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. We prepare our students to make contributions to the scientific fundamentals of our 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. NSE is a world-leading academic department for fission and fusion research.

Highlights from fission include using advanced manufacturing (3D laser printing) to make accident-tolerant fuel, discovering universal laws of boiling water that might allow plants to operate safely at higher output levels, and learning how to optimize thermal properties of materials using machine learning—with the goal of improving the efficiency of new materials in energy production. There is also a great deal of research being done in the space of advanced reactors. Micro-reactors would be transformational for communities and businesses worldwide. The collocated supply-and-demand "nuclear batteries" being developed by Professor Jacopo Buongiorno and collaborators are opening up new opportunities for off-grid, mobile, containerized production and processing.

Highlights from fusion and plasma physics include rapid progress on meeting key milestones for the Soonest/Smallest Privately Funded Affordable Robust Compact (SPARC) project. In this project, MIT is partnering with a startup company and industry to build the world's first net-energy fusion experiment. Professors Dennis Whyte and Zach Hartwig and their team are leveraging advances in high-temperature superconductors and tackling major engineering challenges. Within a decade, SPARC will operate and demonstrate net energy, and it is the stepping stone to a larger device—the Affordable, Robust, Compact (ARC) reactor—which would be a demonstration reactor, producing electricity from fusion power. In addition, NSE students are heavily involved in research associated with the Center for Advanced Nuclear Diagnostics and Platforms for Inertial ICF and HEDP at Omega, NIF and Z, which is part of the National Nuclear Security Administration of the US Department of Energy (DOE). The center, housed at the Plasma Science and Fusion Center (PSFC), will focus on properties of plasma under extreme conditions of temperature, density, and pressure. Center partners collaborate closely with the Lawrence Livermore National Laboratory, the Los Alamos National Laboratory, the Sandia National Laboratory, the Laboratory for Laser Energetics, and General Atomics.

NSE has introduced a new flexible undergraduate degree, 22-ENG. This degree allows students to explore the intersection of traditional branches of nuclear science and engineering with other disciplines at MIT or to focus on topics not traditionally covered in undergraduate nuclear education (e.g., materials in extreme environments, advanced artificial intelligence/machine language modeling for nuclear systems, quantum engineering, nuclear security, and nuclear policy). Unlike the regular bachelor's degree of nuclear science and engineering offered by NSE, the 22-ENG degree is not accredited. Also, in the area of undergraduate education, the department is in the process of inaugurating a new makerspace sponsored by PSFC, NSE, and MIT's Office of Environmental Health and Safety. The space was used during the 2020 Independent Activities Period (IAP) for a highly successful "build your own fusor" workshop developed by PSFC staff and NSE alumni.

In mid-March, members of the Department of Nuclear Science and Engineering joined forces with colleagues in Boston's medical community to answer a question of critical importance during the COVID-19 pandemic: Can gamma irradiation sterilize disposable N95 masks without diminishing the masks' effectiveness? This research was led by Professor Michael Short in collaboration with colleagues from across the Institute.

The White House has announced the launch of the COVID-19 High Performance Computing Consortium, a collaboration among various industry, government, and academic institutions that will aim to make their supercomputing resources available to the wider research community in an effort to speed up the search for solutions to the evolving pandemic. Professor Ben Forget, who also leads the department's efforts to collaborate with the MIT Stephen A. Schwarzman College of Computing, is involved in the new consortium.

Fusion researchers endorse the push for a pilot power plant in the United States. The fusion energy community published a unified statement on priorities in a report for the Department of Energy's Policy Advisory Group. Faculty, students, and postdocs in the department have been very active in the community planning process, providing input into a new strategic plan for the DOE Office of Fusion Energy Research (FES). In addition, as part of the federal Fusion Energy Sciences Advisory Committee, NSE faculty are working on drafting the FES strategic plan.

The department is also very active in research unrelated to fission power and fusion energy. Our faculty members are atomic engineers—they study how to engineer new systems and devices at the atomic scale, including new materials with improved energy storage and energy transfer characteristics. For example, Professor Bilge Yildiz and coworkers have shown how a material's insulating properties can be tuned at will. Most materials have a fixed ability to conduct heat, but applying voltage to thin film changes its thermal properties drastically. Also, Professor Yildiz and Professor Ju Li have shown how to design an electronic device that operates like a brain synapse but can handle the heat needed to operate complex energy-intensive neural network artificial intelligence (AI) systems. In addition, Professor Li is part of an MIT team that has devised a new type of lithium metal anode that could improve both the lifetime and capacity of future batteries. Our faculty are also quantum engineers. They have learned how to exquisitely harness the laws of quantum mechanics to build new ways to control energy and transfer information at the quantum scale—setting the stage for new devices to help with global navigation as well as quantum computing.

Faculty and Administration

Emilio Baglietto was promoted to associate professor with tenure.

Professor Jacopo Buongiorno was appointed director for science and technology and strategic R&D partnerships at the Nuclear Reactor Laboratory.

Thomas Dupree, professor emeritus of nuclear science and engineering and physics, passed away at 86. A highly regarded physicist, Professor Dupree was well known for studying plasma turbulence in terms of coherent structures.

Ben Forget was promoted to full professor and appointed associate head of the Department of Nuclear Science and Engineering.

R. Scott Kemp was promoted to associate professor with tenure.

Michael Short was named the Class of 1942 Career Development Professor.

Anne White was promoted to full professor and named head of the Department of Nuclear Science and Engineering. She became an American Physical Society Fellow, cited for her "outstanding contributions and leadership in understanding turbulent electron heat transport in magnetically confined fusion plasmas via diagnostic development, novel experimentation, and validation of nonlinear gyrokinetic codes."

Research Highlights

Upon becoming NSE department head on July 1, 2019, Professor Anne White stepped down from the role of PSFC associate director for education and outreach and is no longer a deputy leader of the PSFC magnetic fusion experimental subdivision, where she had previously spent several years coordinating on-campus aspects of collaborations with tokamak and stellarator experiments in the United States 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 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 ARC. White and her group are engaged in research at three major tokamaks (ASDEX upgrade [AUG], DIII-D, National Spherical Torus Experiment [NSTX]/NSTX upgrade) where they lead experiments, develop diagnostics, and lead validation projects using advanced turbulence simulation codes. Four students and two postdocs currently work in Professor White's group. Postdoc Pablo Rodriguez Fernandez performs predictive modeling for SPARC, develops new optimization tools at AUG, and leads a new collaboration with the JET tokamak on integrated modeling. He also supports students in the group working on tokamaks. NSE students Rachel Bielajew and Christian Yoo and postdoc Pedro Molina Cabrera continue development and optimization of correlation electron cyclotron emission (CECE)/nT-phase systems at AUG. Molina Cabrera is focused on the physics of isotope scaling, Bielajew is studying edge turbulence in edge localized mode (ELM)-free high-performance plasmas, and Yoo is exploring the use of machine learning and AI applied to understanding the scaling of turbulence and transport across a wide range of engineering and plasma parameters. Undergraduate Research Opportunities Program (UROP) student Calvin Cummings has joined the group for summer 2020; he will work on new control room visualization tools for CECE access at AUG. NSE student Bodhi Biswas, who is co-advised by Paul Bonoli at PSFC, works on developing reduced models of edge turbulence to study how injected radio frequency waves interact with turbulence in a tokamak. NSE student Xiang Chen is working on a feasibility study for a new diagnostic that would be used to measure electron-scale temperature fluctuations. As a member of the Lawrence Livermore National Laboratory doctoral supervision committee for students working in the area of high-energy-density physics, Professor White is also involved in collaborations with the SPARC tokamak, the W7-X stellarator in Germany, and the PSFC pedestal physics and boundary physics groups.

Professor Buongiorno began research on a new project sponsored by Lubrizol that was launched in late 2019. The objective of the project is to develop and test a series of non-aqueous engineered fluids with appropriate nanoparticle loadings to maximize the single-phase heat transfer properties of the fluids while not significantly impacting other critical fluid properties (e.g., viscosity) important for viability in fluid heat transfer applications (e.g., thermal management of high-performance batteries for electric vehicles).

In addition, a project that seeks to develop a new taxonomy for abnormal events at nuclear power plants was launched in early 2020. The objectives are to enable more effective communication with non-technical stakeholders, thus improving the response to a radiological event, and to mitigate the effects of such an event on the long-term social acceptability of nuclear energy.

Professor Buongiorno also contributes to a project at the Pacific Northwest National Laboratory that is examining the use of micro-reactors to decarbonize off-grid applications. Micro-reactors can serve as the backbone in supplying electricity and heat for containerized agriculture and manufacturing facilities, district heating, data centers, seaports and airports, and disaster relief efforts, to mention a few applications.

A TEPCO-sponsored project on Japan’s nuclear energy systems for 2030 and beyond was completed in early 2020. Briefly, in this project Buongiorno and his group identified three new missions for nuclear plants that will operate in the Japanese energy market in the 2030s and beyond: (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, the group selected three of them to satisfy 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.

The group deems that such technologies can be deployed commercially in Japan by 2030 and that they have a high likelihood of meeting important requirements for economics (i.e., cost competitiveness with liquified natural gas, low operation and maintenance costs), operational capabilities (i.e., load following, grid resilience), and safety and security (i.e., insensitivity to external events, emergency planning zones limited to site boundaries).

Buongiorno and his group developed notional layouts for three representative sites in Japan (TEPCO's Higashidori power plant, Mitsubishi Chemical Co.'s Kamisu Ibaraki plant, TEPCO's Hachijō-jima power plant) at which commercial demonstrations 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, decrease reactor building costs, and enhance physical security.

Lastly, the group explored several innovations in automation and digitalization of plant operation and maintenance that could result in new nuclear plants being even more cost effective and valuable to Japan.

The Computational Reactor Physics Group (CRPG), led by Professor Forget and Professor Kord Smith, is continuing the development of high-fidelity open source software for reactor analysis, namely the deterministic code OpenMOC and the stochastic code OpenMC, as well as the development of methodologies for data processing. Recent highlights include the completion of a multi-year study on the generalization of equivalence factors needed for high-fidelity deterministic simulations. This work has enabled the use of noisy Monte Carlo simulations to extract multi-group cross sections and local equivalence factors for use in highly resolved OpenMOC simulations. Major improvements were also achieved in the development of transport-corrected multi-group cross sections to facilitate the treatment of anisotropic scattering in deterministic simulations. Additionally, improved vectorization and parallelization techniques were implemented in OpenMOC to reduce the computational burden of fully converged 3D steady state, full core light water reactor simulations. These improvements finally enable the resolution of highly complex problems on accessible computing clusters rather than the previous reliance on leadership class systems.

On the Monte Carlo side, recent work has focused on accelerating the convergence of multi-physics simulations via the use of the novel data format developed in prior years. The new formalism allows for the calculation of temperature derivatives on tallied quantities that can be used in conjunction with a physics-based multigrid approach that accelerates the source convergence of Monte Carlo simulations but also enables the possibility of iterating with fluid dynamics and heat transfer, thus reducing the reliance on costly simulations. This approach was highly successful in reducing the time to solution in the presence of non-linear feedback mechanisms. Additional research in support of the Exascale Computing Project has led to further improvements in the depletion capabilities of OpenMC and integration of the novel continuous material depletion algorithm previously demonstrated. CRPG has also completed a contract on the use of subcritical graphite piles for method validation and developed experiments to support the group's educational mission.

Over the past year, Professor Nuno Loureiro and his group have focused on several aspects of nonlinear plasma dynamics with applications ranging from magnetically confined fusion to space and astrophysical plasmas. Highlights include the continuation of earlier work in collaboration with Professor Stas Boldyrev (University of Wisconsin) on the role of magnetic reconnection in strong plasma turbulence and, in work led by graduate student Muni Zhou, an investigation of the conditions for the inverse transfer of magnetic energy in *magnetohydrodynamics* plasmas. These efforts have led to several publications and invited talks at international conferences.

Along with Professor Paola Cappellaro (NSE) and Hari Krovi (BBN), Professor Loureiro was awarded a DOE grant to investigate the potential of quantum computing for numerical simulation of nonlinear plasma dynamics. Work on this front is currently under way in collaboration with groups at the University of Maryland and IST Lisbon.

Professor Ian Hutchinson continues his research on plasma electron holes: electrostatic structures that result from kinetic instabilities and are widely observed in space plasmas. His work on the transverse stability of initially one-dimensional holes culminated in the discovery of the mechanism responsible for the very slow growing instabilities at high magnetic fields. He showed that these instabilities are actually negative energy perturbations in which the resonances between electrons bouncing on trapped orbits and the oscillations of the kinking hole are stabilizing (not destabilizing as was previously thought). This work also indicates that the interaction with long wavelength perturbations external to the hole is a side effect of the hole's instability rather than an intrinsic part of the instability mechanism. The eventual shape of multidimensional holes and how long they last are critically affected by such instabilities. In recent work, he has shown that electrons trapped in multidimensional holes are subject to a resonant detrapping mechanism arising from their transverse electrical field. The overlap of trajectory "islands" gives rise to stochasticity that enables electrons to escape the potential well. The result is that only deeply trapped particles can contribute to hole sustainment. This work is part of the development of a quantitative theory of multidimensional electron holes that has eluded theorists for decades but that Professor Hutchinson is currently working on.

Professor 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's principal role is in the leadership of the SPARC Toroidal Field Model Coil Project. This project is a unique joint collaboration between PSFC, a world leader in high-field fusion energy science and high-field magnet engineering for over 40 years, and Commonwealth Fusion Systems (CFS), a private company seeking to commercialize fusion energy. CFS sponsors the research and participates closely with PSFC science and engineering staff in research and development.

The goal of the two-year SPARC project, which involves over 60 scientists, engineers, and technicians, is to design, build, and test a first-of-its-kind high-temperature superconductor magnet at the scale and performance required for magnetic confinement fusion experiments. The project completed the first of its two years on June 1, 2020, achieving success in research and development and groundwork for building the magnet and test infrastructure despite the challenges imposed by COVID-19. Participating in and helping lead this work with Professor Hartwig were PhD students Erica Salazar, Theodore Mouratidis, and Richard Ibekwe and several UROP undergraduates.

Professor Hartwig also plays a key role in PSFC's efforts in the development of technology for future fusion energy power plants. He continues to be the principal investigator on three key projects:

- The development of a new method for modifying materials to replicate the evolution of materials in a fusion power plant due to the bombardment of high-energy particles from 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 (e.g., steels), plasma-facing materials (e.g., tungsten), and functional materials (e.g., superconductors). The method enables a faster approach to the study and qualification of materials for fusion environments. The key results over the past year are the completion of the facility to perform these experiments (including cyclotron and irradiation hardware; a high-vacuum, high-temperature irradiated materials test stand; and development of the computational workflow for analysis) and the first test cycles. These efforts are being led by PhD student Steven Jepeal.
- The continued development of a method to irradiate superconductors under high-fidelity conditions, including cryogenic and magnetic fields. Using accelerators to replace the bombarding particle inside a fusion power plant enables research on how robust superconductors will be inside a fusion power plant. New equipment was deployed that substantially increased the performance of the system, with initial measurements under different conditions being completed toward the end of the period. This work is being led by postdoctoral associate Leigh Ann Kesler.
- Designing and deploying an experiment to advance the science of molten salt blankets for fusion energy power plants. These blankets are 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, lower cost, more maintainable, and safer fusion power plants. The first experimental step taken toward this concept, the construction of a molten salt simulant flow loop experiment within a 2 tesla magnet field, has been completed. The primary purpose is high-fidelity exploration of how strong magnetic fields in fusion power plants will affect the thermal hydraulics of molten salt. This work is being led by PhD student Caroline Sorensen under the co-supervision of Professor Whyte.

Professor Short oversaw the development of Chalk River Unidentified Deposits (CRUD)-resistant materials for nuclear reactors through to completion at MIT, with efforts to demonstrate industrial-scale success in a commercial US reactor under way for spring 2022. His group discovered that radiation actually slows corrosion in molten salts (see Figure 1), a huge potential boon to molten salt cooled fission and fusion reactors. He continues to chip away at the question of how to measure smaller and smaller doses of radiation damage to materials, with the goal of nuclear forensics of proliferation, nuclear weapon production, and reactor usage as a means of ending nuclear terror.

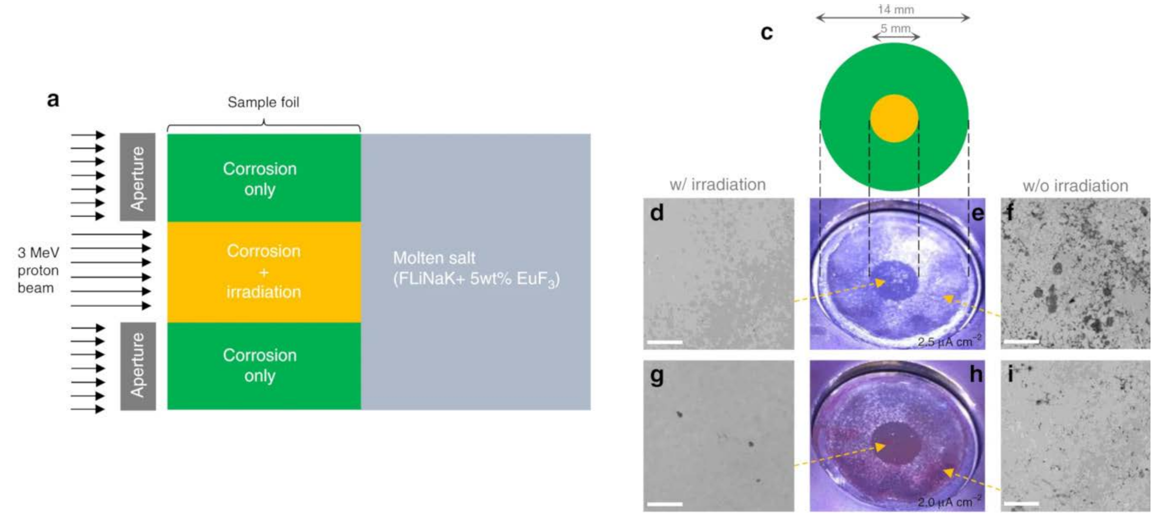

Figure 1. Evidence of radiation-decelerated corrosion in molten salt at 650°C. Note how the round spot in the center, where the protons hit the metal, exhibits far less corrosion. (Source: Zhou et al.*)*

Charles Forsberg has initiated a project aimed at building a forced-circulation liquid salt loop at the MIT reactor that includes heating the salt to 700°C in the irradiation zone and cooling it outside the radiation zone. This loop will simulate the behavior of salt coolant in (1) a molten salt reactor (fuel in salt), (2) a fluoride salt-cooled high-temperature reactor with clean salt and solid fuel, and (3) a salt blanket in a fusion reactor. The general-purpose test loop will allow investigation of corrosion, tritium, and fission product transport and be a test bed for instrumentation and salt cleanup systems. It is the first such reactor in the United States in over 40 years. Project partners include the University of California, North Carolina State University, and the Oak Ridge National Laboratory. Related work includes prediction from first principles of tritium transport in liquid salts and development of methods to predict radiative heat transport in these semi-transparent high-temperature salts.

The addition of wind and solar to the electricity grid creates volatile wholesale electricity prices with periods of near-zero prices and times of high prices. Two thermal storage technologies are being developed. The Firebrick Resistance Heated Energy Storage system using conductive firebrick converts low-price electricity when available to stored heat at temperatures ranging from 1000°C to 1500°C. The high-temperature heat is delivered as hot air, when needed, for use in industry or gas turbines. In parallel, work is under way to develop crushed-rock heat storage systems at the 100-gigawatt-hour scale to enable base-load reactors to provide variable electricity to the grid. At times of low electricity demand, heat from the reactor goes to heat storage. At times of high demand, heat from the reactor and storage is converted to electricity. This enables nuclear plants to replace fossil plants in the role of providing variable dispatchable electricity to the grid.

Professor Baglietto has completed his five-year role as the thermal hydraulics focus area lead for the Consortium for the Advanced Simulation of Light Water Reactors (CASL). The modeling approaches developed by Baglietto's group have considerably advanced the capability of predicting heat transfer in nuclear fuel up to its critical condition, providing a first implementation of virtual fuel design that has been assessed and executed at Westinghouse. The work has leveraged a massive research effort under the support of the Department of Energy.

The Baglietto group's advancements in modeling capabilities have been enabled by close synergy with the experimental work of Professor Matteo Bucci, which provides the fundamental physical insights necessary to drive a more general representation of boiling heat transfer. The modeling approach assembled by Baglietto and his team has demonstrated the potential to extend applications to include the effects of varying heater and coolant evolution, which is becoming relevant to support life extension of both light water reactor and Canada Deuterium Uranium (CANDU) fleets. Ontario Power Generation and the Canadian Nuclear Laboratories have identified the potential of this approach for assessing the evolution of the critical heat flux in strained CANDU channels and are supporting continuation of the modeling work toward high void fraction regimes. The National Aeronautics and Space Administration (NASA) has also identified the value of the approach as part of the new lunar exploration program, wherein a key concern relates to long-term storage and transfer of fuels in a cryogenic state on the lunar surface and in orbit. Two projects have been funded to assemble the boiling closure as part of the NASA simulation tools and to produce new closure models for cryogenic fluids in collaboration with Professor Bucci's team.

The Baglietto group is also driving the advancement of turbulence modeling and turbulence modeling assessment and uncertainty quantification in support of the design and licensing of advanced nuclear power reactors. Their demonstration of the accuracy of a novel hybrid resolution turbulence model, STRUCT, is playing an important role in advancing the design of high-temperature concepts and is a fundamental component of the DOE Center of Excellence for Thermal Hydraulics. Also, a new collaboration with the Universidad Politécnica de Madrid is demonstrating the importance of improved hybrid turbulence modeling to support optimization of high-speed transport to reduce emissions.

Professor Bucci is expanding his research activities in two-phase heat transfer. Bucci's Red Lab develops cutting-edge experimental capabilities and high-resolution diagnostics to investigate two-phase heat transfer phenomena. The core of the Red Lab research focuses on understanding and enhancing boiling performance. The team is leading many projects aimed at elucidating the mechanisms of boiling heat transfer and the boiling crisis. Despite decades of research, understanding of these phenomena is still marginal, and predictions often rely on engineering rules with large uncertainty margins. This issue is crucial for nuclear reactors and many other engineering systems (e.g., high-power electronic devices).

Since 2016, the Red Lab experimental team has collaborated with Professor Baglietto and his computational group, informing the development of their mechanistic two-phase heat transfer modeling framework. This achievement has been possible thanks to the support of the Department of Energy (through CASL). This effort successfully came to an end in 2020.

The group is currently leading three projects (sponsored by DOE through the Nuclear Energy University Program, Exelon, and Fluor Marine Propulsion) aiming at elucidating different aspects of boiling heat transfer related to the physical and chemical properties of the boiling surface. In one of these projects, the group has collaborated with the teams of Professors Short, Yildiz, and Evelyn Wang to develop a special nuclear fuel cladding that resists the formation of fouling deposits and uptake of hydrogen while increasing critical heat flux. Specifically, the boiling heat transfer team of Professors Bucci and Wang has demonstrated a robust and scalable surface treatment to increase the critical heat flux in pressurized water reactor conditions (i.e., high pressure and temperature).

Professor Bucci has received an award from the National Science Foundation to study the fundamentals of boiling heat transfer. Specifically, the team will explore "the percolative scale-free nature of the boiling crisis," a new fundamental theory put forward in 2018 by Professor Bucci.

Artificial intelligence has changed the research landscape in many areas of science and engineering. However, its penetration into two-phase heat transfer research has been marginal to this point, primarily limited to interpolation of experimental data. Professor Bucci's team is leading efforts at the intersection of experimental research, advanced diagnostics, and AI. The team has developed a machine learning tool to analyze huge amounts of data (e.g., from high-resolution, high-speed video and infrared cameras) online and in real time. This development removes an important limitation associated with the use of high-resolution diagnostics: post-processing. Motivated by this success, Professor Bucci has launched a project aimed at creating an autonomous "heat transfer lab." The team will develop an experiment run autonomously via AI, without any operator control.

Professor Koroush Shirvan has completed a study (supported by the French company EDF) focused on improving near-term water-cooled small modular reactors. The project's findings have provided key insights into the strong correlation between safety goals and economics modeled with a licensed methodology and a new bottom-up reactor cost tool. The results showed the importance of reactor power density and cycle efficiency as the driving forces behind lowering the cost of a first-of-its-kind nuclear concept.

Professor Shirvan has continued his work on improving light water reactor sustainability through safety and economic efficiencies. In this research, supported by DOE and conducted in collaboration with nuclear utilities and vendors, he has been able to quantify the economic value of near-term accident-tolerant fuels and high burnup fuel through first-of-its-kind testing and simulations of cladding ballooning, burst and nuclear fuel cracking, fragmentation, and relocation. The US nuclear industry plans to adopt high burnup fuel and selected near-term accident-tolerant fuels by 2025 to improve safety and reduce nuclear fuel cycle costs. Professor Shirvan is also continuing his work with Free Form Fibers on additive manufacturing of an optimized fuel form. In addition, he has made headway on his Advanced Research Projects Agency–Energy (ARPA-E) grants on formulating design spaces for high-temperature gas reactors and molten chloride fast reactors. He is investigating a horizontal high-temperature gas reactor configuration that can decrease power density by a factor of three to reduce cost and construction risk. In the case of molten chloride fast reactors, he is investigating distributed fiber optic sensing technologies through irradiation testing and modeling.

Professor Shirvan has also started a new project focused on application of artificial intelligence (AI) to nuclear reactor core design. Inspired by Google's Deepmind and its ability to beat world experts in gameplay, an AI technology based on reinforcement learning is being developed to improve the economic efficiency of nuclear fuel reloading. The AI technology has shown the ability to learn efficiently nuclear core design tactics that are difficult to quantify and adopt with classical optimization techniques. The work, performed in collaboration with MIT Quest for Intelligence, is funded by the nuclear plant operator Exelon, which plans to deploy the technology for use in its nuclear core reload engineering.

Professor Cappellaro's Quantum Engineering Group has continued to make significant contributions to the development and control of novel quantum devices. Among key results, they found quantum error correction (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 result promises to bring the strength of QEC to near-term devices, where it was thought not to be achievable.

In addition, the group identified novel quantum defects in diamond and exploited them to perform entanglement-enhanced quantum metrology with the goal of improving sensitivity beyond what is possible with classical devices. With collaborators at Harvard, they explored novel control techniques to improve the sensitivity of dense spin qubit ensembles, wherein the couplings dominate the qubit sensor coherence, typically limiting the sensitivity.

By exploiting this precise control over strongly interacting systems, they were able to not only eliminate the couplings, thus increasing sensitivity, but also engineer the couplings themselves at will. This control technique enables exploring novel regimes of quantum many-body dynamics. One of the most powerful means of protecting qubits from noise and achieving quantum simulation is to drive interacting qubits with periodic modulations. While the periodic driving can even give rise to new phases of matter, with artificial dimensions and novel properties, the driving introduces heating and ultimately drives the system to a featureless state with an infinite temperature. In seminal work, the group experimentally probed the time scale over which such heating occurs and explored the existence of quasi-conserved quantities that can enable robust quantum operations (such as quantum computation and sensing) over exponentially long periods. The group further optimized such periodic driving protocols to reach optimal fidelity in the desired simulated evolution.

In addition to explorations of thermalization in many-body systems, another novel focus of interest was quantum thermodynamics, where the group made seminal contributions both experimentally (in a collaboration with Italy enabled by an MIT International Science and Technology Initiatives grant) and theoretically. This research explored the validity and extension of the Jarzynski inequality (a fundamental law akin to the second law of thermodynamics) to open quantum systems.

Professor Li's group continued to develop radiation- and helium-tolerant materials for fission and fusion energy as well as radiation-resistant metal-organic frameworks for efficient separation of krypton and xenon gases from spent nuclear fuel. The group has developed theories and methods for utilizing high-powered electron and laser radiations, elastic strain, and electrochemical driving forces to engineer phase and defect configurations of matter for new sensors and information processing hardware (in collaboration with Professor Yildiz). Another continuous activity is the development of new redox chemistries such as hybrid anion- and cation-redox cathodes and mixed ionic-electronic conductor Li-metal anodes for electrical energy storage. During the COVID-19 pandemic, the Li group performed air filtration tests on disposable face masks. Gamma irradiation damages the electret filter material of N95 face masks after disinfection and irreversibly reduces the filtration efficiency of 0.3 μm to 1 μm particulates. Ultraviolet radiation is found to be better at maintaining the masks' filtration efficiency after disinfection.

Professor Yildiz 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 impact the design of novel materials and interfaces to enable high-energy efficiency for solid oxide fuel cells and electrolytic splitting of water and CO_2, brain-inspired analog computing and memristive information storage, solid state batteries, and corrosion- and hydrogen-resistant films.

Professor Yildiz has made significant contributions in advancing molecular-level understanding of oxygen reduction, oxidation, ion diffusion and intercalation, and charge transfer on mixed ionic-electronic solids. She has uncovered the effects of elastic strain, dislocations, and strong electric fields on the reactivity, efficiency, and degradation of mixed ionic-electronic materials in these applications. In her approach, she has combined theoretical, computational, and experimental analyses of electronic structures, defect mobility, and composition.

More specifically, Professors Yildiz, Li, and Jesus del Alamo have designed and demonstrated a protonic electrochemical random-access memory (ECRAM) synapse as an all solid state device with very low energy consumption, nearly symmetrical behavior, and a long cycling lifetime. The core material system comprising WO_3 as the channel and PdHx as the gate electrode was chosen in order to be complementary metal-oxide-semiconductor (CMOS) compatible. In the complete range from 0 to 1 H per WO_3, the research team achieved continuous modulation of conductance (G) and a high G_{max}/G_{min} ratio of 10^7. The lower protonation regime features high symmetry in the potentiation/depotentiation processes, while the high protonation regime features small open-circuit potentiometry changes and a large ΔG per unit amount of proton insertion. This understanding provides guidance for the selection of an operating window to achieve the desired device properties. In addition, the team confirmed the topotactic nature of the conductivity modulation of its device through electronic and atomic structure analyses. Proton intercalation increases both carrier density and mobility without any solid state reactions requiring extensive bond breaking or structural reorganization. Thus, the protonic ECRAM also reveals good reversibility, with the observed volume change much smaller than Li-intercalation compounds, thus promising smaller residual stress and a longer cycle life.

Professor Yildiz, together with Gang Chen, has designed and demonstrated electrical bi-directional tuning of thermal transport over a wide range of ceramic materials. Unlike the wide-ranging dynamic control of electrical conductivity, there is no analogous ability to tune thermal conductivity by means of electric potential. The traditional picture assumes that insertion of atoms into a material's lattice acts purely as a source of scattering for thermal carriers, which can only reduce thermal conductivity. In contrast, Yildiz and Chen showed that electrochemical control of oxygen and proton concentration in an oxide provides a new ability to bi-directionally control thermal conductivity. Upon electrochemically oxygenating the brownmillerite $SrCoO_{2.5}$ to the perovskite $SrCoO_{3-d}$, the thermal conductivity increases by a factor of 2.5, while protonating it to form H-$SrCoO_{2.5}$ effectively reduces the thermal conductivity by a factor of 4. This bi-directional tuning of thermal conductivity across a nearly 10(±4)-fold range at room temperature is achieved by using ionic liquid gating to trigger "tri-state" phase transitions in a single device. The effects of these anionic and cationic species and the resultant changes in lattice constants and symmetries on thermal conductivity were elucidated by combining chemical and structural information from X-ray absorption spectroscopy with thermoreflectance thermal conductivity measurements and ab initio calculations. This ability to control multiple ion types, multiple phase transitions, and electronic conductivity spanning metallic through insulating behavior in oxides by electrical means provides a new framework for tuning thermal transport over a wide range.

Professor Mingda Li's Quantum Measurement Group continues to lead efforts employing neutron and X-ray scattering techniques to explore topological materials. Through a combination of quantum theory and inelastic scattering, the group theoretically predicted and experimentally discovered the first Kohn anomaly in topological materials. This work shows that electronic topology can leave hallmark traces in ionic degrees of freedom and can be used to build devices with chirality degrees of freedom.

Professor Areg Danagoulian's group has continued its work in the field of nuclear security, focusing on the development of technologies for the purposes of verification of arms control treaties. They authored a paper detailing the use of epithermal neutron beams to compare and verify the geometric and isotopic makeup of a nuclear device in a physically cryptographic manner. This allows hoax-proof verification without revealing the specifics of a device's design—a critical requirement if the technique is to be acceptable to future treaty participants. This work was followed up with research on the development of compact platforms for performing this verification. These experiments have received much recognition both in scientific circles and in the policy community, earning the team the 2019 Arms Control Association Persons of the Year award. Additionally, Professor Danagoulian was honored with the American Nuclear Society's Radiation Science and Technology Award "for technology-critical contributions exploiting nuclear resonance phenomena for warhead verification in nuclear disarmament and nuclear detection techniques in cargo security."

Richard Lanza is part of a multi-national group (World Federation of Scientists) concerned with the resilience of infrastructure to both natural disasters and deliberate attacks. Increasingly, the close physical coupling of infrastructure systems and the increased vulnerability to cyber-attacks have led to concerns regarding the impact of failures on societies. Efforts initially concentrated on energy networks such as electric grids and gas pipelines but now have expanded to other areas such as water and communications. In addition to interactions between various parts of the infrastructure, there are different temporal and spatial scales (see Figure 2) that must be taken into account when establishing response priorities. The increased standardization of control systems, generally referred to as supervisory control and data acquisition, has enabled centralized control and enhanced efficiency in infrastructure, but the commonality of commercial control software has led to numerous attacks on these systems.

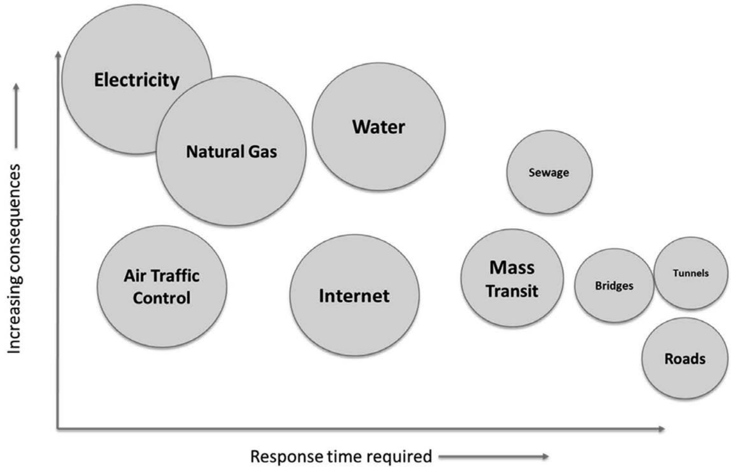

Figure 2. Response time versus consequences.

Lanza and Ruaridh Macdonald have been working on a new technique for isotopically sensitive imaging. The fundamental idea is to use the extremely narrow resonances characteristic of nuclear resonance fluorescence (NRF), which are nuclear isotope dependent. Isotopic composition is critical in non-proliferation and quality control efforts. For example, in the reprocessing of spent fuel from nuclear reactors, measurement of isotopic composition is important in detecting diversion of weapons grade materials from a commercial/civilian stream.

NRF attenuation dominates non-resonant attenuation at resonant energies, creating eV-wide holes in the MeV transmitted photon spectrum. These “fingerprints” can be used to identify an isotope. Although transmission NRF as a means of material identification is the subject of active investigation, current approaches require the use of either a complex laser-accelerator combination or a large non-pulsed electron accelerator, as well as large numbers of expensive high-resolution detectors with limited count rates and hence long measurement times.

The new approach (see Figure 3) requires neither special accelerators nor energy-resolved detectors and instead filters a high-energy photon beam through a set of alternating absorbers rotating at a known frequency, usually in the range of a few hundred hertz. The integrated signal can be enhanced by orders of magnitude by analyzing the Fourier transform of the signal at the alternation frequency of the absorbers. The same approach might be able to be used with neutrons with an appropriate choice of materials. Current work is focused on simulating the system and developing proof-of-concept experiments at lower photon energies. An example of using the technique for fuel assay is shown in Figure 4.

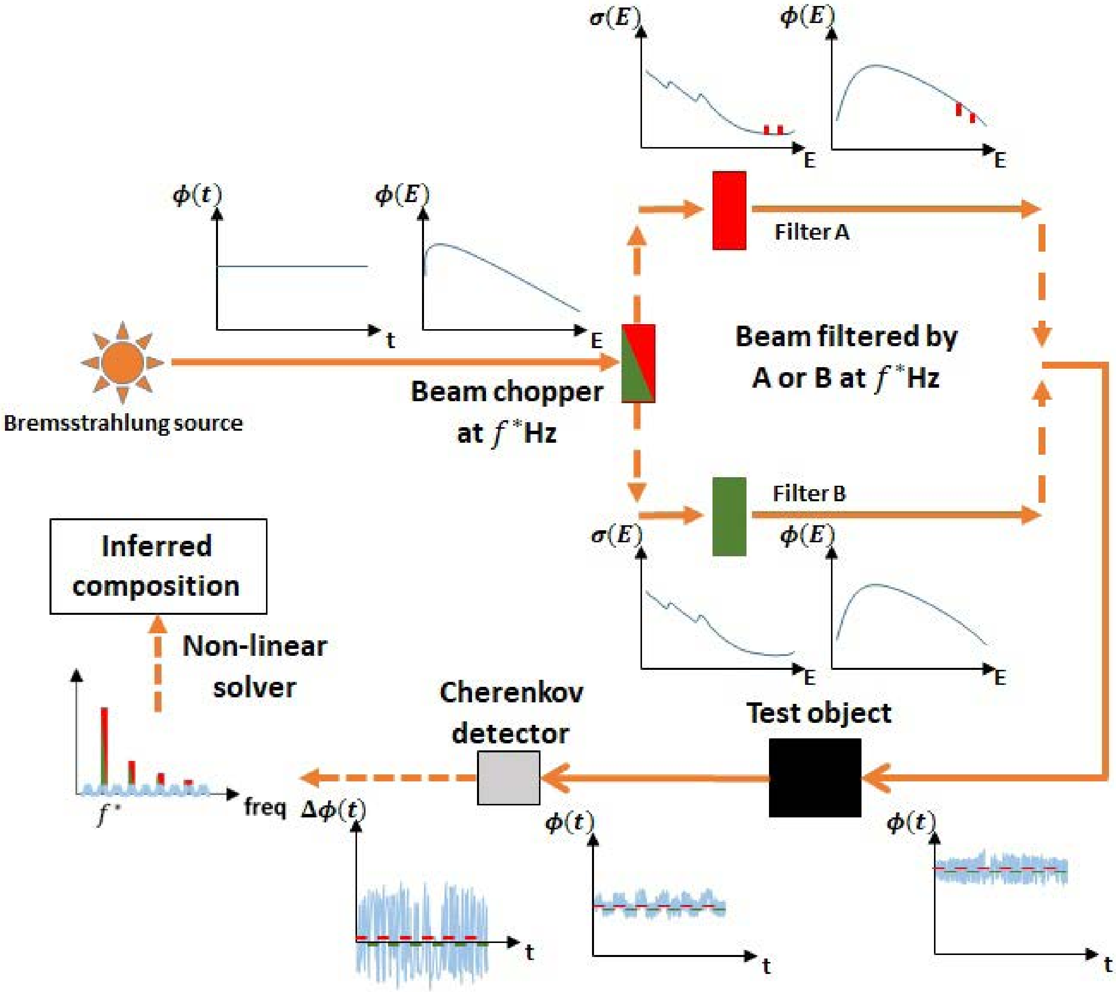

Figure 3. Signal processing to extract composition. The signal from the Cherenkov detector, which is time modulated at the chopper frequency, can be extracted from the noise through various techniques. The research team is using a phase-locked amplifier.

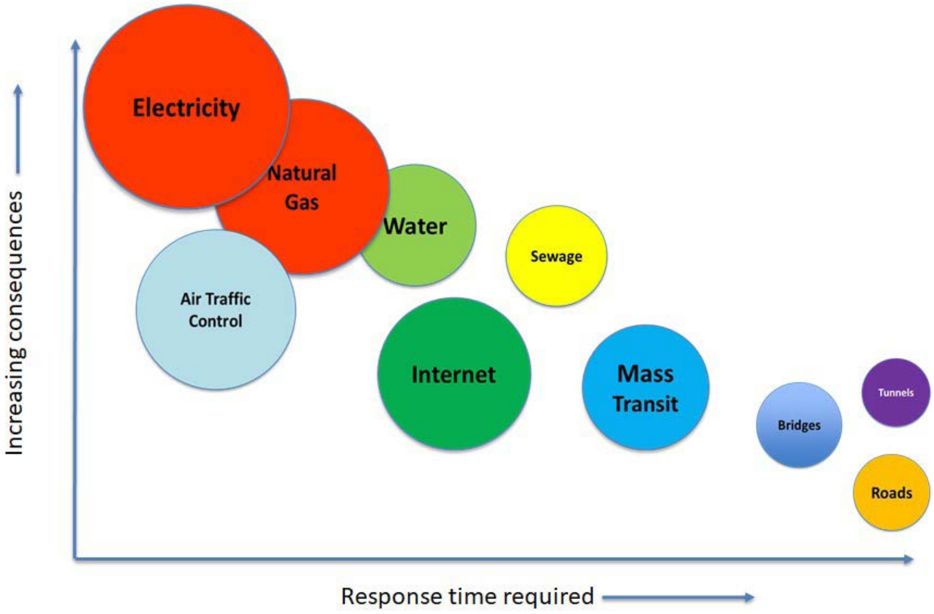

Figure 4. Diagram of a simulated spent fuel measurement.

Professor Emeritus Sidney Yip continued his professional activity in the form of collaborative research in deformation and flow of glassy materials and service to the materials simulation community at large.

Professor Emeritus J. P. Freidberg, in collaboration with Professor Antoine Cerfon (New York University) and Daniel Segal, has completed research comparing steady state versus pulsed tokamak reactors. A paper is in preparation. A brief summary of the conclusions is as follows:

- Pulsed reactors are competitive with steady state reactors and, in fact, are predicted to be slightly more desirable in terms of several performance measures.
- Smaller reactors (e.g., 500 MW versus 2,500 MW) are desirable from an industrial competitiveness point of view. Their designs are driven more by plasma physics than is the case with large reactors, wherein technological constraints dominate.
- Both small steady state and pulsed reactors require an enhanced value of the multiplying factor H to achieve power balance.
- High field is a potential game changer for steady state reactors, improving performance on virtually all fronts.
- Although high field helps pulsed reactors, the effect is not as pronounced as with steady state reactors. The maximum achievable field is advantageous for the overhead transformer but not for the toroidal field. For the toroidal field, the optimum is below the maximum value achievable technologically.
- Several important problems remain before moving forward with fusion electricity, including improving H, handling the divertor heat load, and addressing first wall survival.

In collaboration with Professor Luca Guazzotto (University of Auburn), Professor Freidberg has initiated research on exact analytic tokamak equilibria. These equilibria are simple, general, realistic, robust, analytic solutions to the well-known Grad-Shafranov equation. What is meant by all of these adjectives? “Simple” refers to the fact that the equilibria contain only a few terms that are intuitively simple to visualize. “General” indicates that the equilibria are valid for a wide range of configurations, including smooth surfaces, double null surfaces, single null surfaces, and finite and inverse triangularity. “Realistic” implies that the profiles are continuous and monotonic, with the pressure, pressure gradient, and toroidal current density smoothly vanishing at the plasma edge. Finite edge pedestals in pressure and toroidal current density are also allowed if desired. “Robust” refers to the fact that only five input parameters are required to obtain a solution (three geometrical and two simple physically intuitive parameters). The model leads to well-behaved solutions every time, with no delicate choosing of parameters. Lastly, “analytic” indicates that the solutions are exact solutions to the Grad-Shafranov equation, expressed in terms of known functions. Simple analytic expressions for the flux function and, importantly, its first and second derivatives have been derived.

Professor Emeritus Michael Driscoll continued his long-standing involvement with other faculty members and with students in support of fission reactor research projects.

Professor Emeritus Sow-Hsin Chen's collaboration with Professor Francesco Mallamace's group at the University of Messina has resulted in a number of published papers over the past year. The collaboration between Chen and Professor Piero Baglioni's group at the University of Florence also continues. Their research has concentrated on cement: nanoclays functionalized with carboxyl or polycarboxyl groups have been used to modify the micro- and macro-structures of both calcium silicate hydrate and magnesium silicate hydrate pure phases. Their influence on the micro-structure of the gels has been investigated via a multi-technique approach including small- and wide-angle X-ray scattering and scanning electron microscopy. The incorporation of natural and synthetic nanotubular fibers (halloysite, helium) improves the mechanical properties of the MgO-based cements without introducing additional heterogeneity in the composition. Helium structures act as "cross linkers" between magnesium silicate hydrate and calcium silicate hydrate phases due to the reactivity of the outer silica-rich surface. This innovative approach opens the way to nano-engineering of cement formulations to produce functional and sustainable building materials through bottom-up strategies.

Education

A total of 104 students pursued graduate degrees in nuclear science and engineering, of which 46% worked in the fission energy field, 26% in fusion and plasma physics, and 28% in other nuclear science and technology applications, including materials, nuclear technology management and policy, nuclear security, and quantum engineering. The department awarded 11 SM degrees and 14 PhD degrees. Sixteen students entered the graduate program in fall 2019.

A total of 21 students (six sophomores, seven juniors, six seniors, and two fifth-year students) were enrolled in the undergraduate program during the past year. Between September 2019 and June 2020, five students completed the requirements for a bachelor's degree in nuclear science and engineering and three students completed the requirements for a bachelor's degree in engineering.

The NSE Communication Lab (Comm Lab) continued to be a well-used departmental resource, both when services were provided on campus and during the campus shutdown. The Comm Lab is a discipline-specific peer-to-peer program that was launched in 2014 to help students and postdocs with their writing, speaking, and visual design needs. Under the management of Marina Dang, six graduate students served as communication fellows and held 225 one-on-one coaching sessions supporting 69 unique clients, including 10 non-NSE students. Roughly 35% of NSE undergraduate students and 42% of NSE graduate students used the resource, most commonly for slide presentations, theses and thesis proposals, and faculty applications. The client return rate of 61% testifies to users' satisfaction with the program. After five years of programming, we have noticed that an increasing number of students are working to elevate their communication skills without being prompted by a course instructor. Only 12% of one-on-one sessions were associated with a course this year, as compared with 34% in the previous year and 50% the year before. This suggests that more students see effective communication as an important part of their technical work and professional development.

In addition to coaching sessions, 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. Furthermore, the 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 helped MIT Summer Research Program (MSRP) students pursue graduate degrees. In light of the COVID-19 pandemic, the Comm Lab added online services to its portfolio and supported the department in hosting its annual Graduate Research Expo event.

The 22.011x Nuclear Energy: Science, Systems and Society EdX course, which debuted last year, was offered again in spring 2020. More than 6,000 learners from around the world signed up for the course, doubling last year's number.

Professor Short continues to co-lead the NSE undergraduate program, having launched the new 22-ENG flexible major, one of the goals of which was to boost enrollment in NSE. This has been effective, with the incoming cohort twice the size of the previous one. He also co-leads the New Engineering Education Transformation (NEET) Renewable Energy Machines thread. This thread, which has built a cohort of 20 students from six different departments, is focused on project-based learning around how to deploy zero-carbon, large-scale renewable energy. The thread has set its sights on decarbonization of Ulaanbaatar, Mongolia, as its first impactful target.

Faculty Awards, Honors, and Activities

Professor Baglietto was appointed NSE faculty community equity officer in April 2020 and will work closely with the department head to develop an NSE strategic plan focusing on diversity, equity, and inclusion. Professor Baglietto served as thermal hydraulics focus area lead for CASL.

Professor Bucci received the Ruth and Joel Spira Award for Excellence in Teaching. Bucci serves as the NSE UROP coordinator, and in spring 2020 he also took on the role of undergraduate recruitment officer. Under his leadership, NSE faculty have become re-energized and deeply engaged in first-year undergraduate activities, with plans for five of the 18 faculty members to serve as first-year student advisors in the next academic year.

Professor Buongiorno presented many seminars and invited lectures over the past year. Examples include "New Nuclear Needs a DD&D Paradigm and Market Inversion" (North Carolina State University, September 2019), "The Future of Nuclear Energy in a Carbon-Constrained World—Findings from a Recent MIT Study" (online lecture, Yale University, November 2019), and "Nuclear Energy: A New Beginning?" (webinar, Stanford University, April 2020). In addition, Professor Buongiorno served on the scientific advisory committee of the Nuclear Energy Division, Commissariat a l'Energie Atomique; was a member of the DOE SEAB Space Working Group; and was editor of a special issue on nuclear energy for *The Bridge* (National Academy of Engineering).

Professor Cappellaro was honored by her graduate students as "Committed to Caring" for her adaptability and stable guidance as an advisor, helping her students weather setbacks and continue to find delight in discovery even in the midst of a pandemic.

Professor Danagoulian received the 2019 Radiation Science and Technology Award from the American Nuclear Society's Isotopes & Radiation Division.

Professor Li was included in the 2019 Clarivate Highly Cited Researchers list in the cross-field category.

Professor Loureiro co-organized a mini-session (Turbulence, Waves, and Magnetic Reconnection from Magnetohydrodynamics to Kinetic Scales) at the 2019 American Geophysical Union conference. He also received the PAI Outstanding Faculty Award, presented by the student chapter of the American Nuclear Society.

Professor Shirvan continued as co-director of the Reactor Technology Course for Utility Executives and co-organizer of CASL.

Professor Emeritus Yip continued to represent NSE on the School of Engineering Ad Hoc Committee on Faculty Awards and Recognition. He remained a member of the Concrete Sustainability Hub at the Institute and actively supported the merging of the Center for Computational Science and Engineering and the newly established MIT Stephen A. Schwarzman College of Computing. He is one of the two editors-in-chief of the *Handbook of Materials Modeling*, a six-volume reference work published in March 2020.

Student Awards and Recognition

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

Rachel Carr, Ahmed Sami Helal Ali Elwakeil, and Sara Ferry received the Postdoctoral Service Award for exceptional service to the department, MIT, or the world at large through activities outside the lab.

Guillaume Giudicelli won second best paper at the Mathematics & Computation for Nuclear Science and Engineering conference. He also won best poster awards at the American Nuclear Society's annual meeting and the CASL Summer Institute.

Sterling Harper won best paper at the Mathematics & Computation for Nuclear Science and Engineering conference.

Liam Hines received the Irving Kaplan Award for academic achievement by a junior in nuclear science and engineering.

Mariam (Rathbun) Kresher received the American Nuclear Society Alan F. Henry/Paul A. Greebler Graduate Scholarship.

Hin Yeung "Jimmy" Lee was presented the Outstanding TA & Mentorship Award for exceptional contributions in the department as a teaching assistant and mentor to other students.

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

Warner McGee won the Roy Axford Award for academic achievement by a senior in nuclear science and engineering.

Thanh Nguyen received the Sow-Hsin Chen Fellowship in Neutron Science.

Gavin Keith Ridley received a three-year Department of Energy Nuclear Energy University Program fellowship.

Pablo Rodriguez Fernandez received the Del Favero Thesis Prize for "Heating by Cooling: Perturbing Fusion Plasmas to Predict SPARC Performance." This prize, established in 2014 with a generous gift from alum James Del Favero SM '84, is awarded annually to a PhD graduate in NSE whose thesis is judged to have made the most innovative advance in our field.

Myles Stapleberg received the Outstanding UROP Award for exceptional contributions to a research project by a junior or senior in nuclear science and engineering.

William "Robbie" Stewart won the Manson Benedict Award, presented to a graduate student for excellence in academic performance and professional promise in nuclear science and engineering.

Guanyu Su received the Postdoctoral Outstanding Research Award for research of outstanding academic quality conducted within the past year.

Amelia Trainer, Isaac Meyer, Miriam Kreher, and Sam McAlpine received Outstanding Student Service Awards for exceptional service to the department.

Charlotte Wickert was presented the Outstanding UROP Award for exceptional contributions in an NSE project by a freshman or sophomore.

Haowei Xu won the $70,000 MathWorks Engineering Fellowship for an "outstanding academic record, exceptional background, and promising future."

Outstanding Poster awards at the 2020 NSE Graduate Research Expo were presented to Gustavo Matana Aguiar ("Using Laser and an Infrared Camera to Understand the Flow and Heat Transfer Characteristics of Nucleating Vapor Bubbles"), Ethan Klein ("Epithermal Neutron Resonance Imaging for Nuclear Disarmament"), Yi-Xiang Liu ("High-fidelity Trotter Formula for Digital Quantum Simulation"), Julie Logan ("Uncovering the Fundamental Driver of Semiconductor Radiation Tolerance"), and Erica Salazar ("High Temperature Superconductor Testing for a Compact Fusion Energy Device").

Staff Awards and Activities

Peter Brenton won the School of Engineering's Ellen Mandigo Award. This award recognizes staff members who have demonstrated, over an extended period of time, intelligence, skill, hard work, and dedication to the Institute.

Brandy Baker received the Outstanding Staff Award, presented by the student chapter of the American Nuclear Society. Also, Baker organized and led a new pilot mentoring program for first-year graduate students in the department. This "Orientation 2.0" brings members of the incoming graduate student class together throughout their first year in NSE for a series of in-depth Q&A sessions with the department head and presentations from MIT staff about graduate student resources (e.g., Office of Graduate Education, Graduate Student Council, MIT Libraries). The new program was highly rated in student surveys and feedback forms and will continue next year.

Heather Barry spearheaded the new department outreach program for increasing graduate student diversity. Barry attended several conferences that serve primarily Black and Hispanic scholars and students in the United States and made presentations about opportunities for research in nuclear science and engineering for prospective graduate students. She also ran the second NSE Winter School, a program conducted during IAP that brings together approximately 10 undergraduate women and underrepresented minority students for an intensive networking and mentoring experience. NSE Winter School students have gone on to participate in the MSRP program in NSE and other departments.

Anne E. White
Department Head
SoE Distinguished Professor of Engineering