.65J), offered for the eighth time in the spring 2005 term. Based

on their research and teaching experience, course faculty, including professors Jefferson W. Tester (Department of Chemical Engineering), Michael J. Driscoll (Department of Nuclear Science and Engineering [NSE]), and Michael W. Golay (NSE), Dr. Elisabeth M. Drake, and William A. Peters, published an 872-page textbook *Sustainable Energy: Choosing Among Options* (MIT Press, 2005). LFEE faculty lectures were broadcast to Cambridge University in support of the Cambridge-MIT Institute's master's of philosophy programs in engineering for sustainable development and technology policy.

The Summer Air Quality Symposium Series, held annually at Endicott House, is also affiliated with LFEE. Proceedings from the symposia are posted on the LFEE website. The lab has responded to interest on the part of private industry in how climate change and other energy-related issues may affect the future of their businesses. LFEE recently hosted groups from Conoco and Citibank, among others.

LFEE includes both core component and affiliated programs. The component programs in LFEE for FY2005 were AGS (international focus); the MIT/AGS Consortium on Environmental Challenges (focus on science and technology in environmental decision making); the Carbon Management and Sequestration Program; the Analysis Group for Regional Electricity Alternatives; and the Political Economy and Technology Policy Group. Affiliated research programs are also supported in the Center for Advanced Nuclear Energy Systems (CANES); the Sloan Automotive Laboratory; the Building Technology Program; CEEPR; the Materials Systems Laboratory; and the MIT Center for International Studies.

The LFEE Education Program develops sustainability curricula and programs at Institute, local, national, and international levels. LFEE administers both the Martin Family Society of Fellows in Sustainability and the Future Energy Fellows, established in 2004 with support from EECS graduates Charlene '79 and Dirk Kabcenell '75.

## Component Programs

### Alliance for Global Sustainability

Research supported by the Alliance for Global Sustainability brings together scholars from the four partner universities (MIT, the Swiss Federal Institute of Technology [ETH], the University of Tokyo, and Chalmers University of Technology, Sweden), and stakeholders from industry, NGOs, government, and other leading academic institutions to address complex environmental problems that transcend geographical and disciplinary boundaries. In March 2005, MIT hosted the annual AGS meeting in Cambridge. Approximately 300 participants attended, including the director general and executive director of The Energy and Resources Institute, New Delhi, which held a side event in conjunction with the AGS meeting.

AGS projects have traditionally fallen within three major focus areas: water, energy, and mobility. In addition, many of these projects addressed multidisciplinary topics such as urban systems; cleaner technologies; policies and institutions; and communications and outreach in support of sustainable development. AGS project leaders have raised more

than $20 million to supplement these projects and related sustainability research at the partner universities.

Building upon past integrated, collaborative research activities, AGS has inaugurated a large-scale research program focused on near- and medium-term energy scenarios. These focus on the cost-effective reduction of anthropogenic greenhouse gas and other emissions, including the broad-based deployment of technologies leading to sustainable energy systems appropriate to different regions of the world. The new flagship program, Near-term Pathways to a Sustainable Energy Future, is comprised of a set of regional projects that focus on key energy sectors. These projects will look in detail at how alternative portfolios of technologies and policies can affect the development of a region's energy infrastructure. AGS has already invested in sustainability-focused energy research and can present a credible worldwide analysis while at the same time providing a neutral forum for the development of integrated scenarios that will require political and regulatory action. To increase the profile of the AGS and promote synergy among Near-term Pathways research activities, the program will also include crosscutting communication, outreach, and learning initiatives.

In addition to its research programs AGS supports education and outreach initiatives to raise awareness of the important role of science and technology in meeting the sustainability challenge to future development and to equip the next generation of leaders with the knowledge and skills they need to address sustainability issues throughout their careers. In conjunction with the 2005 AGS Annual Meeting, LFEE organized a workshop on communication and education, a major poster session, and a keynote address for the annual meeting of the World Student Community for Sustainable Development. On behalf of the AGS Education Team, LFEE also launched a template for deploying research results in a web-based educational environment at the 2005 Annual Meeting. This template will be the basis for online education in the AGS energy flagship program. LFEE coordinated MIT student and faculty participation in the ETH/AGS-supported Youth Encounter on Sustainability and faculty participation in ETH's Educators Seminar on Teaching Sustainability, in Braunwald, Switzerland. Professors David Marks and Jeffrey Steinfeld are the MIT coordinators for AGS.

### MIT/AGS Consortium on Environmental Challenges

This year, the MIT/AGS worked with the international AGS program primarily in the area of energy futures and transport, with substantial support from the Ford Motor Company.

— Stephen Connors, director of the Analysis Group for Regional Electricity Alternatives [AGREA], coordinates MIT's participation in the AGS flagship program, whose activities at MIT place particular emphasis on sustainable mobility.

—Professor John Heywood (Department of Mechanical Engineering [ME]), head of the Sloan Automotive Lab (see below), has been working on analyzing the conditions that must be met to field a robust fleet of hydrogen-powered vehicles, and on other types of alternatives, including the continuing refinement of internal combustion engines. The environmental impacts and efficiency of such engines have been rising steadily.

—Professor Kenneth Oye (Department of Political Science) has been working on determining which incentive structure would be most likely to encourage a major "first mover" to devote serious resources to developing diesel transport technologies.

—Howard Herzog's program on carbon sequestration technologies continues to draw increasing amounts of attention from industry and government as a short-term solution to control $CO_2$ emissions into the atmosphere at various stages of petroleum extraction and use.

—Visiting scholar Simon Pitts, of the Ford Motor Company, and Paul Killgoar, also of Ford, have been working with the Joint Program on the Science and Policy of Global Change on greenhouse-gas markets.

—The Cambridge-MIT Alliance project on energy security and competitiveness in the U.K. has also received support from the Ford Motor Company.

—AGS activities involving China and India and on the impacts of renewables on emissions portfolios are also under development at MIT.

### Carbon Capture and Sequestration Technologies Program

The field of carbon capture and sequestration is attracting much interest due to increasing concerns about global climate change. Our continuing work on carbon sequestration technologies, led by Howard Herzog, focuses on three areas: assessment, education/outreach, and basic research. Some of key research thrusts are:

—An integrative assessment of carbon sequestration technologies in collaboration with Professor Henry Jacoby (Sloan) and the Joint Program on the Science and Policy of Global Change. The focus of the current project in this area is investigating potential penetration rates of sequestration technologies.

—The Carbon Sequestration Initiative, an industrial consortium on carbon management. Our 12 members are Alstom Power, American Electric Power, American Petroleum Institute, Aramco Services Company, ChevronTexaco, Electricité de France, Electric Power Research Institute, ExxonMobil Corporation, Ford Motor Company, General Motors Corporation, Marathon Oil Corporation, and Peabody Energy.

—An investigation of social and political factors that will affect the future of carbon capture and sequestration technologies. These factors involve siting, permitting, regulatory, environmental justice, etc. The investigation includes:

- An effort to develop a carbon sequestration information system (using a geographic information system as a platform)
- A survey to determine attitudes toward global warming and climate change mitigation technologies, the level of public understanding of global warming and the carbon cycle, and public awareness of carbon dioxide capture and storage (or carbon sequestration). Over 1,200 people, representing a general population sample of the United States, responded.
- An economic analysis of the concept of "capture-ready" power plants.

In addition, the program has been involved in many national and international efforts related to carbon capture and sequestration. Specifically, Howard Herzog is a coordinating lead author for the Intergovernmental Panel on Climate Change Special Report on Carbon Dioxide Capture and Storage, which will be issued in fall 2005. He has also been designated as one of the two US members of the Technical Group for the Carbon Sequestration Leadership Forum (a ministerial-level agreement among about 20 countries to promote research into carbon sequestration technologies).

Funding for the program comes from a diverse number of sources including the US Department of Energy, private industry, NGOs, and AGS. Additional information can be found on the program website at http://sequestration.mit.edu/.

### Analysis Group for Regional Energy Alternatives

LFEE research in the area of strategic planning for energy infrastructures and environmental performance is centered in the Analysis Group for Regional Energy Alternatives (AGREA), led by Stephen Connors. The scenario-based multiattribute tradeoff–analysis approach, developed in the 1980s by Energy Laboratory researchers, is the primary tool used by AGREA. Recent notable research activities include the AGS China Energy Technology Program, the Mexico City Integrated Air Quality Program, and Environmental Protection Agency (EPA) Avoided Emissions from Solar Power Generation projects.

Current projects include identifying long-term, low-carbon strategies for Scandinavia (TRANSES, in collaboration with Chalmers University in Sweden, and NTNU in Norway), and the potential economic and environmental benefits of offshore wind energy along the New England coast (the Offshore Wind Consortium with University of Massachusetts-Amherst). These and past research efforts comprise the primary toolkit being incorporated into AGS's new flagship energy program.

To develop these and other research activities, Mr. Connors also supervises students looking at the fuel consumption and emissions impacts of worsening traffic congestion; behavioral barriers to the widespread deployment of distributed generation technologies; the institutional challenges to electrification in Africa; and the application of real options to the challenge of redirecting energy investments addressing the combined challenges of climate change, economic growth, and energy security. To reflect its broadening research portfolio, AGREA changed its name from Analysis Group for Regional Electricity Alternatives to Analysis Group for Regional Energy Alternatives in spring 2005.

## Political Economy and Technology Policy Group

The Political Economy and Technology Policy Group, led by Professor Kenneth Oye, is a joint program of the LFEE and the Center for International Studies. Its purpose is to identify means to improve the quality of public and private responses to critical environmental problems by combining expertise on problems of political economy with fundamental understanding of scientific and technical issues. In 2004–2005, the group's research focuses on two key areas for improving environmental decision making.

The first area is the use of scientific information in public policy making. The intent is to identify methods for more robust and integrated assessments of policy options and for credible assessments of risks in areas of environmental policy controversy, and to improve the capacity of political institutions to adapt to new information. Lawrence McCray (Department of Political Science) produced papers on third-party assessment of knowledge on environmental risks and on policy environmental adaptation, while also serving with a National Research Council panel on toxicology and risk. Kenneth Oye joined with Daniel Hastings and Dava Newman (both of the Department of Aeronautics and Astronautics and ESD), and Roe Smith (History Faculty and Program in Science, Technology, and Society) to continue with the National Science Foundation (NSF)–funded Program on Emerging Technologies (PoET), with a focus on improving responses to uncertainty associated with the environmental, security, and economic effects of rapid technological change. Oye and McCray also joined with Bruce Beck of the University of Georgia and with Kenneth Reckhow of Duke University to organize the TransAtlantic Uncertainty Colloquium (TAUC) to bring together officials from the EPA and the European Environment Agency to develop and evaluate better methods for coping with uncertainty in environmental regulation. TAUC will be funded by EPA and NSF.

The second area is the assessment of the private effects of public environmental policies, with specific attention to the competitive position of firms, sectors, and nations. The group currently is conducting a study of links among regulation, the utilization of technologies, and industrial structure. James Foster, Kenneth Oye, and Christine Ng worked with the Finnish Environmental Institute, the Swiss Federal Institutes of Technology, and the Stockholm School of Economics on a comparative analysis of the implications of divergent national regulatory regimes on environmental performance and competitive positions of the pulp and paper industry in a study on potential environmental effects of accelerating the phase-in of cleaner diesel fuels and of applying emerging heavy-duty vehicle engine and after-treatment technologies to light-duty vehicles.

In addition, the group worked with scientists and engineers to ensure that assessments of technical options includes analyses of political and economic constraints and opportunities. Members of the group worked with the LFEE project on carbon sequestration and the Joint Program on the Science and Policy of Global Change assessment of developing country $CO_2$ options, and are now developing oil and water policy projects with the Department of Earth, Atmospheric, and Planetary Sciences and the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics under the new Kuwait-MIT Center for Natural Resources and the Environment.

## Affiliated Groups

### Building Technology Program

Research in the Building Technology Program (BTP) has its principal focus on energy efficiency and sustainable design for buildings. In the United States, buildings consume almost 40 percent of the total energy used and more than two thirds of the electricity. The long life and the difficulty of renovation mean that mistakes in today's buildings will create energy and environmental problems for much of this century. In many instances, investment in new energy efficiency technologies for buildings is more cost effective than investment in new energy production facilities. If done properly, energy efficient and sustainable design will also lead to better indoor health, comfort, and productivity. It has been frustrating to deal with the lack of focus of the federal government in this area. The sorry state of energy efficiency of MIT's own buildings, including the Stata Center and Simmons Hall, is another example of this lack of attention.

Four of the five faculty members in the BTP group have had a strong input to our energy research and teaching: Professors Marilyne Andersen, John Fernandez, Leon Glicksman, and Les Norford (all from the Department of Architecture). Professor Andrew Scott, of the Department of Architecture, is also a member of our group and is active in many of our projects. Many of the activities involve substantial joint efforts with faculty members and students in the departments of Civil and Environmental Engineering, Electrical Engineering and Computer Science, and Mechanical Engineering, as well as Harvard School of Public Health, Cambridge University (UK), Chalmers University (Sweden), ETH (Switzerland), and Tsinghua University (China). Typically we have 15 to 20 graduate students carrying out building technology research. Some students receive degrees in architecture, others in engineering disciplines.

Several major projects—discussed below—are under way or were recently completed.

#### *Natural Ventilation of Commercial Buildings*

When natural ventilation is properly designed and operated, indoor air quality is improved and a substantial portion of the energy used for cooling can be saved (typically 33–50 percent in Boston and up to 100 percent in the UK). A joint project with Cambridge University under the Cambridge-MIT Institute program includes the development of basic models to predict the airflow and thermal conditions in complex open plan buildings under buoyancy and wind forces. In addition, BTP faculty members have done one of the first detailed monitorings of a large, commercial, naturally ventilated building during occupancy, and are developing proper similitude rules to allow small-scale experiments to closely simulate large buildings. They have also developed methods for in situ measurement, modeling, and control of building performance, with the goal of optimally cooling buildings when outdoor temperatures permit, as is often the case at night.

#### *Design Tools*

Currently, energy studies are lengthy and costly and typically are not undertaken until a building design is near finalized form. Simple web-based tools are under development

that will allow designers to get real-time feedback of design scenarios during the conceptual design phase. Advanced technologies such as double-skin facades and natural ventilation are simulated in the tool. Recent additions include a real-time (1–2 minute running time) optimizer that considers the optimum choice of up to 30 different design parameters to yield the lowest yearly energy consumption for heating, cooling, and lighting. In a parallel effort a design tool is being developed for material selection that allows a designer to screen conventional and newly developed materials and trade-off characteristics such as embodied energy and nonrenewable content.

### *Fault Detection, Monitoring, and Control*

Studies in Texas have shown that better commissioning of heating, ventilating, and air conditioning (HVAC) equipment and ongoing detection of major problems reduced energy consumption by more than 20 percent in over 100 buildings. BTP researchers are working with EECS faculty (Professor Steven Leeb) on techniques to detect faults in and monitor the performance of a wide range of HVAC equipment in buildings and ships, using high-speed electrical measurements and signal processing.

### *Sustainable Buildings for Developing Countries*

The largest increase in energy use and $CO_2$ production is occurring in the developing world. Each year China is building upwards of 10 million housing units. In a recently completed project group members worked with Chinese developers, architects, and academics at Tsinghua University to develop technical solutions and building designs appropriate to Chinese buildings. This was supplemented by design workshops in China and will culminate in a book to be published by the end of this year.

In earlier projects in the developing world, BTP scholars developed a low-cost retrofit insulation that could be used in the mountainous regions of Pakistan and analyzed village houses in India, where lack of kitchen ventilation poses a serious problem for women and children.

### *Daylighting*

Energy for lighting is the larger segment of energy use in a commercial building. The level of daylight in the outdoor is one to two orders of magnitude higher than that required within a building. A new faculty member is leading our efforts to develop innovative materials and systems to bring daylighting deeper into commercial buildings. In most cases this would be more efficient than using photovoltaics to generate electricity for conventional lighting systems.

### *Real Options*

Option theory has been applied to determine the value of flexibility in the initial building design. This flexibility allows the option of less costly future renovations such as the installation of chillers to supplement natural ventilation if global warming causes more severe summer conditions.

### *MIT Facilities*

Several design projects have been carried out to evaluate advanced techniques to substantially improve the energy efficiency and performance of MIT buildings. These include control optimization, exterior wind conditions around the Stata Center, and use of displacement ventilation (based on the US design guidelines for this technology developed by the BTP group).

### *Education*

A number of subjects with an energy focus are offered by our group to both graduate and undergraduates. These include lecture, laboratory subjects, and design workshops.

## Center for Advanced Nuclear Energy Systems

The Center for Advanced Nuclear Energy Systems (CANES) develops research concepts for nuclear energy systems that promise more favorable economics, safety, proliferation resistance, and environmental impact. The center's programs involve development and application of methods for the design, operation, and regulation of current and advanced nuclear reactors and fuel cycles. These efforts require advances in knowledge about scientific and engineering disciplines, such as reactor physics and thermohydraulic statics and dynamics, as well as modern methods of systems reliability, probabilistic safety analysis, and decision analysis, together with human interactions and management science. About 10 professors, 12 research scientists and postdoctoral associates, and 40 graduate students are engaged in center projects. Professor Mujid S. Kazimi is the founding and present director of CANES.

CANES programs involve four major thrusts: (1) developing advanced reactor plants with water, helium, or other coolants and power cycles, (2) investigating alternative nuclear fuel cycles from the technical and economic points of view, (3) providing methods to enhance performance and reliability of nuclear power plants in a risk-informed framework, and (4) assessing the role of nuclear energy in a sustainable world, such as in production of transportation fuels and in desalination.

Center research activities are funded mainly by various Department of Energy (DOE) programs and by national and international industry. In the past year, DOE, Idaho National Laboratory (INL), and Sandia National Laboratory supported several projects on advanced reactors, including two on advanced fuels for light water cooled reactors (LWRs) under the direction of Professor Kazimi and Professor Neil Todreas (NSE and ME), and the Fast Gas Cooled Gas Turbine Reactor under the direction of Professor Michael Driscoll. Dr. Pavel Hejzlar (NSE) investigated the heat transfer in gas coolants under mixed (forced and natural) convection. Professor Jacopo Buongiorno (NSE) initiated investigations in the use of nanofluids as coolants in pressurized water reactors, partially supported by AREVA and INL. Toshiba supported a comparative study of passive and active reactor systems under Professor Kazimi and Dr. Hejzlar.

Since 2002, CANES has had a collaborative agreement with the Nuclear Regulatory Commission (NRC) focused on the technology and regulatory aspects of advanced reactor systems. Four areas were supported in the past year by this agreement: (1) safety

analysis of the new Canadian reactor, called the ACR-700, under Professor Buongiorno, (2) methods for risk-informing the regulation of new reactors under professors George Apostolakis (NSE and ESD) and Michael Golay, (3) modeling the performance of high-burnup light water reactor fuel during steady-state irradiation and transients, and (4) stability analysis of advanced boiling water reactors (BWR) under Professor Kazimi. NRC also funded a specific task for establishing a methodology for assessing safety margins in a probabilistic framework under the guidance of Professor Apostolakis.

A collaboration that started in 1999 between MIT and Tokyo Electric Power Company (TEPCO) for nuclear engineering continued. The collaboration supported several projects in the past year, including: (1) the lessons learned from risk-informing operations of US nuclear power plants and how those may be of benefit to TEPCO, led by Professor Andrew Kadak (NSE), (2) the use of annular fuel to enhance safety and economy in BWRs, led by Professor Kazimi, and (3) the environmental factors' effects on weld cracking in pipes of boiling water reactors, led by Professor Ronald Ballinger (NSE and Department of Materials Science and Engineering).

A significant effort was directed toward investigating the design features in nuclear plants that increase the efficiency of producing hydrogen from water by electrolysis, or a hybrid approach of electrolysis and thermochemical reactions. In addition, the use of catalysts as constituents in wall materials of heat exchangers so that they can be applied for thermal decomposition of hydrogen-bearing chemicals is now under investigation with support from Sandia.

A one-day symposium, The Role of Simulation in the Nuclear Fuel Cycle, was held in October 2004, and a two-day symposium, Next Generation Nuclear Plant: Goals and Challenges, was conducted in February 2005. Electronic proceedings can be ordered on the web at http://web.mit.edu/canes/symposia/symposia.html.

Professor Ballinger added a new short summer course on degradation of materials in radiation environments to the three other professional short courses offered by the CANES faculty: Nuclear Plant Safety, Reactor Technology for Utility Executives, and Reliability in Operational Decision Making. Details can be found at http://web.mit.edu/canes/.

### Sloan Automotive Laboratory

Many of Sloan Automotive Laboratory's projects involve quantitative and cross-disciplinary study of complex energy and environmental systems. The laboratory is directed by Professor John Heywood, with participation from Professor Wai Cheng (ME), Professor Doug Hart (ME), Professor James Keck (ME), Dr. David Schmidt, Dr. Tian Tian, Dr. Victor Wong (ME) , and Professor William Green (Chemical Engineering). It continues to pursue promising research to improve engine performance, efficiency, and fuel utilization in internal combustion engines and reduce adverse emissions.

Focusing on new engine and fuel technologies, the Engine and Fuels Research Consortium continues to explore critical fuel/air mixture preparation and emission formation mechanisms in developing engine concepts, with potential application to

both gasoline and diesel engines. Complementing the engine and fuels studies, the Consortium on Lubrication in Internal Combustion Engines involves major engine component and lubricant manufacturers in addressing issues in oil consumption and engine friction reduction. Members in these consortia also sponsor separate research projects on related topics of specific application to the individual sponsors. For example, Professors Wai Cheng and John Heywood work with Ford Motor Company on three projects related to engine transients: fuel/air mixture preparation behavior during start up, emission benefits of engine operation in hybrid electric vehicles, and actual in-use vehicle emissions in stop-and-go traffic. A new consortium with 10 members, focused on developing low ash producing lubricants to enable significantly improved diesel emission control has been formed with strong support from the diesel engine industry.

Sloan Automotive Laboratory researchers are also involved in multidisciplinary studies assessing new vehicle and propulsion system technologies for future road transportation use. Currently these are being done cooperatively with the Paul Scherrer Institut (Switzerland), connected with ETH Zurich, as part of AGS. The Sloan Laboratory also engages actively in basic combustion and friction research on advanced engine systems with DOE support.

In a joint project with the Plasma Science and Fusion Center, Professor John Heywood and Sloan Automotive Laboratory graduate students are exploring opportunities for lean operating spark ignition engines in which a plasmatron device—an electrical discharge-initiated fuel reformer—supplies hydrogen to enable the lean burn. A license to develop this technology has been taken out by ArvinMeritor, and a substantial cooperative research and development program with DOE/ArvinMeritor funding is in progress.

### Center for Energy and Environmental Policy Research

The Center for Energy and Environmental Policy Research is an activity jointly sponsored at MIT by LFEE, the Department of Economics, and the MIT Sloan School of Management. CEEPR funds policy-related research in energy and environmental economics. The center receives financial support from corporate sponsors and government agencies such as the EPA and the US National Oceanic and Atmospheric Administration.

CEEPR research is focused on evaluating the functioning and performance of markets created for environmental services and for electricity and associated network services. Past environmental research has been concerned with emissions trading, with particular attention to the US $SO_2$ Allowance Trading Program and the Northeastern NOx Budget Program. Recent work includes analysis of the market for carbon created under the European Emissions Trading Scheme. The electricity research is concerned with restructuring decisions with respect to asset ownership, transmission access, and customer choice. CEEPR is also involved in evaluating the future of nuclear and coal energy, in development of markets for oil and natural gas and renewables. Research includes analysis of financing large scale investments as well as the price dynamics and risk in these markets.

### Joint Program on the Science and Policy of Global Change

The Joint Program on the Science and Policy of Global Change, codirected by Professors Jacoby of the Sloan School and Ronald Prinn of the Department of Earth, Atmospheric, and Planetary Sciences, draws on MIT's traditional strengths in science and economics to conduct the serious interdisciplinary work needed to provide a basis for global climate policy. The now 13-year-old joint program is one of the world's leading centers for the integrated assessment of climate change. The MIT Integrated Global Systems Model, developed by program researchers, provides a facility for research on the climate issue and assessment of policy proposals. An interdisciplinary team of faculty, professional staff, and graduate students carries out the work, and it produces a continuing flow of reports, articles, student theses, and professional and public presentations on the science and policy of global warming. Five US-government agencies, 20 corporate sponsors in North America, Europe, and Japan, and one foundation support the work.

### *Education and Curriculum Initiatives*

The mission of the LFEE Education Program is to enhance environmental literacy and to strengthen the environmental dimension of educational experiences, particularly among the leaders of tomorrow's science and technology communities. The program is dedicated to increasing awareness of the complexity of environmental and sustainability challenges, and to increasing the multidisciplinary capacity of learners to respond effectively to these challenges. A special challenge of the mission of the program is to ensure that environmental issues and concerns are part of the education of every MIT student, not just those who will become environmental scientists, engineers, and planners. Professor Jeffrey Steinfeld directs the LFEE Education Program; Dr. Amanda Graham is program manager.

Major campus initiatives during the past year include:

- Establishing a Campus Sustainability Education Fund in cooperation with the Environmental Programs Office. This fund will support student research on environmental aspects of campus operations.
- Offering an Independent Activities Period (IAP) course for graduates and undergraduates. Dr. Graham and program coordinator Beth Conlin cotaught the IAP course Implementing the Cambridge Climate Protection Plan for the third time. The students researched and presented findings on the effectiveness of utility energy audit programs for Cambridge residents.
- Assessing students' response to EnviroClasses, LFEE's web-based listing of environmental classes at MIT, viewable at *http://enviroclasses.mit.edu/*.
- Publishing final documentation of Urban Focus, the MIT–Cambridge Public Schools Collaboration on Education for the Environment. Urban Focus was a supplemental environmental project undertaken by MIT as part of its consent decree with the EPA and the US Department of Justice. In collaboration with the Environmental Programs Office, LFEE oversaw the three-year program and prepared web and print documentation to distribute lessons learned to educators and other research institutions.

In addition, the program continues to:

- Manage fellowship programs for scholars in sustainability, including the Martin Family Fellowship Program in Sustainability, for outstanding upper-level MIT graduate students, and the Knut and Alice Wallenberg Foundation Postdoctoral Fellowships for the Environment and Sustainability, for promising Swedish scholars. School of Architecture and Planning dean Adèle Santos addressed the Martin fellows at their annual induction dinner in September. The program coordinates an environmental fellows group to engage all environmental fellows at MIT; activities this year included a retreat on ridge-top wind energy in the Berkshires, a fellow-to-fellow research exchange, and a major invitational lecture (James Gustave Speth, dean of the Yale School of Forestry and Environmental Studies).
- Support efforts by the MIT Council on the Environment to improve coordination and coherence among academic, research, and activity offerings for undergraduates, including coordinating with the Admissions, Careers, and Orientation offices to better serve prospective students and future alumni. The program cohosted MIT's first "Environmental Careers Panel" in January.
- Support and participate in the development of subjects and programs for environmental majors and graduate students.
- Participate in campus-wide events such as the International Development Forum and Earth Day celebrations.

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**Professor of Engineering Systems**

**Ernest J. Moniz**
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*More information about the Laboratory for Energy and the Environment can be found online at http://lfee.mit.edu/.*