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 the field; 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 fall 2018, the department celebrated the 60th anniversary of its founding. As part of the celebration, the department dedicated its conference room to Manson Benedict, the first department head, in commemoration of his legacy of scientific excellence, comradery, and collegiality.

Faculty and Administration

- Senior Research Scientist Richard Lanza retired in June 2019.
- Professor Michael Short was named the Class of 1942 Career Development Professor.

Research Highlights

Professor Jacopo Buongiorno and his team finished the MIT 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 was produced by MIT to serve as a balanced, fact-based, analysis-driven guide for stakeholders involved in nuclear energy. Following the release of the report in September 2018, a series of rollout events were held in the United States, Asia, and Europe. Since then, more than 30 presentations have been held with a myriad of stakeholders in industry, government, academia, and think tanks. The study's findings have been featured in dozens of articles in the press.

In fall 2018, Professor Buongiorno launched a new project (sponsored by the Tokyo Electric Power Company [TEPCO]) focused on Japan's nuclear energy systems for 2030 and beyond. The project identifies three new missions for nuclear plants that will operate in the Japanese energy market in the 2030s and beyond. They are: (1) flexible electricity generation at existing power plant sites to replace retiring coal/natural gas capacity and to complement variable generation from solar and wind; (2) flexible co-generation of electricity and heat at industrial sites to support the production of valuable products, including hydrogen for transportation; and (3) generation of power and heat for niche markets such as remote communities/islands, military bases, mining sites, disaster relief, district heating, data centers, and freight ship propulsion. After assessing a broad set of reactor technologies, three were selected as satisfying the above missions, respectively: (1) a small modular boiling-water reactor for flexible electricity generation, (2) a high-temperature gas-cooled reactor for co-generation of electricity and heat at industry sites, and (3) a heat pipe micro-reactor for niche markets.

It is expected that such technologies can be deployed commercially in Japan by 2030 and will have a high likelihood of meeting the important requirements for economics (i.e., cost competitiveness with liquified natural gas, low operation, and maintenance cost), operational capabilities (i.e., load following, grid resilience), safety, and security (i.e., insensitivity to external events, emergency planning zone limited to the site boundary). We developed notional layouts for three representative sites in Japan—TEPCO's Higashidori power plant, Mitsubishi Chemical Company's Kashima plant, and TEPCO's Hachijō-jima power plant—at which commercial demonstration of these reactor technologies could take place. The site layouts were informed by consideration of optimal construction and operations. Particular emphasis was placed on evaluating the merits of embedding the nuclear island below ground to reduce seismic loads, reduce reactor building cost, and enhance physical security. Lastly, several innovations in automation and digitalization of plant operation and maintenance were explored in order to make new nuclear plants more cost effective and valuable to Japan.

Professor Anne White continues to lead the Plasma Science and Fusion Center's (PSFC) Magnetic Fusion Experimental subdivision, coordinating on-campus aspects collaborations with tokamak and stellarator experiments in the US and abroad. Since January 1, 2019, Professor White has served as the PSFC associate director for education and outreach. 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.

Professor White's graduate student Juan Ruiz Ruiz collaborated with Walter Guttenfelder of the Princeton Plasma Physics Laboratory (PPPL) to compare electron-scale density fluctuation measurements from the National Spherical Torus Experiment directly with theory and simulation. Ruiz successfully defended his thesis in the Spring and is now pursuing postdoctoral research at Oxford University. White's graduate student Pablo Rodriguez-Fernandez collaborated with PPPL's Brian Grierson on understanding propagation of "cold pulses." Rodriguez-Fernandez successfully defended his thesis in the spring. He showed that modeling of Alcator C-Mod and the DIII-D National Fusion Facility experiments with local turbulent transport models can reproduce both steady state and perturbed heat transport in tokamak plasmas. Rodriguez-Fernandez is now a postdoctoral associate at the PSFC at MIT.

Graduate student Alexander Creely published an article on cross-machine validation of reduced turbulent transport models using data from C-Mod and the Axially Symmetric Divertor Experiment Upgrade (AUG). He successfully defended his thesis in the fall and is now employed by Commonwealth Fusion Systems. Postdoctoral associate Simon Freethy made a successful transition away from the MIT group to a permanent position as a scientist at the Culham Centre for Fusion Energy in the United Kingdom, where he works on the MAST-U (Mega Ampere Spherical Tokamak Upgrade) Tokamak. Currently, Professor White has three students and one new postdoctoral associate working in the group. Graduate student Rachel Bielajew and postdoctoral associate Pedro Molina Cabrera continue development and optimization of CECE/nT-phase systems at AUG. NSE student Bodhisatwa Biswas, who is co-advised by Paul Bonoli at the PSFC, works on developing reduced models of edge turbulence to study how injected radio frequency (RF) waves interact with turbulence in the tokamak. Graduate student Xiang Chen is working on a feasibility study for a new diagnostic that would be used to measure electron-scale temperature fluctuations.

Professor White is also involved as a member of the doctoral supervision committee for students working on collaborations at the W7-X stellarator located in Germany, and she participates in the Pedestal Physics group at PSFC. In addition, White supervises Undergraduate Research Opportunities Program (UROP) projects involving the development of small, table-top electrostatic inertial confinement devices for aid in classroom teaching at MIT.

Professor Nuno Loureiro continued his research on a broad set of topics, ranging from fundamental plasma physics to fusion theory and plasma astrophysics. In particular, he has developed the first theoretical model for turbulence in electron-positron (pair) plasmas in collaboration with Professor Stanislav Boldyrev, from the University of Wisconsin–Madison. Work led by his student, Elizabeth Tolman, investigated both theoretically and computationally the possible behavior of fusion-born alpha particle populations in high-magnetic-field tokamaks such as SPARC. Together with Professor Paolo Ricci from the École polytechnique fédérale de Lausanne (EPFL), Professor Loureiro has co-advised Mr. Rogério Jorge (EPFL) in performing the first exact investigation of the effect of collisions on two of the most fundamental plasma oscillations: drift waves and electron plasma waves.

Professor Ian Hutchinson's group investigates the basic nonlinear physics of flowing plasma, using their Particle in Cell codes and analytic theory. The observation of disruption of plasma wakes by nonlinear growth of soliton-like electron holes and their occurrence in magnetic reconnection has led to renewed interest in these free-standing, self-sustaining phenomena. Professor Hutchinson's analysis predicted that the solar wind wake of the Moon should be a region of intense electron hole production. The NASA-funded project to analyze satellite data has confirmed this prediction from in situ observations: the Moon's plasma wake is full of holes! How long electron holes last is determined by kink-like instabilities that eventually break up the holes. Over the past year, Professor Hutchinson has completed a comprehensive and rigorous analysis of the kink instability, which disproves prior speculative interpretations and identifies unambiguously the instability mechanisms instead.

Professor Zachary Hartwig holds a co-appointment in the Department of Nuclear Science and Engineering and at the Plasma Science and Fusion Center. His efforts are principally focused on accelerating the development of fusion energy. Professor Hartwig's principal role is in the leadership of the SPARC (Soonest/Smallest Private-Funded Affordable Robust Compact) project, a collaboration between the PSFC and Commonwealth Fusion Systems, a private company seeking to commercialize fusion energy. Commonwealth Fusion Systems sponsors the research and participates in development. The primary objective of the project is the design, construction, and operation of the SPARC tokamak by 2025, which will be the first demonstration of net fusion energy production in a controlled manner relevant to electricity generation.

The SPARC subdivision at the PSFC is part of the Magnetic Fusion Energy division. During 2018–2019, Professor Hartwig was a co-investigator on SPARC with PSFC director Dennis Whyte, closely cooperating on the financing, hiring, and direction of the SPARC project in its critical first year. In addition, Hartwig was a principal investigator on a major high-current superconducting magnet development project. This effort resulted in the demonstration of robust, manufacturable, and scalable superconductor technology that is based on a new generation of high-temperature superconductors. The principal applications for these conductors are in large-bore, high-field superconducting fusion magnets, although other applications in medicine, energy, and industry can be foreseen. Participating and helping lead this work with Hartwig were PhD students Erica Salazar and Richard Ibekwe.

Professor Hartwig was the principal investigator on the development of a new method for modifying materials to replicate the evolution of materials in a fusion power plant from the bombardment of high-energy particles due to the fusion process. This method uses a new generation of superconducting cyclotrons to produce powerful beams of protons that can be used to modify structural materials (steels), plasma-facing materials (tungsten), and functional materials (superconductors). The method enables a faster approach to the study and qualification of materials for fusion environments. The facility to perform these experiments was completed along with the first cycle of irradiation, testing, and analysis for a material specimen. These efforts were led by PhD student Steven Jepeal.

Professor Hartwig continued to develop a method to irradiate superconductors under high-fidelity conditions, including cryogenic and magnetic fields. Using accelerators to replace bombarding particles inside a fusion power plant allows scientists to study how robust superconductors will be inside a fusion power plant. During AY2019, new equipment was deployed that substantially increased the performance of the system, and initial measurements of the superconductor under different conditions were completed. This work was led by postdoctoral associate Leigh Ann Kesler.

Finally, Professor Hartwig participated in designing and executing an experiment to advance the science of molten salt blankets for fusion energy power plants. The blanket is the component that is primarily responsible for converting fusion energy into heat so that it can be used for practical applications. The molten salt blanket concept could revolutionize fusion blanket design, enabling vastly simpler, cheaper, more maintainable, and safer fusion power plants. During AY2019, the first experimental steps towards this concept have been completed, including the construction of a molten salt simulant flow loop experiment within a 2-tesla magnetic field. The primary purpose is the high-fidelity exploration of how strong magnetic fields in fusion power plants will affect the thermal hydraulics of molten salt. This work was led by PhD student Caroline Sorensen.

Charles 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 operating at full capacity to minimize costs. Forsberg is examining a Nuclear Air-Brayton Combined Cycle plant with two different heat storage systems that enable the power station to buy or sell electricity depending upon electricity market prices. This enables the reactor to provide dispatchable electricity to the grid, replacing the historic 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 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.

Professor Emilio Baglietto's group has advanced considerably in understanding and modeling boiling heat transfer up to its critical limit (critical heat flux)—the grand challenge for the nuclear thermal-hydraulics community. The synergy of the Baglietto group's modeling approach with the experimental work of Professor Matteo Bucci opens up new avenues for advancement in high-heat removal systems. The work is chiefly sponsored by the Consortium for Advanced Simulation of Light Water Reactors. Additional support comes from the Knoll Atomic Power Labs and from private industry (Mitsubishi Heavy Industries). The Baglietto group's modeling work is a broad and multifaceted effort and involves five PhD students, three master's degree students, and one postdoctoral associate.

Professor Baglietto's group has made important contributions to the application of high-fidelity methods in the design and licensing of advanced nuclear power reactors through a novel approach to quantifying modeling errors in turbulent flow simulations. This method was supported by TerraPower (a company launched by Bill Gates), with additional support from the Argonne National Laboratory. The work will be presented at the 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics in August 2019.

The Computational Reactor Physics Group, led by Professors Benoit Forget and Kord Smith, has pursued the development of high-fidelity open-source software for nuclear reactor analysis, namely the deterministic code OpenMOC (Method of Characteristics code) and the stochastic code OpenMC (Monte Carlo code). Recent highlights in OpenMOC include the acceleration of the 3D linear-source method through proper vectorization and memory management, the proper derivation of transport-corrected cross sections for preserving neutron migration area, and advancements in equivalence theory to preserve reaction rates during the energy-condensation process. Recent highlights in OpenMC include improved multi-physics coupling, depletion acceleration and validation, and code-base modernization. Additionally, the novel data format based on a pole and residue formalism was further improved through the integration of vector fitting in the data-generation process. A new data processing code was developed to streamline the process and improve performance. This data format also simplified the analysis of nuclear data uncertainties and its propagation through realistic nuclear systems.

Professor Matteo Bucci continued his research on heat transfer in his Red Laboratory. The lab develops cutting-edge experimental capabilities and high-resolution diagnostics to investigate boiling phenomena. Research in the lab focuses on the enhancement of the boiling performance in nuclear systems, i.e., in flow boiling, high-pressure conditions. PhD student Limiao Zhang is working on a new paradigm for explaining and predicting the boiling crisis—one of the most challenging and controversial problems for the thermal science community. This fundamental work has been published in *Physical Review Letters* and was featured in an MIT News press release.

Another important lab milestone is the launch of a first-of-a-kind experimental apparatus to perform high-resolution investigations of high-pressure flow boiling in prototypical nuclear reactor conditions. With this facility, the Red Lab team will be able to see phenomena as it has never been seen before. Investigations using the new apparatus will be instrumental in developing advanced thermal-hydraulics computational tools, validating the qualification of nuclear-accident-tolerant fuel materials supported by the US Department of Energy, and exploring surface engineering solutions to enhance the safety and efficiency of nuclear reactors.

Assistant Professor Koroush Shirvan has finished an integrated research program on accident tolerant fuels (ATFs) for light-water reactors sponsored by the Department of Energy. ATF concepts aim to improve the safety of existing water-cooled reactors worldwide while also improving economics by enhancing fuel reliability. Key findings from the project have been instrumental in the further commercialization of coated clad accident tolerant fuels, which is being pursued by all the major nuclear vendors in the United States. For the first time, key failure modes for coated clad ATFs were identified through an integrated system-level approach based on experimental and computational research. Professor Shirvan appeared as an expert on the Nuclear Regulatory Commission's panel in support of coated clad licensing. Based on the success of the project, Professor Shirvan was awarded a follow-on project to quantify the economic benefit of ATF when coupled with other innovative safety systems. This work is being pursued in collaboration with the University of Wisconsin Nuclear Reactor and the Idaho National Laboratory.

Professor Shirvan continued his work with Free Form Fibers, funded by a Small Business Innovation Research grant, to utilize fiber additive manufacturing technology to fabricate a first-of-a-kind ceramic fuel form with higher economic potential than the tristructural-isotropic (TRISO) fuels commonly used in high-temperature gas reactors. The feasibility of printing such fuel was experimentally demonstrated and its detailed thermo-mechanical performance was simulated and found to be superior to that of TRISO fuel. In addition, the silicon carbide fibers printed by the fused filament fabrication technology were found to be more irradiation- and corrosion-resistant than commercial nuclear-grade fibers utilized in the nuclear industry.

Professor Shirvan also continued to develop key metrics to improve the attractiveness of near-term, water-cooled, small modular reactors. The project is supported by Électricité de France. He is also collaborating with the State University of New York at Buffalo to explore new design spaces for advanced reactor technologies brought about by innovations in seismic isolation and civil engineering. The project is supported by the Advanced Research Projects Agency–Energy program and is part of a national initiative to accelerate adoption of modern innovations in nuclear energy. The DNB (departure from nucleate boiling) heat flux is an operational and safety limit for worldwide water cooled reactors and its precise prediction has been pursued for many decades. This past year, a unified DNB heat flux model based on purely mechanistic formulations was derived. The application of the mechanistic model against a "blind" nuclear fuel rod bundle experimental database showed noticeable improvements in accuracy and precision compared to 15 other organizations, including nuclear vendors. When calibrated with the use of machine learning, the achieved prediction accuracy and precision was unmatched when compared to all existing calibrated models for rod bundle analysis.

In addition to the commercial impact of Professor Shirvan's research, a key scientific contribution has been realized this past year. For the first time, the mechanism behind the improvements to boiling heat transfer under gamma radiation (which is present in nuclear reactors) was fully explained. This research is a joint effort with the Sandia National Laboratories Gamma Irradiation Facility. Through testing of various materials at different gamma ray irradiation rates, combined with microscopy, surface energy and electro-chemical potential measurements, it was found that gamma rays in the presence of oxygen result in significant micro-scale oxidation of the surface. The commercial implication of such a discovery is currently under patent process.

Professor Paola Cappellaro's Quantum Engineering Group is working on developing novel quantum devices and their control. In the past year, a focus of this research has been in improving the control and coherence of nosy, intermediate-scale quantum devices. With collaborators from Singapore University of Technology and Design, the group devised a novel control technique that allows unprecedented spatial resolution (at the nanoscale) by exploiting a quantum controller (a single spin in diamond) to drive the evolution of other nuclear spin qubits. With collaborators from Yale University and the California Institute of Technology, the group found new quantum error correction (QEC) codes that do not require noise-free ancillary qubits to achieve noise-protected quantum sensing. These ideas were further extended to find QEC codes that provide an *exponential* saving in the number of qubits required to protect quantum information against the noise of a common random fluctuator. This promises to bring the strength of QEC to near-term devices, which was not thought to be achievable. In addition, with collaborators from Argentina, the researchers studied the limits to the control of complex quantum systems, investigating whether decoherence and relaxation would pose a fundamental limit to the control of quantum devices of increasing size. In particular, Cappellaro's group found that by exploiting Hamiltonian engineering techniques, it is possible to reach the prethermal regime, which displays quasi-conserved quantities at exponentially long times. This work was done in collaboration with Professor Lloyd at MIT and colleagues from Dartmouth College and Duke University. Similar to localized systems investigated last year, these long-lived quantum systems are promising for quantum technology applications, such as quantum memories.

Professor Cappellaro's group also continued their work on quantum sensing. Reaserchers addressed the problem of measuring static fields by exploiting additional ancillary qubits in the system. This strategy is poised to significantly improve the performance of quantum sensors, even achieving Heisenberg scaling in time, by exploiting small amounts of quantum entanglement. The group first demonstrated how to use a nuclear spin qubit associated with the NV center to frequency up-convert a DC signal and detect transverse magnetic fields to which the sensor is typically insensitive. This enables using a single nanoscale sensor to implement vector magnetometry—a task that thus far required an ensemble of sensors. In addition, inspired by optimal control techniques that have found broad success for quantum computation, Cappellaro and her collaborators from the European Laboratory for Non-Linear Spectroscopy developed a novel approach for designing optimal control for quantum sensing. While in quantum computation, the goal is perfect fidelity of the operation. Sensing is typically a compromise between canceling noise effects while retaining the interaction with the external signal to be measured. A novel metric for optimization based on the sensitivity is thus needed for optimization.

Professor Ju Li's group has employed Angstrom-sized electron beam radiation to displace and manipulate single atoms. His group has developed batteries with high gravimetric and volumetric energy densities by using a class of dense cation-redox and anion-redox hybrid cathodes. Collaborating with the University of Maryland, his group has also produced high-entropy-alloy nanoparticles for applications in catalysis and energy conversion.

Professor Mingda Li's research is focused on synthesizing novel topological materials of high quality and large crystal size with fine-tuned Fermi levels. The large size enables a broader category of high-precision measurements, such as neutron scattering and thermal transport. In terms of the neutron scattering, the research shows that the singularities called Weyl nodes can induce an anomalous softening of lattice vibrations of phonons, namely the Kohn anomaly. In terms of thermal transport, the research demonstrated an approach that is able to break the fundamental limit between thermopower and electrical conductivity by order-of-magnitude using the topological protection.

Professor Michael Short continues to lead the effort to develop coatings for nuclear fuel which resist the formation of fouling deposits, the uptake of hydrogen, and which increase critical heat flux—all to decrease the cost and increase the safety of operating current nuclear power plants. Most recently Professor Short's fouling-resistant coatings have survived exposures in nuclear reactor-prototypical conditions, both in his group's flowing reactor loop and after six months in the MIT reactor's flowing water loop with irradiation. A combination of electron microscope analysis, Raman spectroscopy, and light scattering analyses confirm that some of the designed coatings can survive half-year operation in a real nuclear reactor. Lead test rods, the last step before widespread commercialization, are tentatively scheduled for late 2020 in a US commercial power plant.

Professor Short also continues to push the use of in situ, non-contact, non-destructive methods of measuring material degradation during irradiation, both for advanced fission reactor and fusion reactor conditions such as at the MIT ARC reactor. His group built the world's first on-ion beam transient grating spectroscopy system, which successfully reproduced a typical void swelling experiment in 5,000 times less time, with 1,000 times increased resolution. Collaborators are starting to line up to use this facility, which is also free to use through the US Department of Energy's National Scientific User Facility system.

Professor Areg Danagoulian leads the applied nuclear physics group, which focuses on the application of a variety of nuclear physics techniques on problems in nuclear security. In particular, Professor Danagoulian's group examines the use of a variety of nuclear processes and nuclear experimentation techniques to address long-standing problems in nuclear security that stem from large stockpiles of nuclear weapons and fissile materials. Danagoulian researches nuclear resonance processes for developing physically cryptographic verification concepts for arms control treaties. He also studies and uses nuclear resonance phenomena to produce photon probes for screening the flow of commerce for the presence of fissile materials. His group uses an academic setting to perform the basic necessary scientific research so that industry (e.g., cargo security) and national labs (e.g., warhead verification) can adopt and continue with more applied stages of development.

In the past year, Professor Danagoulian's group published two concepts that use nuclear resonance fluorescence and neutron resonance transmission analysis to achieve physically cryptographic verification of nuclear weapons. The work was done via Monte Carlo simulations and experimental measurements. These concepts will be useful in treaties that stipulate verification of the dismantling of the large stockpiles of nuclear weapons that make up the Russian and US arsenals. Additionally, Danagoulian's group has been working on a novel radiographic concept that leverages nuclear reactions to achieve high-precision dual-energy-transmission radiography of commercial cargoes. This method uses monoenergetic gammas from deutron-on-boron reactions whose well-defined energies result in a much more information-rich signal than traditional bremsstrahlung-based methods.

Senior Research Scientist Richard Lanza, along with students in Nuclear Science and Engineering and the Media Lab, and in collaboration with Massachusetts General Hospital, is carrying out research to develop low-cost digital x-ray systems for patients in the developing world. Lanza is also a member of a multi-disciplinary team that is developing a state of the art approach to Nanoscale X-ray Tomosynthesis for Rapid Assessment of Integrated Circuit Dice. The project's goal is the development of tools to rapidly image current and future integrated circuit chips.

The group's work on chip imaging is temporarily on hold, but it is clear that the approach has potential for the biological imaging of individual cells. Current approaches to tumor analysis have relied on DNA sequencing, which in general provides information about the "static code" that exits in the nucleus of the cell but not information about the manifestation of the DNA code in the cytoplasm or the cell surface. Consequently, DNA sequencing only provides a partial picture of the tumor biology and the pathology embedded in it. Ultra-high-resolution x-ray images will complement the information obtained by DNA sequencing and provide a more complete picture of the ultra-structure of the cell surface and cytoplasm of the altered DNA. For example, most chemical therapies work by interacting with receptors on the cell surface. Alteration of the surface properties of the receptors often leads to drug resistance and eventually ineffective drugs. The ability to rapidly determine the ultra-structural details at the cell surface, particularly receptors, will allow a more robust response to drug resistance and therapy selection and significantly reduce the risk of drug resistance.

Professor Emeritus Sidney Yip continued to be active in professional service as a faculty member in Nuclear Science and Engineering and to collaborate on research with colleagues and associates across the Institute.

Professor Emeritus Michael Driscoll concluded a long-standing research effort on the use of deep boreholes for spent nuclear fuel disposal. Since its inception in 1990, some 14 student theses and three dozen other publications have been generated. During AY2019, the project focused on the qualification of boreholes in Permian Basin–bedded salt. The work involved laboratory tests by two undergraduate students and showed that salt surfaces can be coated to avoid dissolution by the water introduced in the cement used to fill voids and plug the boreholes. Future research at MIT is on hold in view of the Department of Energy's announcement that it will end work on deep boreholes.

Professor Emeritus Sow-Hsin Chen was involved in water-related collaborative research with Professor Francesco Mallamace's group at the University of Messina and Professor Piero Baglioni's group at the University of Florence. The group has published six papers. The group's research established the contrast between hydrophilic and hydrophobic interactions in water solutions. For the first time, by means of nuclear magnetic resonance spectroscopy, experimental results with the Messina Group proved that these interactions have different effects as a function of the temperature and composition. In particular, it was observed that there is a crossover temperature (about 285K) defining the dominance of one interaction with respect to the other: above the crossover all the system structure and dynamics are governed by hydrophobicity, whereas below it the Hydrogen-Bond (hydrophilicty) plays the main role.

Additionally, the group studied the water in supercooled regimes by re-analyzing thermodynamic and scattering data and demonstrated a maximum presence in the isothermal compressibility of the region located at the so-called dynamic crossover. These results are relevant for the understanding of processes involving water, in particular biological processes. With the Messina group, further results on the pressure-temperature evolution of this compressibility maximum indicate the existence of a critical point at about 175 MPa and 190K.

Education

A total of 115 students pursued graduate degrees in the Department of Nuclear Science and Engineering: 41% in the fission energy, 23% 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 four SM degrees and two PhD degrees in September 2018. Twenty-six students entered the graduate program in fall 2017.

During the past year, 29 students were enrolled in the undergraduate program, including nine sophomores, seven juniors, 12 seniors, and one fifth-year student. Eleven students completed the requirements for the bachelor's degree in Nuclear Science and Engineering from September 2017 through June 2018.

The NSE Communication Lab (Comm Lab) experienced a surge in use this year, and has begun to make an impact beyond NSE. This discipline-specific peer-to-peer program was launched in 2014 to help students and postdoctoral associates with their writing, speaking, and visual design needs. Under the management of Marina Dang, five graduate students served as communication fellows and held 296 one-on-one coaching sessions (compared to 182 the previous year) to support 95 unique clients, including 14 non-NSE students. As 70% of NSE undergraduates and 50% of NSE graduate students used the Comm Lab, NSE has seen a shift from a last-minute culture to one that seeks feedback ahead of deadlines. The most common reasons for using the Comm Lab were course-related reports, slide presentations, and faculty applications. A client return rate of 60% testifies to satisfaction with the service. In addition, the Comm Lab offered NSE-specific communication workshops and collaborated with instructors from six undergraduate and graduate courses to strengthen the communication aspect of the curriculum.

The Comm Lab extended its services to include newly updated online resources written by the communication fellows, supported underrepresented minority students from other institutions through the first NSE Winter School, and co-hosted the third annual MIT Communication Lab Summer Institute (a four-day workshop for outside institutions to learn about the Comm Lab model and adapt it for their own science, technology, engineering, and mathematics communities). Dang co-authored a paper, presented at this year's American Society for Engineering Education conference, describing Comm Lab adaptations at MIT, Brandeis University, and the Rose-Hulman Institute of Technology.

Professor Shirvan continued his various summer education initiatives as co-director of the reactor technology course for utility executives, co-organizer of the Consortium for Advanced Simulation of Light Water Reactors (CASL) Institute, and co-organizer of the Nuclear Innovation Bootcamp.

Professor Short spearheaded the creation and launch of the 22-ENG flexible nuclear engineering degree, which was approved by a full faculty vote in May 2018. This new degree will allow students to select six courses as a specialized discipline directly related to, but not necessarily consisting solely of, nuclear science and engineering courses. This degree is expected to boost enrollment in the department, as many students were interested in majoring in Course 22, but were discouraged by the sheer number of requirements in the focused major.

Professor Neil Todreas and Benoit Forget directed the 53rd offering of the Nuclear Plant Safety course—the longest running professional education summer course at MIT. The course is intended for degree-holding engineers and scientists who are or will be participating in the design, construction, operation or regulatory safety review of nuclear power generation or spent fuel management installations. The June 2019 course had 33 attendees from installations in the US (about one-third) and around the world. Lectures were delivered by experts in nuclear technology familiar with current reactor or fuel facility safety issues as well as strategies for plant operations and design of current or future reactors. Lecturers came from industry, government (including regulatory agencies), and academia, including MIT's Department of Nuclear Science and Engineering.

Faculty Awards, Honors, and Activities

Professor Emilio Baglietto received the Office of Graduate Education's Committed to Caring Award. Professor Baglietto serves in the role of thermal hydraulics focus area lead for the Consortium for Advanced Simulation of Light-Water Reactors.

Professor Jacopo Buongiorno received the MIT Teaching with Digital Technology Award in June 2019 and the American Nuclear Society Outstanding Teacher Award in May 2019. He is a member of many boards and steering and advisory committees, serving as chair of NURETH-18 (the 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics), vice chair of the Virtual International Research Institute of Two-Phase Flow and Heat Transfer, and co-chair of the International Conference on Boiling and Condensation Heat Transfer.

Professor Buongiorno presented many invited talks on nuclear energy, including "The Future of Nuclear Energy in a Carbon-Constrained World - Findings from a New MIT Study," which he presented approximately 20 times to stakeholders in industry, government, academia, and think tanks.

Professor Sow-Hsin Chen received a recognition certificate from MIT president Rafael Reif on the occasion of completing 50 years of service to the Institute in March 2019.

Professor Ian Hutchinson remains on the editorial boards of the journals *Physical Review E* and *Physical Review Letters*, and *Plasma Physics and Controlled Fusion*.

Richard Lanza was named an American Physical Society Fellow. He was cited for his "innovative application of physics and the development of new technologies to allow detection of explosives and weapon-usable nuclear materials, which has greatly benefited national and international security." Dr. Lanza presented the annual Glenn Knoll memorial lecture at the University of Michigan. This lecture commemorates Professor Knoll by inviting a prominent scientist in nuclear measurements to present to University of Michigan students.

Professor Ju Li was included in the Clarivate Highly Cited Researchers list in the Materials Science field in 2018.

In collaboration with Professor Leonid Levitov (Department of Physics) and Professor Dirk Englund (Department of Electrical Engineering and Computer Science), Professor Nuno Loureiro was awarded a Bose Grant to perform investigations on electron dynamics in graphene sheets—a topic that lies at the interfaced of condensed matter and plasma physics.

Professor Loureiro co-organized a workshop on the plasma physics of neutron star mergers, held in October 2018 at the Center for Computational Astrophysics of the Flatiron institute in New York. The meeting gathered world-renowned experts in plasma physics and astrophysics, and aimed to identify cutting-edge plasma physics topics whose resolution is critical to understanding the electromagnetic component of the observations of neutron star mergers. Loureiro also co-organized the 2019 edition of the School of Plasma Physics, held at the École de Physique des Houches in France. This is a two-week long program aimed at educating students in a broad set of topics in plasma physics and related disciplines.

Professor Koroush Shirvan received the Best Paper Award at the Young Professional Thermal-Hydraulic Research Competition at the American Nuclear Society Conference for "Machine Learning-Based Critical Heat Flux Predictors in Subcooled and Low-Quality Flow Boiling."

Professor Dennis Whyte received the 2018 Leadership Award from the Fusion Power Associates (FPA) board of directors for his leadership in the quest for fusion power. FPA President Steve Dean wrote: "The Board especially notes the leadership you have been providing to the world fusion effort by emphasizing the importance of seeking continued improvements in both scientific and engineering foundations that will improve the prospects for fusion's commercial success."

Professor Bilge Yildiz and her research team won the Ross Coffin Purdy award for 2018 for their paper, "Improved chemical and electrochemical stability of perovskite oxides with less reducible cations at the surface."

Professor Sidney Yip concluded his service on the advisory board for the Department of Nuclear Engineering and Radiological Sciences at the University of Michigan. He continues to represent NSE at the School of Engineering Ad-Hoc Committee on Faculty Awards and Recognition. As a member of the Concrete Sustainability Hub, he continued giving lectures and publishing research, with a focus on understanding the molecular mechanisms of soft-matter rheology through atomistic simulations. He is the co–editor-in-chief of the *Handbook of Materials Modeling*, a Springer reference work in five volumes, to be published in 2019.

Student Awards and Activities

Patrick Adrian was awarded the Department of Energy National Nuclear Security Administration's Stewardship Science Graduate Fellowship.

Dakota Allen won the Best in Operations and Power Division for his presentation at the 2019 American Nuclear Society Student Conference.

Norman Cao won Best Student Poster Prize at the 24th Joint EU-US Transport Task Force Meeting in Austin, Texas. The prize was awarded based on his work on experimental data analysis and reduced modelling of plasma confinement hysteresis experiments on the Alcator C-Mod.

Jared Conway received the Roy Axford Award for academic achievement by an NSE senior.

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

Pablo Philippe Ducru received a Schwarzman Scholars Graduate Fellowship and second prize (with an award of $10,000) of the Rabobank-MIT Food and Agribusiness Innovation Prize for his project Velaron, which "aims to create a first-ever marketplace for commercially farmed and traded seafood, helping to promote and achieve more sustainable aquaculture globally by enabling risk-hedging and trading."

Silvia Espinosa was named Laureate of the International European Nuclear Society High Scientific Council PhD award. She also received the National Spanish Nuclear Society award for the best PhD thesis in Science and Technology and the annual meeting best presentation award.

Sara Ferry received a fellowship from the MIT Energy Initiative Society of Energy Fellows.

Ethan Klein received a Nuclear Nonproliferation and International Safeguards Fellowship from the National Nuclear Security Administration for 2019–2020 and a second place Student Paper Award from the Nonproliferation and Arms Control Division of the Institute for Nuclear Materials Management at their 2019 Annual Meeting.

Miriam Kreher received an American Nuclear Society (ANS) Graduate Scholarship from the society's local Pittsburgh section.

Stephen Lam was awarded the Alexander Graham Bell Fellowship from the National Science and Engineering Research Council of Canada.

David Layden received the Manson Benedict Award, presented to a graduate student for excellence in academic performance and professional promise in Nuclear Science and Engineering.

Abhilash Mathews received a three-year postgraduate scholarship from the Natural Sciences and Engineering Research Council of Canada.

Warner McGhee received the Irving Kaplan Award for academic achievement by an NSE junior. He also received an ROTC Honor Award from the Armed Forces Communications and Electronics Association.

Myles Stapelberg received the Outstanding Undergraduate Research Opportunities Program Award for outstanding contributions to a research project by a sophomore in Nuclear Science and Engineering.

Jayson Vavrek won the Best Student Presentation in the Advances in Nuclear Nonproliferation Technology and Policy section of the 2018 ANS Winter Meeting for his presentation "Warhead Verification Eexperiments Using Nuclear Resonance Fluorescence."

Xingang Zhao won the 2018 Young Professional Thermal Hydraulics Research Competition at the 2018 ANS Winter Meeting in Orlando, FL, in November 2018.

Jiayue Wang and Muni Zhou received Outstanding TA Awards for exceptional contributions as teaching assistants in Nuclear Science and Engineering.

Patrick White, Miriam Kreher and Travis Labossiere-Hickman received Outstanding Student Service Awards in recognition of exceptional service to the department.

Dennis G. Whyte
Department Head
Hitachi American Professor of Engineering