Department of Nuclear Science and Engineering

The faculty and students of the Department of Nuclear Science and Engineering (NSE) study nuclear reactions and radiation, their applications, and their consequences. The work of the department involves generating, controlling, and applying nuclear reactions and radiation for the benefit of society and the environment. The mission of the department is to help develop the next generation of leaders of the global nuclear enterprise and to provide technical leadership in energy and non-energy applications of nuclear science and technology. As a leading academic department in the field, NSE also has a responsibility to inform public debates on the wise and humane uses of nuclear science and technology.

Increasing global energy needs and rising concerns over climate change are bringing new attention to the role of nuclear energy around the world, even as the safety of nuclear fission power plants is receiving renewed public scrutiny in the aftermath of the Fukushima nuclear accident in Japan. Many important non-energy applications of nuclear science and technology are also under development. The department offers what is probably the widest spectrum of research and educational activities of any nuclear science department in the country. Our faculty and students develop nuclear reactors for electricity generation as well as other diverse uses, including waste management, fluid fuels production, and space propulsion. They work in direct support of the International Tokamak Experimental Reactor (ITER), a project aimed at demonstrating the scientific and technical feasibility of fusion power. They contribute to security by developing new ways to monitor nuclear materials and to detect nuclear threats. They apply nuclear technologies to the physical and life sciences in areas ranging from neutron interferometry to radiation modeling, magnetic resonance imaging, and quantum information processing.

Faculty and Administration

The department welcomed Michael Short as a new assistant professor this year. The main focus of his research is the characterization, design, and enhancement of bulk material interfaces in nuclear systems.

Paola Cappellaro and Benoit Forget were promoted to the rank of associate professor without tenure. Paola Cappellaro was appointed the Esther and Harold Edgerton career development associate professor.

Anne White was appointed Norman C. Rasmussen career development professor of nuclear science and engineering.

Mujid Kazimi continues as director of the Center for Advanced Nuclear Energy Systems. He also continues as director of the Kuwait–MIT Center for Natural Resources and the Environment.

Richard Lester continues to serve as faculty co-chair of the MIT Industrial Performance Center.

Emeritus professor George Apostolakis continues his service as a member of the US Nuclear Regulatory Commission.

Dr. Koroush Shirvan was hired as a research scientist.

Research Highlights

Fission energy research is mainly conducted through the department's Center for Advanced Nuclear Energy Systems. Research on advanced reactor designs, new fuel-cycle technologies, and innovative reactor materials and components is carried out by the faculty and staff of the center working with more than 70 graduate students and postdoctoral fellows.

NSE plays a leading role in the Consortium for Advanced Simulation of Light Water Reactors (CASL), the US Department of Energy (DOE) Nuclear Energy Innovation Hub based at the Oak Ridge National Laboratory. Professor Kazimi serves as the principal investigator of the CASL–MIT project. Professors Emilio Baglietto and Jacopo Buongiorno lead a CASL program to develop and validate advanced simulation methods and diagnostics for multiphase flow and heat transfer. Professor Short has advanced the simulation of corrosion-related unidentified deposits in pressurized water reactor cores. Professor Bilge Yildiz has provided models for the migration of oxygen and hydrogen through the corrosion products into the metallic fuel cladding as well as cladding creep behavior. Professor Mike Demkowicz of the Department of Materials Science and Engineering and professors Ken Kamrin and David Parks of the Department of Mechanical Engineering are investigating fretting and wear in grid-supported rod bundles.

Professor Forget is developing advanced methods for reactor physics calculations that promise to enable much faster simulation of core behavior. Recent analyses include full core characterization of hot-zero power startup physics tests of an operating pressurized water reactor plant, with comparisons to actual plant data.

NSE also plays an important role in the Center for Exascale Simulation of Advanced Reactors (CESAR), a DOE Office of Science co-design center. Professor Forget and professor Kord Smith are investigating new ways of reducing memory footprint and improving performance of stochastic and deterministic radiation transport methods. Recent highlights include novel parallelization of a method-of-characteristics neutron transport solver on GPGPU (general-purpose computing on graphics processor units) and linear scalability of Monte Carlo eigensolvers on two of the world's largest supercomputers.

NSE's computational reactor physics group, led by professors Forget and Smith, have also been pursuing the development of high-fidelity open source software. The flagship code is OpenMC, a general geometry Monte Carlo neutron transport code designed specifically for leadership-class computing. OpenMC is being leveraged by both the

CASL and CESAR initiatives. Additionally, OpenMOC has been released. OpenMOC is a 2D deterministic-based neutron transport code that is being used for performance analysis on innovative computing platforms.

Professor Baglietto continues his research in the field of computational fluid dynamics. An important goal of this research is to improve the safety and reduce the operating costs of nuclear power plants. A new scale-resolving turbulence model is being developed for predictive simulation of the unsteady flow behavior that drives vibrational and thermal failures in reactor components. Professor Baglietto's group has also implemented a new computational fluid dynamics (CFD) application to heat transfer and crossflow predictions for sodium-cooled fast reactor simulations. In other research, Professor Baglietto has developed a comprehensive new CFD-based dataset for heat transfer validation in gas-cooled reactor pebble cores.

Professor Kazimi and Drs. Thomas McKrell, Gordon Kohse, and Edward Pilat continue their studies of the feasibility of ceramic materials including silicon carbide and coated zirconium alloys as cladding material for enhanced accident tolerance in light-water reactors (LWRs). Professor Kazimi, joined by Dr. Shirvan, continues his investigation of thermal hydraulics and fuel performance in tight-lattice boiling-water-cooled high fissile conversion, even breeding reactors. He and his colleagues initiated an investigation of nitride fuel to enhance the fissile conversion potential in LWRs. The use of thorium oxide to burn plutonium in LWRs is also being investigated. Support for this activity is provided by DOE funding through Westinghouse, two Nuclear Energy University Program (NEUP) projects, and three other industrial companies.

Several events were sponsored by the Center for Advanced Nuclear Energy Systems this year. A one-day review of accident tolerant fuels organized by Dr. McKrell was held in early May. A two-day symposium on nonconventional fissile fuel futures organized by Dr. Charles Forsberg and Professor Kazimi was held in late June.

The fluoride salt-cooled high-temperature reactor (FHR) project sponsored by DOE and led by Dr. Forsberg and Dr. Lin-Wen Hu of the Nuclear Reactor Laboratory will begin irradiation experiments in the MIT reactor in September. The objective is to understand the corrosion characteristics of prototypical materials in liquid salt coolants at 700°C. The FHR is a new reactor concept with the capability to couple to air-Brayton combined cycles—the same technology used in natural gas plants. The use of auxiliary natural gas holds out the possibility of substantially improved nuclear plant economics via base-load electricity production and peak electricity production.

Dr. Forsberg also initiated a joint project with Idaho National Laboratory to determine the viability of a nuclear shale-oil renewable electricity system. Shale oil (kerogen) must be heated to release oil. The heating is done underground over a period of several years. A nuclear plant operating at constant output with steam to heat shale oil at times of low electricity demand and to generate electricity at times of high electricity demand will enable the nuclear plant to provide economic low-carbon variable electricity to back up renewables while minimizing the carbon footprint from liquid fuels production.

Professors Neil Todreas and Ronald Ballinger are evaluating aggressive power uprates for nuclear power plants as part of life extension programs for operations beyond 60 years. An integrated decision analysis methodology is being developed based on analysis of the performance, safety, and economics associated with plant performance at the added capacity afforded by the adoption of high-performance fuels.

New research led by Professor Buongiorno on the measurement and modeling of the onset of nucleate boiling (ONB) for rapidly escalating heat fluxes was started this year under the sponsorship of France's Commissariat à l'énergie atomique et aux énergies alternatives. A combination of advanced diagnostics including high-speed video and IR thermography will enable a rigorous identification of ONB as well as the investigation of heat transfer mechanisms of nucleate boiling beyond ONB.

Professor Buongiorno continues his studies of engineered surfaces for the enhancement of nucleate boiling, critical heat flux, and quenching heat transfer. Current research, sponsored by Areva, focuses on elucidating the effects of pore size, pore volume, and porous layer thickness on critical heat flux to enable more mechanistic modeling of surfaces with porous layers and the development of optimized surfaces. This research is being carried out in collaboration with professors Michael Rubner, Robert Cohen, and Kripa Varanasi (of the Departments of Materials Science and Engineering, Chemical Engineering, and Mechanical Engineering, respectively).

With support from Idaho National Laboratory, Professor Buongiorno is also continuing his research on uncertainty quantification of safety codes using a Bayesian approach with data from separate- and integral-effects tests.

Emeritus professor Michael Driscoll was awarded a three-year DOE NEUP research grant on the use of deep boreholes for disposal of used nuclear fuel and high-level waste, continuing a nearly 25-year long NSE research program in this area. This research is being carried out in collaboration with Sandia National Laboratories and also involves Professors Baglietto, Buongiorno, and Lester.

Professor Michael Golay's research this year has been concerned with improving systems for risk-informed safety regulation and organizational performance, understanding the mechanisms for gaining public acceptance of socially controversial technological projects, and improving methods for analysis of safety performance of nuclear systems.

Professor Ju Li's group is developing the new field of elastic strain engineering. In recent research, they have achieved unusual materials properties through the application of ultrahigh tensile and shear elastic strains. The Li group is also developing liquid microelectromechanical systems cells for in situ transmission electron microscopy observations of corrosion and electrochemical processes. In other recent research, Professor Li has been investigating liquid-solid interactions dynamically at 1nm resolution.

Professor Cappellaro's quantum engineering group investigates the dynamics and control of quantum systems with the goal of building computational and measurement devices that exceed the power of their classical counterparts. Over the past year, Professor Cappellaro has been exploring the use of the nuclear spin associated with the nitrogen-vacancy (NV) center in diamond in a stable, three-axis gyroscope. In other research, her group devised a novel strategy for controlling an NV-based quantum magnetometer that allows a greater flexibility in its application to practical signals; in addition, they developed a novel technique that simultaneously extracts information about the time evolution of the magnetic field and protects the sensor from noise. This technique can be further integrated with compressive sensing strategies for substantial time savings in the task of field reconstruction.

Professor Ian Hutchinson's computational plasma physics research is aimed at providing a comprehensive understanding of the interaction of flowing plasmas with solid objects. Probes in the edges of magnetic fusion plasmas require this knowledge in order to deduce the flow velocity, but the problem is also characteristic of spacecraft and lunar interactions with the interplanetary plasma, and the behavior of dust in plasmas. Recent highlights include the development of a new computational technique to provide complete distribution function information on an unstructured mesh, the explanation of the observation of ion beam velocity and density in near-lunar satellite measurements, and a comprehensive investigation of forces on dust in collisional plasmas.

Professor White's research group deployed a new fast two-color interferometer at Alcator C-Mod which provided a data set of density fluctuations that has been used to verify the synthetic model used to interpret phase contrast imaging, a workhorse of transport model validation efforts at the laboratory. In addition, the new correlation electron cyclotron emission radiometer system deployed last year yielded the first measurements of turbulent fluctuations of electron temperature in the core plasma at Alcator C-Mod.

Professor Parra Diaz's research on turbulent transport of particles, energy, and momentum in tokamak plasmas continued this year. With one of his doctoral students, he discovered the key role played by diamagnetic flows in momentum transport and explained how radio frequency wave injection affects rotation in experiments. He and another student have proposed up-down asymmetric tokamak designs that can drive strong toroidal rotation without momentum input. Research undertaken with post-doctoral associate Michael Barnes yielded key charge and mass scalings in impure tokamak plasmas, and explained the puzzling and robust experimental observation that rotation in tokamaks reverses at high densities. Finally, Professor Diaz and his collaborator Ivan Calvo were able to extend their treatments of rotation to the fully electromagnetic case in stellarators as well as tokamaks.

During the past year, Dr. Peter Catto's research has focused on demonstrating that a current-driven kink instability can be modeled by fully electromagnetic turbulence simulations. In addition, he and his colleagues continued to improve analytic and numerical modeling of ion flow, bootstrap current, and collisional ion radial heat transport in the presence of the strong radial density and temperature gradients

associated with the pedestal region at the outer edge of the core plasma during high-confinement tokamak operation. This poorly understood region plays a key role in tokamak performance.

Senior research scientist Richard Lanza initiated two new research projects during the past year. The first, through a Defense Advanced Research Projects Agency grant, is investigating a new approach to medical imaging based on phase contrast x-ray imaging. This project also involves researchers in the Department of Electrical Engineering and Computer Science, the Computer Science and Artificial Intelligence Laboratory, and Massachusetts General Hospital. A second collaboration with Ionetix Corporation is developing an ultra-compact superconducting cyclotron for applications to medicine and security. The prototype, installed at MIT, weighs approximately 25 times less than conventional machines.

Professor Scott Kemp launched the new Laboratory for Nuclear Security and Policy this year. The laboratory is organizing the department's research, seminars, and collaborations in nuclear security. Members include Professors Golay, Kemp, and Lester from Nuclear Science and Engineering; Professors Aron Bernstein and Peter Fisher from Physics; and Drs. Lanza and Forsberg from Nuclear Science and Engineering. Professor Kemp also initiated two research projects, one involving the design of a new international arrangement to secure fuel supplies for nuclear power plants without the proliferation of sensitive uranium-enrichment technology; the other, in collaboration with Dr. Lanza, involves the development of "zero-knowledge" methods to authenticate nuclear warheads for verifying arms-control agreements without revealing sensitive information. Professors Kemp and Bernstein have also established a study group on force posture de-alerting to reduce the risk of accidental nuclear war.

At the Industrial Performance Center (IPC), Professor Lester continued his studies of innovation management and policy. As part of the work of MIT's Task Force on Production in the Innovation Economy, Professor Lester, IPC executive director Dr. Elizabeth Reynolds, and their students continued their research on the scale-up strategies of innovating firms.

Education

A total of 114 students pursued graduate degrees in nuclear science and engineering in the 2012–2013 academic year. Sixty-three percent of these students worked in the fission energy field, 23% in fusion and plasma physics, and 14% in other nuclear science and technology applications. The department awarded 11 SM degrees, 12 PhD degrees, and one ScD degree. Twenty-five students entered the graduate program in fall 2012.

A total of 27 students were enrolled in the undergraduate program during the past year, including 10 sophomores, 6 juniors, and 11 seniors. Eleven students completed the requirements for the bachelor's degree in nuclear science and engineering in AY2013.

New subjects introduced over the past year included 22.315 Applied Computational Fluid Dynamics and Heat Transfer, a graduate class taught by Professor Baglietto; 22.04 Nuclear Technology and Society, an undergraduate class taught by Professor Kemp; and

a suite of subjects in the field of nuclear security developed in collaboration with Penn State University and Texas A&M University and piloted at MIT by Drs. Lanza and Kohse of the Nuclear Reactor Laboratory.

In professional education, the department completed the 20th annual offering of the Reactor Technology Course for Utility Executives, delivered in collaboration with the Institute for Nuclear Power Operations. A new executive education course, the International Nuclear Leadership Education Program, was offered for the first time this year. The course aims to promote the safe and responsible use of nuclear power in countries that are new to the technology by bringing together senior leaders from these countries for an intensive introduction to the technical and institutional requirements for launching a successful national program. The course was attended by leaders from Jordan, Japan, Kenya, Nigeria, Slovakia, the United Arab Emirates, and Vietnam.

Faculty Awards, Honors, and Activities

Ronald Ballinger has been appointed by the Nuclear Regulatory Commission to the Advisory Committee on Reactor Safeguards for a four-year term.

Jacopo Buongiorno—along with Gregory DeWitt, Thomas McKrell, Lin-wen Hu, and Rae Joon Park—received the Best Paper Award at the 9th International Topical Meeting on Nuclear Thermal Hydraulics, Operation and Safety (NUTHOS-9) in Kaohsiung, Taiwan, September 9–13, 2012).

Paola Cappellaro, Bilge Yildiz, and Anne White organized the first Rising Stars in Nuclear Science and Engineering Symposium. Held at MIT in March 2013, the symposium featured research presentations by 12 outstanding young women researchers in the field.

Benoit Forget received the Landis Young Member Engineering Achievement Award from the American Nuclear Society.

Mujid Kazimi continues as a member of the DOE Nuclear Energy Advisory Committee and the International Advisory Board on nuclear energy to the government of the United Arab Emirates. He joined the visiting committee of the School of Nuclear Engineering of Purdue University.

Scott Kemp serves on the American Physical Society's Panel on Public Affairs, where he is a member of the five-person committee established to draft the American Physical Society's official position on climate change.

Richard Lester continues as a member of the Board on Science, Technology, and Economic Policy of the National Academy of Science.

Ju Li led a large team—including professors Golay, Ballinger, Baglietto, Forget, Lester, Yildiz, Smith, and Whyte, and Drs. Hanson and Lanza of NSE, along with researchers from the Moscow Engineering Physics Institute and elsewhere—which

won an international competition to establish a new center for research, education, and innovation in nuclear systems and materials at the Skolkovo Institute of Science and Technology.

Neil Todreas served as honorary chairman of two international nuclear thermal hydraulic conferences—the 9th International Topical Meeting on Nuclear Thermal Hydraulics, Operation and Safety (NUTHOS-9) held in September 2012 at Kaohsiung City, Taiwan, and the 15th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-15) in May 2013 in Pisa, Italy. Professor Todreas was also selected as one of the inaugural group of NURETH Fellows for his distinguished continuous contributions and support to the NURETH conference series.

Anne White received the PAI Outstanding Faculty Award, presented by the MIT student chapter of the American Nuclear Society.

Student Awards and Activities

The MIT student section of the American Nuclear Society hosted the American Nuclear Society 2013 Student Conference, with almost 650 participants from the United States and overseas. The conference set new records for the number of papers and posters presented.

In May 2013 William Boyd won an award for Best Paper at the International Conference for Mathematics and Computation Applied to Nuclear Engineering for his paper "A Massively Parallel Neutral Particle Transport Code for GPUs."

Yue Fan received the Manson Benedict Award for excellence in academic performance and professional promise by a graduate student in NSE. He was also awarded the Wigner Post-Doctoral Fellowship by Oak Ridge National Laboratory.

Lindsey Gilman received a 2013 Graduate Women of Excellence award, given to 47 graduate women at MIT who are nominated by their peers, faculty, and staff.

John Hanson received an Outstanding Poster Award at the 2012 Materials Research Society Fall Meeting for his presentation, "Investigating Bridging Elements Against H-assisted Intergranular Fracture in Nickel-Base Superalloys."

Lulu Li received the American Nuclear Society's Outstanding Grader award, presented by the MIT student chapter of the American Nuclear Society.

Ekaterina Paramonova received the MIT International Science and Technology Initiatives (MISTI) Program Ambassador Award, presented annually to an MIT student who exemplifies MISTI's mission and has served as an outstanding MISTI representative both abroad and at MIT.

Katia and Cameron McCord were awarded Advanced Certificates of Engineering Leadership for successfully completing the requirements of the two-year Bernard M. Gordon–MIT Engineering Leadership Program. Cameron French and Jake Jurewicz earned Certificates of Engineering Leadership for completing their first year in the program.

Ethan Peterson received the Roy Axford Award for excellent academic achievement by a senior in NSE. He was also awarded the National Scholar-Athlete Award by the National Football Foundation for his academic prowess and achievements on the football field.

Tat Nghia Nguyen and Carolyn Coyle received Outstanding UROP Awards for outstanding contributions to a research project by a junior or senior in NSE.

Kathryn Biegel, Minh Dinh, and Jedidiah Phillips received Outstanding UROP Awards for outstanding contributions to an NSE project by a freshman or sophomore in NSE.

Jeremy Roberts, Caleb Waugh, Giancarlo Lenci, and Lindsey Gilman received Outstanding Service Awards for exceptional service to the department.

Eugeny Sosnovsky received the Outstanding TA award for exceptional contributions as a teaching assistant in NSE.

John Stempien received an award for one of the best papers at the 2013 National American Nuclear Society (ANS) Student Conference.

Victoria Winters received an Undergraduate Poster Award at the annual meeting of the American Physical Society, Division of Plasma Physics, in Providence, RI. She also received the Irving Kaplan Award for academic excellence by an NSE junior and the Friends of Todai Global Leadership Award for summer research at the University of Tokyo.

Yang Yang was awarded an MIT-China Scholarship Council Fellowship for 2012–2013.

Derek Sutherland, Ruaridh MacDonald, Aditi Verma, and Alexander Salazar were finalists in the 2012 American Nuclear Society Student Design Competition for their project, Production of Biodiesel and Biogasoline via Coupling a LBE-cooled Reactor to Hydrogen and Biofuels Plants.

Giancarlo Lenci, Lindsey Gilman, Jeremy Roberts, and Caleb Waugh received Outstanding Student Service Awards in recognition of their exceptional service to the department.

Samuel Brinton, Ekaterina Paramonova, Nathan Gibson, and Mark Reed received Outstanding Student Service Awards from the department for their leadership in organizing the 2013 ANS National Student Conference. MIT's ANS Student Section

was recognized with a Samuel L. Glasstone Award Honorable Mention at the opening plenary of the ANS Annual Meeting for its work in organizing and hosting the 2013 ANS National Student Conference at MIT, the largest and most successful ANS student conference to date.

Sam Shaner was awarded a Ronald I. Heller Entrepreneurship Grant by the Martin Trust Center for MIT Entrepreneurship for his leadership in introducing MIT students to entrepreneurship. He also served as co-managing director of the MIT Clean Energy Prize.

A team led by Jacob DeWitte and Joe Yurko won the infrastructure and resources category in the 2013 MIT Clean Energy Prize competition and was also a finalist in the MIT $100K Business Plan Contest.

Richard K. Lester
Department Head
Japan Steel Industry Professor of Nuclear Science and Engineering