Department of Nuclear Science and Engineering

The Department of Nuclear Science and Engineering (NSE) provides educational opportunities for undergraduate and graduate students interested in advancing the frontiers of nuclear science and engineering and in developing applications of nuclear technology for the benefit of society and the environment. The department prepares its students to make contributions to the scientific fundamentals of nuclear engineering; to the development and engineering of nuclear systems for energy generation, security, health care, and other applications; and to the integration of nuclear systems into society and the natural environment.

In December 2017, the department (re)inaugurated the MIT Graphite Exponential Pile, timed to commemorate the 75th anniversary of criticality in the experiment that produced humankind's first controlled nuclear chain reaction—the first criticality of the Chicago Pile at the University of Chicago, on December 2, 1942. This was the culmination of months of effort by Professor Kord Smith, NSE students, and Nuclear Reactor Laboratory staff, and the event drew many NSE students, who worked hard at preparing the pile and who are excited about the hands-on education and research opportunity it provides.

Faculty and Administration

- Professor Ronald Ballinger retired in January 2018.
- Professor Areg Danagoulian was named a Norman C. Rasmussen Career Development Professor.
- Professor Zachary Hartwig was named to the John Clark Hardwick (1986) Professorship Career Development Chair.
- Professor Michael Short has been promoted to associate professor without tenure. He also was named a Norman C. Rasmussen Career Development Professor.
- Professor Bilge Yildiz was promoted to full professor.

Research Highlights

Professor Jacopo Buongiorno led the MIT Energy Initiative's study on the future of nuclear energy in a carbon-constrained world. The study involved seven faculty members from across the Institute, as well as two Harvard faculty members, six external consultants, and seven students. The study's findings were issued in a report, The Future of Nuclear Energy in a Carbon-Constrained World, in September 2018. The report is intended to serve as a balanced, fact-based, analysis-driven guide for stakeholders involved in nuclear energy. These stakeholders include policy makers, utilities, existing and start-up energy companies, regulators, investors, and other power-sector entities who must better understand the challenges and opportunities currently facing nuclear energy in the US and around the world. The report distills results and findings from more than two years of primary research, a review of the state of the art, and quantitative modeling and analysis.

Professor Buongiorno also completed a study on the effect of surface oxidation on critical heat flux (CHF) enhancement in in-vessel retention (IVR) accident scenarios. In certain severe-accident mitigation strategies, the decay heat is removed from the corium by conduction through the reactor pressure vessel (RPV) wall, and by flow boiling on the outer surface of the RPV. To prevent RPV failure, the boiling CHF limit must not be exceeded. Previous studies for prediction of CHF in IVR were predominantly based on data for stainless-steel heaters and deionized water coolant. However, the RPV is made of low-carbon steel, and its surface has an oxide layer that results from pre-service heat treatment as well as oxidation during service; this oxide layer renders the surface much more hydrophilic and rough than an un-oxidized stainless-steel surface, which can have a significant influence on boiling heat transfer. In this study, test heaters were fabricated from low-carbon steel (grade 18MnD5) and pre-oxidized in a controlled, high-temperature, humid-air environment, reproducing the prototypical surface oxides present on the outer surface of the RPV. The heaters were then tested in a flow boiling loop using the IVR water chemistry, that is, deionized water with the addition of boric acid and sodium tetraborate. The CHF was measured in the range of pressures, mass fluxes, inclination angles, and equilibrium qualities encompassing the IVR conditions. Up to 70% enhancement in CHF values was observed for pre-oxidized, low-carbon steel heaters in comparison with the stainless-steel control heaters. The effect of water chemistry on the CHF was found to be marginal. An empirical correlation fitting the CHF data for pre-oxidized, low-carbon steel surfaces with IVR water chemistry was also presented.

Professor Anne White leads the new Plasma Science and Fusion Center (PSFC) Magnetic Fusion Experimental Subdivision, coordinating on-campus aspects of collaborations with tokamak and stellarator experiments in the US and abroad. Professor White's research group focuses on the study of turbulent transport in fusion plasmas, with the goal of controlling the transport and improving the performance of tokamaks. The group's research includes diagnostic development that will enable new heat, particle, and momentum transport experiments, as well as investigations of non-diffusive transport in fusion plasmas. Integrated modeling using reduced transport models plays a key role in developing novel validation tools, some employing machine learning, for the design of future fusion devices, such as the International Thermonuclear Experimental Reactor and the advanced, robust, and compact (ARC) design. Her group is engaged in experimental research at four major tokamaks: the Alcator C-Mod at MIT, the Axially Symmetric Divertor Experiment (ASDEX) Upgrade, the DIII-D National Fusion Facility, and the National Spherical Torus Experiment and Upgrade (NSTX/NSTX-U) at Princeton University's Plasma Physics Laboratory. The team leads experiments, develops diagnostics, and leads validation projects using advanced turbulence simulation codes.

Professor White's graduate student Juan Ruiz Ruiz is using turbulence data sets from a high-k scattering diagnostic (from NSTX) that measures the electron scale density fluctuations directly to compare them with theory and simulation. At the DIII-D tokamak, Professor White's graduate student Pablo Rodriguez Fernandez is collaborating with General Atomics scientist Craig Petty and Princeton's Plasma Physics Laboratory scientist Brian Grierson on understanding the propagation of heat pulses stimulated using electron cyclotron heating. Rodriguez Fernandez recently published a paper in *Physical Review Letters* on the modeling of C-Mod experiments that demonstrated that local turbulent transport models can reproduce both steady-state and perturbed heat transport in tokamak plasmas. At the ASDEX Upgrade tokamak, graduate student Alex Creely and postdoctoral associate Simon Freethy developed a multichannel high-resolution radiometer that allows for measurement of temperature fluctuations; coupled with other instruments at the tokamak, the radiometer allows for measurements of the phase angle between temperature and density turbulence. These measurements have been used to validate the gyrokinetic electromagnetic numerical experiment code. The work has been published in *Physics of Plasmas* and presented at several domestic and international conferences. Professor White is also involved in collaborations at the new W7-X stellarator located in Germany. In addition, Professor White supervises Undergraduate Research Opportunities Program (UROP) projects involving the development of small, table-top plasma devices such as fusors—electrostatic inertial confinement devices—for aid in classroom teaching at MIT.

Professor Nuno Loureiro continued his research on magnetic reconnection and turbulence in magnetized plasmas. Two investigations worth highlighting are his work with postdoctoral researcher Pallavi Bhat on the theory of magnetic reconnection in so-called semi-collisional regimes, work that is pertinent to existing and upcoming experiments; and the theoretical prediction of the existence of a range of scales in turbulent plasmas where the turbulent cascade is mediated by magnetic reconnection. Preliminary numerical simulations by Loureiro's collaborators, as well as by independent groups, and data from the solar wind seem to support these ideas.

Professor Loureiro has continued to collaborate with Professor Sergey Lebedev's group at Imperial College London on laboratory experiments of magnetic reconnection conducted with two interacting Z-pinch plasmas. This has led to interesting observations of plasmoid formation in parameter regimes consistent with theoretical predictions made by Professor Loureiro and to observations of anomalous ion heating, which is not understood and is under investigation.

Professor Ian Hutchinson's group investigates the basic nonlinear physics of flowing plasma, using their particle in cell codes and analytic theory. The disruption of plasma wakes by nonlinear growth of soliton-like electron holes and their observation in magnetic reconnection has led to renewed interest in these free-standing, self-sustaining phenomena. His group has developed a theoretical understanding of the kinematics of electron holes that enables one to apply momentum conservation to predict how their velocity changes. The kinematic theory explains why electron holes cannot move more slowly than a minimum threshold speed with respect to an ion stream. A region of oscillating velocity nonlinear instability separates electron holes from the even slower motion of ion acoustic solitons, and this unstable region answers the long-standing question of how electron holes differ from fluid solitons. Professor Hutchinson's analysis predicted that the solar wind wake of the moon should be a region of intense electron hole production. His NASA-funded project to analyze satellite data has recently confirmed this prediction from in situ observations.

Professor Zachary Hartwig leads multiple efforts in NSE and at PSFC, where he holds a co-appointment. These efforts are principally focused on accelerating the development of fusion energy.

Professor Hartwig had been instrumental in establishing three new major fusion energy initiatives at NSE and PSFC. He is a co-founder of a new private company spun off from PSFC, Commonwealth Fusion Systems, which is raising a substantial amount of capital to commercialize fusion energy. Commonwealth Fusion Systems and PSFC will be close partners in the second major initiative: the aggressive development of a new generation of high-field superconducting fusion magnets based on high-temperature superconductors. Professor Hartwig is overseeing the project along with Professor Dennis Whyte, who is the head of NSE and the director of PSFC; he is also leading the development of superconducting magnet technology. If successful, this effort will result in the design and construction of SPARC (Soonest/Smallest Private-Funded Affordable Robust Compact), a 100 MW, net-energy fusion tokamak that is predicted to produce controlled fusion energy for the first time in human history (Figure 1). The third and final initiative is co-leading the Laboratory for Innovation in Fusion Technologies at the PSFC. The laboratory will pursue medium-term PhD-level research projects in parallel with SPARC and high-temperature superconductor magnet research and development to accelerate the development of fusion energy. The Laboratory for Innovation in Fusion Technologies is expected to sponsor at least six new doctoral students' projects in various areas of fusion technology in the next year.

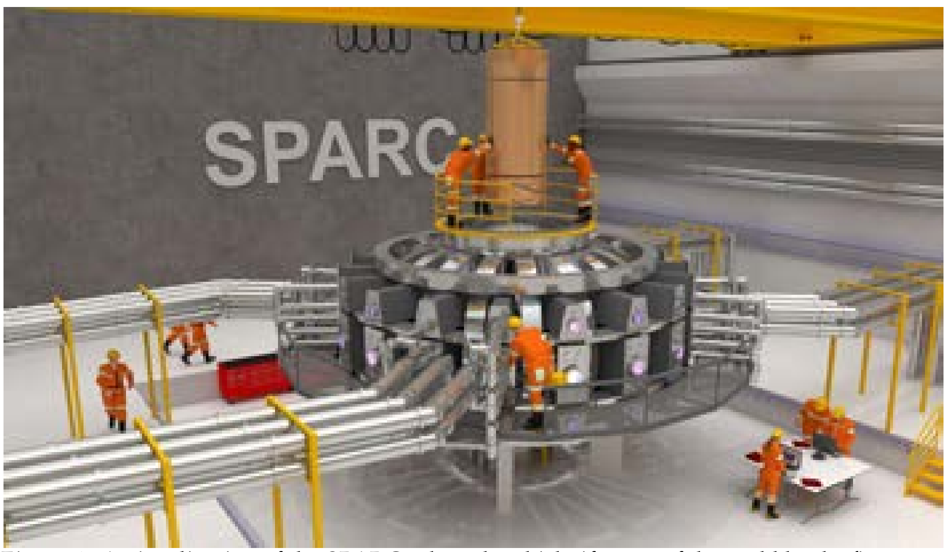

Figure 1: A visualization of the SPARC tokamak, which, if successful, would be the first demonstration of controlled net fusion energy in human history. (Credit: Ken Filar, SB '81.)

Professor Hartwig is also head of the The Vault, a unique laboratory specializing in the application of particle accelerators in the modification and measurement of materials in fusion energy, including plasma-facing materials (tungsten, molybdenum), structural materials (steels), and functional materials (optical glasses, superconductors). Current graduate student research projects include developing advanced in situ measurement techniques to understand the evolution of plasma-facing materials in fusion devices, the application of a new generation of intermediate energy—from 10 to 30 megaelectronvolt (MeV)—superconducting proton cyclotrons to the study of radiation damage in plasma-facing materials, and developing new techniques for the irradiation of high-temperature superconductors under more realistic conditions for fusion magnet applications. The laboratory continues to operate its three accelerators (a two MeV tandem accelerator, a 13 MeV proton cyclotron, and a 14.1 MeV neutron generator) in support of internal research and as an external user facility to provide the unique capabilities of the vault to variety of users.

Charles W. Forsberg, principal research scientist in NSE, leads the Fluoride Salt-Cooled High-Temperature Reactor Integrated Research Project, which includes three other universities and multiple sponsors. The goals of this project are to develop a high-temperature reactor to provide zero-carbon variable electricity and high-temperature heat while the reactor operates at full capacity to minimize costs. Forsberg is examining a nuclear air-Brayton combined-cycle plant with two different heat storage systems (one for the high-temperature turbine and one for the lower-temperature steam cycle); the plant can buy or sell electricity depending on electricity market prices. This enables the reactor to provide dispatchable electricity to the grid, replacing the historical role of fossil fuels, and to balance electricity production with demand in grids with high wind or solar output when high wind or solar conditions create excess electricity. Work is under way on developing the reactor with other universities and industry. Work at MIT includes irradiating materials in the MIT reactor in molten salt, performing experiments to understand tritium behavior, and working to understand radiative heat transport in liquid salts (part of safety analysis)—all at 700°C or higher temperatures. In parallel, work is under way to develop heat storage systems for existing light-water reactors to enable base-load reactors to provide variable electricity to the grid. These systems have the capability to enable the reactor to buy or sell electricity depending on demand, enabling nuclear plants to replace fossil-fuel plants in the role of providing variable dispatchable electricity to the grid and making nuclear plants the enabling technology for large-scale use of wind and solar by providing low-cost energy storage.

Professor Emilio Baglietto's group has made considerable advancements in the modeling of multiphase flow, delivering groundbreaking accuracy in the three-dimensional model of gas–liquid flow distribution through a new generation of physical closures. The approach is applicable across a large range of systems but focused in particular on the design of advanced nuclear fuel, to improve efficiency and the margin to failure. The approach extends to the pioneering capability of predicting boiling heat transfer up to CHF with a three-dimensional approach based on first principles. Leveraging the experimental work of Professor Matteo Bucci, Professor Baglietto's group has been able to demonstrate the soundness and accuracy of the methods. The work was first presented as the keynote lecture at the 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics in Xi'an, China, in September 2017. The work is largely sponsored by the Consortium for Advanced Simulation of Light-Water Reactors, but support also comes from the Knoll Atomic Power Laboratory and from private industry (Mitsubishi Heavy Industries). The Baglietto group's modeling work is a broad and multifaceted effort to which five doctoral students, three master's degree students, and one postdoctoral associate contribute.

Professor Baglietto's work on hybrid turbulence modeling and its extension to computational fluid dynamics uncertainty quantification are supported by TerraPower, Mitsubishi Heavy Industries, and a Nuclear Energy University Project in collaboration with the University of Wisconsin–Madison. This new family of models is the enabling technology to extend the use of computational fluid dynamics to complete reactor systems and safety analysis transients. The project involves two doctoral students and one master's degree student.

The Computational Reactor Physics Group, led by Professors Benoit Forget and Kord Smith, pursued the development of high-fidelity open source software using both deterministic (open method of characteristics [MOC]) and stochastic (open Monte Carlo [MC]) methods. Recent highlights in OpenMOC include two successful paths for high-fidelity full-core light-water reactor simulations using the method of characteristics on petascale architectures. Both approaches require on-node parallelization and domain decomposition. One relies on a priori two-dimensional ray tracing with on-the-fly axial projection on a fixed angular quadrature; the other relies on the novel random ray method that performs full three-dimensional on-the-fly ray tracing in arbitrarily determined directions. Recent highlights in OpenMC include

- the development of a comprehensive windowed multipole library that enables efficient reactor simulations with materials at various temperatures;
- a multi-physics coupling framework that transfers information to any unstructured mesh using an orthogonal basis set and can track neutrons in a continuously varying material; and
- a time-dependent capability for short transients based on advancing an equivalent coarse mesh diffusion operator on fine time steps with occasional coarse time step updates from Monte Carlo.

Novel cross section generation capabilities based on the identification of clusters via machine learning were also developed to reduce data size and accelerate convergence of multigroup parameters. This work also led to the quantification of the error associated with neglecting the angular dependence of the total cross section in the condensation process and the development of a novel equivalence factor for use in deterministic calculations.

Professor Matteo Bucci launched the Red Laboratory, which primarily focuses on studying heat transfer phenomena. The laboratory develops cutting-edge experimental capabilities and high-resolution diagnostics to investigate boiling phenomena in prototypical nuclear reactor conditions. The core of Red Laboratory research focuses on the enhancement of the boiling performance in nuclear systems, that is, in flow boiling, high-pressure conditions. Professor Bucci and Professor Evelyn Wang from the Department of Mechanical Engineering are collaborating on a project sponsored by Exelon to develop a CHF-enhancing treatment for nuclear reactor claddings. They have shown that flow boiling CHF can be enhanced by engineering the boiling surface at the micro- and nano-scales. Professor Bucci is also leading a US Department of Energy project aimed at assessing the thermal hydraulics performance of accident-tolerant materials for the next generation of nuclear reactor fuel claddings. The project is carried out in cooperation with the University of Wisconsin–Madison, Westinghouse Electric Company, and General Atomics. The Red Laboratory’s capabilities are also crucially important for other Department of Energy projects. Recently, the team completed a first-of-a-kind experimental investigation of subcooled flow boiling and CHF using advanced infrared and high-speed video diagnostics. Data were generated at ambient pressure, revealing new details of heat flux partitioning on the boiling surface. This effort will continue with a focus on high-pressure conditions. This research is relevant to the design and the safety analysis of both boiling-water reactors and pressurized-water reactors and is sponsored by the Consortium for Advanced Simulations of Light-Water Reactors, a Department of Energy hub.

A similar effort has focused on the study of transient boiling heat transfer during exponential power escalations. This research, sponsored by the French Commissariat a l'Energie Atomique (French Alternative Energies and Atomic Energy Commission), is relevant to the safety of experimental nuclear reactors used for material testing and the production of radioisotopes used in medical diagnostics. A new research initiative focuses on the development of artificial intelligence algorithms to process experimental data online in real time. This capability is key to accelerating the research output, and consequently, the path toward the deployment of new advanced heat transfer solutions in nuclear reactors.

Assistant Professor Koroush Shirvan continued to lead a team of NSE faculty and research scientists, as well as representatives from four other universities, in a DOE-sponsored research program on accident-tolerant fuel for light-water reactors. The project is analyzing and testing the performance of several engineered coatings for the fuel cladding that will result in a drastic reduction of hydrogen generation during severe accidents, thus mitigating the consequences of accidents like that at the Fukushima Daiichi Nuclear Power Plant in Japan. So far, the project findings show that the combination of chromia-doped uranium dioxide and chromium-coated Zircaloy is a promising accident-tolerant fuel concept. Professor Shirvan also continued his study on a novel reduced-moderation boiling-water reactor concept, supported by Hitachi Ltd., by demonstrating its fuel performance feasibility using multiscale multi-physics simulations. He is continuing his work with the Free Form Fiber company under a Small Business Innovation Research grant to utilize fiber-additive manufacturing technology to fabricate a first-of-kind ceramic fuel form with higher economic potential than the tristructural-isotropic fuels that are commonly used in high-temperature gas reactors. He has also started a new project supported by Électricité de France S.A. (Electricity of France) on optimization of a small modular reactor. The project will focus on improving the economics of the small modular reactor through a combination of advanced construction and manufacturing, compact power cycle components, and innovative safety management strategies

Professor Paola Cappellaro's Quantum Engineering Group works on developing novel quantum devices and their control. In the past year, her group has developed quantum error correction schemes that can help quantum sensors achieve better precision. In addition, the group has devised a combinatorial sensor that exploits an ancillary quantum system to stabilize the primary quantum sensor, achieving stable measurements over hours, beyond what is possible with competing sensors based on microelectromechanical systems. This combinatorial sensor could be used to engineer a stable and robust spin gyroscope. Further improvements in the feedback-based stabilization protocol could be achieved by exploiting inference and machine learning techniques. Moving beyond the measurement of a single scalar field (parameter estimation), the group worked to develop an efficient method for quantum system identification (where all parameters of a quantum system Hamiltonian have to be revealed) and a scheme for vector magnetometry that does not require an ensemble of sensors, thus maintaining the high spatial resolution afforded by single quantum sensors.

A second area of Professor Cappellaro's research has focused on quantum thermodynamics, exploring quantum correlations influences on the precision of temperature sensing. More broadly, she is studying thermodynamic properties of many-body quantum systems out of equilibrium. In particular, exploiting Hamiltonian engineering techniques, Professor Cappellaro explored the transition from a thermalizing system to a prethermal system, which displays quasi-conserved quantities at exponentially long times. Like the localized systems investigated in the past year, these long-lived quantum systems are promising for quantum technology applications, such as quantum memories.

Professor Ju Li's group has used an angstrom-sized electron beam to displace and manipulate single atoms on two-dimensional materials such as graphene and boron nitride. Atomic engineering addresses the nuclear position, nuclear spin, and electronic structure of individual atoms for engineering applications, in which controlling the precise position of a single atom is a crucial step. Professor Li's group made a theoretical prediction in 2014 that several transition-metal dichalcogenides, such as a tungsten ditelluride monolayer, are topological insulators with unique quantum-edge conduction characters. This prediction has been experimentally verified by several groups from Stanford University, the University of California, Berkeley, the University of Washington, Princeton University, MIT, and elsewhere. The first author of the 2014 paper, Xiaofeng Qian, who holds a PhD from NSE and is a former NSE postdoctoral associate, is now an assistant professor at Texas A&M University; he recently received the National Science Foundation CAREER award. The Li group has also recently developed porous electrodes for trapping heavy metals (uranium, cesium, chromium) in water with high specificity, and with the ability to desorb and reuse multiple times. The Li group has continued to develop lab-on-a-chip devices to image and characterize buried solid–liquid and solid–liquid–gas interfaces under electrochemical potential bias. They have applied the technique to study the formation and stability of metal passivation layers in the presence of fluids during mechanical deformation, gas bubble nucleation, growth, detachment, and erosion. Simultaneously, the Li group has continued to develop bulk nanocomposite materials with a metallic matrix (aluminum, iron, zirconium, copper) and zero-dimensional, one-dimensional, and two-dimensional ceramic dispersions that have shown superior room-temperature strength and ductility and high-temperature creep strength, as well as superior radiation and helium resistance. Irradiation of Materials in 3D, a parallel Monte Carlo software that the Li group developed for efficient simulations of primary radiation damage, can describe arbitrary three-dimensional geometries and microstructures; it has been applied to study nano-beam and nano-target effects in ion irradiation.

Professor Mingda Li's group, the Energy Nano Group, is working on materials defects engineering, aiming to utilize defects as effective tools to improve materials functionalities, both theoretically and experimentally. Theoretically, Professor Li has proposed a new quasiparticle, "dislon," as quantized dislocations. This study is a unified quantum field for a common defect called crystal dislocation. It has attracted considerable attention in the field, including a research highlight on the Department of Energy's Office of Science homepage, one publication selected as a *New Journal of Physics* highlight of 2017, one invited review article by the *Journal of Physics: Condensed Matter*, and one invited talk at the Materials Research Society meeting, among other invited talks. Experimentally, the laboratory setup was finished within half a year, including the installation of a physical property measurement system that enables low-temperature electrical and thermal transport measurement, and a tetra arc furnace allowing for growth of high-melting-temperature single crystals.

Professor Michael W. Golay continued his work on improving decision-support methods, supervising three doctoral students in the areas of probabilistic strategy assessment, system design methods, and nuclear power plant multiunit risk assessment. He organized a symposium on recognizing the value of nuclear energy and invited participants from political advocacy nonprofit organizations, foundations, the social sciences—especially communications—and from nuclear energy organizations. Approximately 80 participants attended. The resulting presentations and discussions are being summarized in a proceedings volume.

Professors Michael Golay, Jacopo Buongiorno, and Neil Todreas, working with students, continued their work on the development of the offshore nuclear plant concept. Work during this past year was focused on the creation of a comprehensive security strategy to protect against attacks on an offshore nuclear plant and on methods for systematically including stakeholder requirements when creating an offshore nuclear plant project from initial design through commissioning.

Professor Yildiz's research focuses on laying the scientific groundwork and proof-of-principle material systems for the next generation of high-efficiency devices for energy conversion and information processing, based on solid-state ionic-electronic materials. The scientific insights derived from her research affect the design of novel surface/interface chemistries for

- efficient and durable solid oxide fuel and electrolysis cells;
- redox-based memristive information storage and logic;
- efficient and durable thermo/electrochemical splitting of water and carbon dioxide;
- high-energy density and high power density solid-state batteries; and
- corrosion-resistant films in a wide range of extreme environments, such as nuclear energy generation, concentrated solar energy, and oil exploration.

Key advancements in Professor Yildiz's laboratory this year were on resolving charge transfer and defect chemistry at oxide thin-film hetero-interfaces, important for fuel cells and resistive switching devices; electrochemical control of oxygen content crossing multiple phase boundaries in oxides, giving rise to many orders of change in electronic conductance, important for reliable electronic devices; resolving the electro-chemo-mechanical effects of small cations such as lithium in passive oxide thin films, important for corrosion resistance properties; and resolving the relation of synthesis conditions, interface chemistry, and charge transfer kinetics at solid electrolyte interfaces, important for high-energy density and safe solid-state batteries for energy storage.

Senior Research Scientist Richard C. Lanza, in collaboration with students in NSE and the Media Lab and with Massachusetts General Hospital, is carrying out research to develop low-cost digital x-ray systems for patients in the developing world. The approach is to leverage advances in consumer electronics to develop an approach that will enable diagnostic medical x-ray imaging to be brought to remote areas in developing countries and made available to the two-thirds of the human population that now has no access to diagnostic imaging. The goal is to bring costs down while still maintaining the quality of x-ray imaging. This year, the participants in the project included three undergraduate students in NSE, two students in the Media Lab, and a collaborator at Massachusetts General Hospital, Dr. Raj Gupta. Figure 2 shows an approach that they have been pursuing. A conventional, consumer digital single-lens reflex camera is used to capture an image of an x-ray screen and the resulting digital image is sent by cell phone to a radiologist for reading. The researchers are primarily interested in diagnostic imaging for tuberculosis, a disease associated with poverty worldwide.

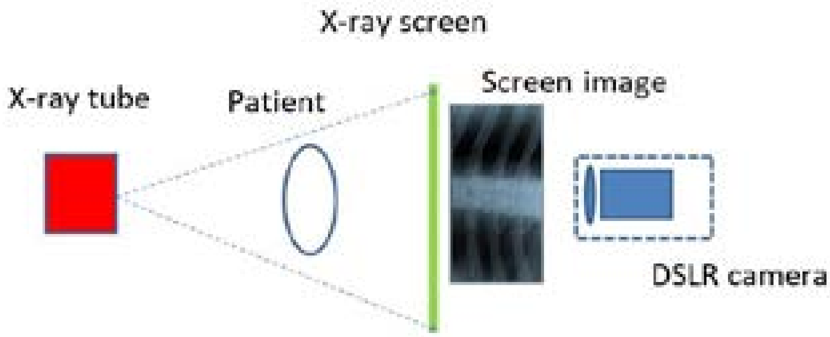

Figure 2: Schematic of the approach to low-cost imaging. The two-dimensional image is formed on a conventional x-ray screen and imaged by a lens-coupled digital single-lens reflex camera.

Richard Lanza is also a member of a multidisciplinary team, with participants from NSE from the Department of Electrical Engineering and Computer Science, the Department of Mechanical Engineering, and Massachusetts General Hospital, that is developing a state-of-the-art approach to nanoscale x-ray tomosynthesis for rapid assessment of integrated circuit (IC) dice. The project is supported by the Rapid Analysis of Various Emerging Nanoelectronics Program of the Intelligence Advanced Research Projects Activity in the Office of the Director of National Intelligence. The project has as its goal the development of tools to image current and future integrated circuit chips rapidly—in particular, to develop a prototype analysis tool for acquiring the images and reconstructing all layers (up to 13 metal layers) from a 10-nanometer (nm) integrated circuit chip within an analysis area of one centimeter squared in less than 25 days. The MIT approach is based on an x-ray tomography system that is capable of resolution down to 10 nm in three dimensions, one to two orders of magnitude beyond the current state of the art. Images of chips will be obtained using both transmission imaging and phase imaging to provide detailed images of chips to confirm that they are consistent with the original design. The goal is not only to verify the chips, but also to enhance the security of critical chip designs. The overall view of the system is shown in Figure 3.

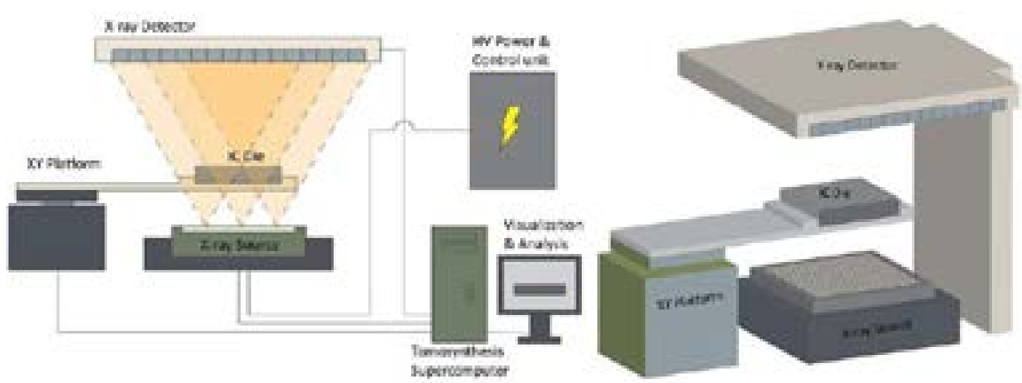

Figure 3: Overall layout of MIT chip imaging system.

Professor Emeritus Sidney Yip continued to be active in professional service as a faculty member in NSE and in collaborative research with colleagues and associates across the Institute.

Professor Emeritus Michael J. Driscoll co-supervised a student thesis written by Kendall Fears SB that developed and evaluated a conceptual design for a latent-heat thermal-energy storage unit based on the use of molten aluminum. The design is suitable for use with advanced nuclear reactors and solar power towers. This design is considerably more compact than designs using sensible heat, and, because of its constant temperature, is well suited to coupling with power conversion systems (e.g., a Rankine steam or supercritical carbon dioxide conversion system). Professor Driscoll also worked with several students to update the prospects for economically competitive recovery of uranium from seawater; their efforts were most recently in support of research projects led by Professor Alex Slocum of Mechanical Engineering.

Education

A total of 125 students pursued graduate degrees in NSE in academic year 2018. Forty-three percent of these students worked in the fission energy field, 21% in fusion and plasma physics, and 36% in other nuclear science and technology applications, including materials, nuclear technology management and policy, nuclear security, and quantum engineering. The department awarded three SM degrees and seven PhD degrees in September 2017. Twenty-four students entered the graduate program in fall 2017.

A total of 28 students were enrolled in the undergraduate program during the past year, including eight sophomores, seven juniors, 12 seniors, and one fifth-year student. Seven students completed the requirements for the bachelor's degree in Nuclear Science and Engineering from September 2017 through June 2018.

The department continued to provide communication support to its students through the NSE Communication Lab, a peer-coaching program launched in 2014 to help students and postdoctoral associates with their writing, speaking, and visual design needs. Staffed by six graduate students serving as communication fellows, the NSE Communication Lab held 182 one-on-one coaching sessions with 66 clients, representing 36% of NSE graduate students and 61% of NSE undergraduate students. A return rate of 65% testifies to their satisfaction with the service. The Communication Lab also offered field-specific communication workshops and collaborated with instructors from eight undergraduate and graduate subjects to strengthen the communication aspects of the curriculum. In particular, NSE Communication Lab Manager Marina Dang continued to implement reforms in 22.911 Seminar in Nuclear Science and Engineering. In a class survey, 86% of respondents felt that their presentation skills had improved as a result of taking this class. In addition, NSE helped to host the second annual MIT Communication Lab Summer Institute, where outside institutions learn how to adapt the Communication Lab model for their own science, technology, engineering, and mathematics communities.

Professors Jacopo Buongiorno, Anne White, Michael Short, and Paola Cappellaro co-developed 22.011x Nuclear Energy: Science, Systems and Society, a massive open online course for edX. Professor Loureiro continued the development of a new graduate subject on advanced topics in plasma physics. Professor Baglietto dedicated particular efforts to advance

22.315 Applied Computational Fluid Dynamics and Heat Transfer. The class has received extremely positive feedback and will continue to evolve to cover the growing student interest.

Professor Golay led the sustainable energy subjects (22.081J/22.811J) with Professor Gregory Stephanopoulos, supported by a large cast of special lecturers from throughout the Institute. The undergraduate and graduate versions of the subjects attracted approximately 35 students each, primarily from the School of Engineering and the Sloan School of Management, but also from Harvard University. The emphasis of the classes is on means of meeting energy needs, particularly in the face of growing climate change. These subjects are likely the largest interdisciplinary electives at MIT. However, definitive data about this are unavailable.

Professor Golay also directed the 26th offering of the Reactor Technology Course for Utility Executives and the 20th offering of the Nuclear Operational Risk Management course under the Executive Education program. Both courses are directed toward utility managers and executives, aiding them in improving their decision-support methods, and are offered jointly with the Institute for Nuclear Power Operations. A course derived from the Nuclear Operational Risk Management course was created and offered under the leadership of Professor Golay for use by the US Nuclear Regulatory Commission. The initial course offering attracted approximately 35 attendees from the agency. It is being revised for subsequent offerings throughout the agency.

Professor Koroush Shirvan continued his multiple summer education initiatives as co-director of the reactor technology course for utility executives, the co-organizer of the Consortium for Advanced Simulation of Light-Water Reactors Institute, and the co-organizer of the Nuclear Innovation Bootcamp. The latter two activities were held at North Carolina State University and the University of California, Berkley; they were attended by nuclear engineering undergraduate and graduate students from across the world.

Faculty Awards, Honors, and Activities

Professor Emilio Baglietto received the Ruth and Joel Spira Award for Distinguished Teaching. Professor Baglietto serves in the role of thermal hydraulics focus area lead for the Consortium for Advanced Simulation of Light-Water Reactors. He also received an MIT Commitment to Caring Award for academic year 2018.

Professor Matteo Bucci received the PAI Outstanding Faculty Award, presented by the student chapter of the American Nuclear Society.

Professor Buongiorno received the Best Paper Award at the 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics. He also completed many invited talks on nuclear energy, including:

- Can Nuclear Energy Thrive in a Carbon-Constrained World? Findings from a New MIT Study. 49th Annual Meeting on Nuclear Technology; Berlin, Germany; May 29, 2018 (plenary session).
- Is There a Future for Nuclear in a Carbon-Constrained World? Findings from a New MIT Study. International Congress on Advances in Nuclear Power Plants 2018; Charlotte, NC; April 9, 2018 (plenary session).

- Nuclear Energy at the Carbon Crossroads: Thrive or Decline? Yale University; March 29, 2018.
- Can Nuclear Energy Thrive in a Carbon-Constrained World? Findings from a New MIT Study. Forum of Indian Nuclear Industry; Kirloskar Brothers Limited Corporate Office; Mumbai, India; January 19, 2018.
- Is Nuclear an Attractive Clean-Energy Option for Singapore? National University of Singapore; January 16, 2018.
- Reducing the Cost of New Nuclear: Innovations that Could Make a Difference. Royal Academy of Engineering; London, UK; November 8, 2017.
- Nuclear Energy in a Carbon-Constrained World: Thrive or Decline? Findings from a New MIT Study. Commissariat a l'Energie Atomique; Saclay, France; October 13, 2017.
- Can Nuclear Energy Thrive in a Carbon-Constrained World? Findings from a New MIT Study. University of Houston, TX; October 5, 2017.

Professor Paola Cappellaro was a recipient of MIT's Commitment to Caring Award in academic year 2018. Professor Ju Li was given the Committment to Caring Award by the Office of Graduate Education. He gave a plenary talk, Elastic Strain Engineering, at the Chinese Materials Conference 2017, in Yinchuan, China.

Professor Michael Short received the Junior Bose Award for Outstanding Contributor to Education. The eligible group is MIT engineering faculty members who are being proposed for promotion to associate professor without tenure.

Professor Anne White served as a member of the Program Committee for the American Physical Society Division of Plasma Physics. She was a reviewer for the 2017 National Academies report, *Interim Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*. She also began service as a member of the Fusion Energy Sciences Advisory Committee, which provides independent advice to the director of the Office of Science, US Department of Energy, on complex scientific and technological issues that arise in the planning, implementation, and management of the fusion energy sciences program.

Professor Bilge Yildiz and her students won the Ross Coffin Purdy Award of the American Ceramic Society, awarded for the most valuable contribution to ceramic technical literature published two years before to the selection year.

Professor Sidney Yip served on the Advisory Board for the Department of Nuclear Engineering and Radiological Sciences at the University of Michigan. He represented NSE at the School of Engineering Ad Hoc Committee on Faculty Awards and Recognition. As a member of the Concrete Sustainability Hub and the Kuwait-MIT Signature Project, his research focuses on mesoscale modeling and simulation of soft-matter rheology. He is the co–editor-in-chief of the *Handbook of Materials Modeling, Second Edition*, a reference work of more than 4,000-plus pages.

Student Awards and Activities

Alex Creely received the Hugh Hampton Young Memorial Fund Fellowship and the 2018 Itoh Project Prize (European Physical Society Conference on Plasma Physics).

Cody Dennett accepted a First Place Innovation in Nuclear Technology R&D Award in the category of Materials Protection, Control, and Accountability from the US Department of Energy's Office of Nuclear Technology Research and Development.

Philip Ducru received the MIT Water Innovation Prize ($7,500) for the project Velaron, which proposes smart monitoring for aquaculture.

Silvia Espinosa received the Spanish Nuclear Society National Award for the Best PhD Thesis in Nuclear Science and Engineering. This national award brings with it the opportunity of giving an invited talk at the Spanish Nuclear Society annual meeting in September 2018 and in the Spanish Nuclear Society seminar series, Nuclear Thursdays. Espinosa also received the highly selective Rafael del Pino Fellowship, 2017–2019.

Pablo Rodrequez Fernandez received the Manson Benedict Award, presented to a graduate student for excellence in academic performance and professional promise in nuclear science and engineering. He was also awarded the Young Engineer Early Career Achievement Award by the alumni association at his former university in Madrid, the Universidad Politécnica de Madrid. He has appeared on Spanish TV, in a show called *Enviado Especial*, talking about fusion at the MIT PSFC in an episode called "Laboratory of the Future." He has also been interviewed by the Madrid public radio station in Madrid, Spain, to discuss fusion and its prospects for the future.

Micah Gale received the Outstanding Undergraduate Research Opportunities Program Award for outstanding contributions to a research project by a junior or senior in NSE.

Sara Hauptman received the Irving Kaplan Award for academic achievement by a junior in NSE.

Richard Ibekwe received the Roy Axford Award for academic achievement by a senior in NSE.

Steven Jepeal received the Outstanding Grader of the Year Award, presented by the student chapter of the American Nuclear Society.

Miriam Kreher received the DOE Computational Science Graduate Fellowship. She also won the MIT section of the American Nuclear Society's Glasstone Award for Best Student Section in the country. The MIT branch of the American Nuclear Society serves as the department's graduate student organization as well as a national student section of the ANS.

Lucio Milanese received the Outstanding Teaching Assistant Award for exceptional contributions as a teaching assistant in NSE.

Isaac Meyer was a member of the Nuclear Engineering Student delegation to Washington, DC.

Eli Sanchez received the American Nuclear Society Robert A. Dannels Memorial Fellowship and the Health Physics Society Fellowship for 2018–2019.

Ben Sheffer received the Outstanding Undergraduate Research Opportunities Program Award for outstanding contributions to an NSE project by a freshman or sophomore.

Jason Vavrek won an award for Best Student Presentation at the 2017 Consortium for Verification Technology Workshop and an award for Best Poster at the 2018 NSE Research Expo.

Chi Wang received the Best Paper Award at the 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (second author) and the MIT Office of Graduate Education Ho-Ching and Han-Ching Fund Award.

Ka-Yen Yau, Guillaume Giudicelli, and Patrick White received Outstanding Student Service Awards in recognition of exceptional service to the department.

Dennis G. Whyte
Department Head
Hitachi American Professor of Engineering