# 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.

Our mission is to develop the next generation of leaders of the global nuclear community, advance basic research, provide technical leadership on energy and non-energy applications of nuclear technology, and inform public discussion about nuclear science and technology in order to address global grand challenges.

While we operated remotely this past year, we nurtured a sense of belonging by holding many events virtually, which opened a new door of opportunity to *expand* our community and *engage* our alumni. The variety of virtual events celebrated the uniqueness of our field and our core discipline of nuclear science and engineering, as well as highlighting the potential for positive global impact of nuclear technologies. Some examples are presented below.

- Professors Mingda Li, Koroush Shirvan, Areg Danagoulian, and Jacopo Buongiorno presented at the Alumni Association Faculty Forums Online, drawing large crowds who were keen to learn about the frontiers of research in NSE.
- Department Head Anne White has reached out to many alums by Zoom to thank them for giving to MIT and NSE, to celebrate their continued success (such as NSE alumni Pablo Rodriguez-Fernandez PhD ’19 and Katia Paramonova ’13 who have been named to the Forbes 30 Under 30 list for 2021), and to learn about their career paths and stories.
- Edith Wun, leadership giving officer in NSE, has spearheaded the formation of the new grassroots, alumni-led Kazimi Fellowship Committee, which is carrying out fundraising for a new named fellowship to honor and celebrate the life of our esteemed colleague Professor Mujid S. Kazimi, who passed away six years ago.
- William D. Magwood, director-general of the Organisation for Economic Co-Operation and Development Nuclear Energy Agency, delivered the 2021 David J. Rose Lecture in March.
- Nuclear Science and Engineering launched a new internal website, Intranet Hub, containing calendar information as well as student and faculty resources.
- Weekly staff meetings were held via Zoom (led by Peter Brenton the administrative officer and regularly attended by the department head).
- The NSE Graduate Student Research Expo was held virtually, and featured best posters selected by the audience and a panel of judges, including alumni judges.

## Diversity, Enrichment, and Inclusion Plan Update

The global pandemic was a stress test for the department, but everyone pulled together in ways that celebrated our shared experiences while highlighting differences in our experiences and identifying places where we have room for improvement.

In particular, the summer of 2020 created moments to pause and reflect on the experiences of women and people from underrepresented minority groups, in STEM fields across the country. This summer saw a letter of demands from the NSE Student RISE Group. There has been renewed interest among faculty and staff to accelerate and strengthen the nascent departmental diversity, enrichment, and inclusion (DEI) efforts.

Beginning in October 2020, a comprehensive DEI plan for NSE began to take shape, with a first draft for the plan developed by Professor Anne White and building largely on the graduate student diversity plan adopted the previous fall. The language in the draft DEI plan was edited and augmented by NSE faculty at the January 2021 faculty meeting. New content was added after feedback sessions with the entire community (including staff and students) via a series of community forums and town halls. The nearly nine-month process culminated in a final draft of the DEI plan presented to the entire community in May 2021. The faculty reviewed the timeline for release of the DEI plan in June 2021 and will hold a final discussion of the DEI plan in summer or early fall 2021.

## Strategic Planning Process

The strategic planning process for the department began in fall 2019 with a successful faculty retreat in September and formation of a small working group charged with exploring all options for NSE. In December 2019, there was a follow-up faculty meeting in which the faculty identified new research and educational opportunities that would position NSE as a leader in the growth of nuclear energy. In addition, strong arguments were made to support a new focus on education and research in quantum engineering, a multi-disciplinary area that would offer opportunities for partnership with the MIT Stephen A. Schwarzman College of Computing. There were also active discussions about how to grow interest in the field of nuclear engineering by making education more hands on, more experiential, and more responsive to societal needs.

In January and February 2020, the working group spent time on one-on-one interviews with all faculty members, senior research staff, and active emeritus faculty. However, the global Covid-19 pandemic and the Institute response for continuity of research and education, starting in March 2020, called for a pause of the strategic planning effort and the development of a new timeline.

The details of the overall NSE strategic plan were completed in spring 2021 through a series of faculty mini-retreats and discussions at faculty meetings led by Anne White and Professor Benoit Forget. The mini-retreat sessions were designed to develop insights on frontier research areas, to discuss plans to revitalize education in NSE, to unify faculty behind a shared set of values, and to perform critical analysis of our strengths and challenges together while also identifying strategic opportunities. Staff and students were consulted as part of the overall planning process and their input was incorporated, especially in the community building portion of the plan. In summer 2020, an expanded strategic working group was called upon to review key elements of the plan and the central messaging. The final language for the updated core, mission, and vision statements was developed by a small task force following adoption of the main messages and draft language at the May 2021 faculty meeting.

Obtaining resources for the new NSE strategic plan was a consideration from the very beginning. With the hiring of Edith Wun as school development officer in 2019, Professor White and Wun began developing a fundraising strategic plan for NSE in partnership with the School of Engineering and MIT Resource Development. The plan details fundraising priorities to support NSE's new strategic plan as well as the accompanying diversity, equity, and inclusion plan.

## Faculty and Administration

Professor Emeritus Sow-Hsin Chen, global expert in neutron science and devoted mentor, passed away in June. Several NSE faculty and staff were able to attend his memorial service.

Professor Emeritus Michael J. Driscoll, leader in nuclear engineering and beloved mentor, passed away in December. His contributions over a span of seven decades advanced nuclear waste disposal and fuel cycle development.

Assistant Professor Jack Hare joined the Department of Nuclear Science and Engineering in January.

Nuno G. Loureiro was promoted to full professor.

Michael Short was promoted to associate professor with tenure.

## Research Highlights

MIT School of Engineering Distinguished Professor of Engineering Anne White is currently head of the department. 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 nondiffusive 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 international thermonuclear experimental reactors and affordable, robust, and compact reactors.

Her group is engaged in experimental research at three major tokamaks (ASDEX Upgrade; DIII-D; and NSTX/NSTX-U) where the team leads experiments and develops diagnostics and validation projects using advanced turbulence simulation codes. Professor White has four students and a research scientist working in the group. Research Scientist Pablo Rodriguez-Fernandez performs predictive modeling for SPARC, develops new optimization tools at ASDEX Upgrade (AUG), and collaborates with the JET tokamak on integrated modeling with a focus this year on the upcoming D-T campaign. He also supports students working on several tokamaks. NSE students Rachel Bielajew and Christian Yoo continue development and optimization of CECE/nT-phase systems at AUG. Bielajew is studying edge turbulence in ELM-free, high-performance plasmas, and Yoo is exploring the use of ML/AI applied to understanding scaling of turbulence and transport across a wide range of engineering and plasma parameters.

Undergraduate Research Opportunities Program (UROP) student Calvin Cummings joined the group in summer 2020, working on new control room visualization tools for CECE access at AUG. He has expanded his work in 2021 to develop a benchtop test of the optics setup at AUG to better characterize the spatial resolution of the instruments via direct tests in the laboratory at MIT. NSE student Bodhi Biswas, who is co-advised with Paul Bonoli at the Plasma Science and Fusion Center (PSFC), works on developing reduced models of edge turbulence to study how injected RF waves interact with turbulence in the tokamak. Biswas gave an invited talk in November 2020, "Study of Turbulence-Induced Refraction of Lower Hybrid Waves Using Synthetic SOL Blobs," at the 62nd Annual Meeting of the APS Division of Plasma Physics. He also published two papers in 2020 in *AIP Conference Proceedings* and in *Physics of Plasmas* on his research.

NSE student Xiang Chen completed a feasibility study for a new, soft X-ray based diagnostic that could be used to measure electron temperature fluctuations in NSTX-U. His work was published in *Review of Scientific Instruments*. Professor White is also involved as a member of the doctoral supervision committee with students working in the area of high-energy-density physics at Lawrence Livermore National Laboratory, on collaborations with the SPARC tokamak, at the stellarator W7-X located in Germany, and in the pedestal physics and boundary physics groups at PSFC.

The Computational Reactor Physics Group, led by Professor Benoit Forget, continues 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 nuclear data representation and processing. Recent highlights include a series of three papers describing in detail the foundation of the pole representation in scattering theory and establishing its many advantages over the current form. This new data representation approach was leveraged in a recent PhD thesis to compute temperature derivative of processed quantities to accelerate the coupling between neutron transport and thermohydraulics, as well as to propagate nuclear data uncertainties in large-scale Monte Carlo simulations. Current work is focused on the development of nuclear data covariance matrices in the proposed formalism as well as the development of novel data representations for the thermal and unresolved energy ranges. As part of the Exascale Computing Project, a novel asynchronous parallel acceleration approach was developed and tested. This work demonstrated a way to combine independent Monte Carlo neutron transport simulations to properly evaluate the variance of reaction rate estimators while also accelerating source convergence and improving load balancing.

Professor Jacopo Buongiorno, together with Professor John Lienhard and John Parsons, led a project titled "Water for a Warming Climate: A Feasibility Study of Repurposing Diablo Canyon Nuclear Power Plant for Desalination." Briefly, California has a pressing need for additional sustainable fresh water supplies and for carbon-free energy. This project explores the feasibility and economic benefits of co-locating a large seawater desalination plant at the Diablo Canyon Nuclear Power Plant (DCNPP) to supply potable water to the state. A key challenge for any desalination plant and for continued operation of DCNPP is compliance with California's regulations protecting marine organisms from large intake structures. We show how a new brushed-screen intake structure, serving both the nuclear power plant and the desalination plant, achieves compliance. The proposed arrangement has the potential to reduce the cost of desalinated water from approximately $1.84 per m$^3$ of fresh water for a stand-alone plant to less than $1.00/m$^3$. These cost savings are mostly due to the benefits of shared infrastructure and reduced energy costs. Additional savings are possible at larger scales.

Professor Buongiorno founded the Advanced Nuclear Energy and Production Expert Group (ANPEG). ANPEG is a global consortium dedicated to developing low-carbon energy systems based on a plug-and-play nuclear microreactor (or, nuclear battery) that will provide flexible, resilient, and cost-effective energy solutions to support advanced production activities, energy equity, and climate change mitigation and adaptation. ANPEG has over 40 members, including several energy companies, Department of Energy (DOE) national labs, and leaders in clean energy and the environment.

Professor Nuno Loureiro's group focus is on theory and simulations of nonlinear plasma dynamics. Over this reporting period, work continued on turbulence, magnetic reconnection, and the interplay between the two phenomena. Particularly noteworthy has been work by graduate student Lucio Milanese on uncovering the novel mechanism of dynamic phase alignment in turbulence in both plasmas and neutral fluids, which underlies the joint direct cascade of energy and helicity in turbulence. This work was published in *Physical Review Letters*.

A parallel research direction has been the derivation of efficient quantum algorithms for the potential quantum simulation of nonlinear plasma problems. In collaboration with researchers at the University of Maryland, we have proposed a novel algorithm based on a mathematical technique known as Carleman linearization. This work was featured in *Quanta Magazine*.

Professor Ian Hutchinson continues his research on plasma electron holes: solitary electrostatic structures that result from kinetic instabilities and are widely observed in space plasmas. Recent satellite observations have shown that under some circumstances these positive potential peaks, sustained by the plasma alone, move at very slow speeds relative to the ions. This is surprising because past theory and simulation has shown that slow electron holes generally accelerate themselves quickly to much higher speeds by means of interaction with reflected ions. Hutchinson's theory has demonstrated that to avoid this self-acceleration requires that the ion velocity distribution be double humped with the hole's velocity lying in its local minimum. Almost simultaneously with the development of this understanding, analysis of multisatellite observations of the Earth's plasma sheet established that the slow holes observed there have velocities that do indeed lie in a local ion velocity distribution minimum. This remarkable agreement between theory and experiment is in the process of publication.

Professor Zachart Hartwig leads multiple efforts in the Department of Nuclear Science and Engineering and at the Plasma Science and Fusion Center. These efforts are principally focused on accelerating the deployment of commercial fusion energy through the advancement of fusion science, engineering, and technology.

Professor Hartwig's principal role during this period has been as the principal investigator (PI) and project head of the SPARC Toroidal Field Model Coil (TFMC) project. The TFMC project is a two-year collaborative effort between MIT Plasma Science and Fusion Center and the Commonwealth Fusion Systems (CFS), a private company spun off from MIT to focus on fusion energy commercialization. The primary objective of the TFMC project is to design, build, and test the world's highest performance, large-scale superconducting magnet, as well as to develop and construct the technology and test facility required to properly test the magnet. If successful, the TFMC will provide a full-scale demonstration of the MIT-CFS high-field magnet technology, opening a pathway to a high-field fusion device called SPARC that seeks energy break-even in the mid-2020's as well as application of the magnet technology in other areas of research and industry. At the time of this writing, the TFMC test facility has been successfully constructed and commissioned at full performance and the TFMC has been completed and is ready for installation within the test facility. The initial full performance tests are expected to take place in August 2021, when the TFMC will be cooled and energized to attain over 20 T peak magnetic field-on-coil.

Jack Hare began his appointment as an assistant professor in January 2021 and has begun to build his research group, focusing on the behavior of magnetized, high-energy-density plasmas. His group is carrying out design work for the new PUFFIN (PUlser For Fundamental INvestigations) pulsed-power facility, which will be housed at the Plasma Science and Fusion Center and will deliver microsecond, mega-Ampere pulses of electrical current to convert thin metal wires into high-temperature, high-density plasma accelerated by large magnetic fields. PUFFIN will be used to study fundamental plasma physics processes, including magnetic reconnection, which leads to potentially catastrophic solar storms that can cause significant damage to satellites and electrical grids.

Professor Hare was recently awarded four experiment days on the Z facility run by Sandia National Laboratories, as PI of the MARZ (Magnetically Ablated Reconnection on Z) collaboration. Z is the largest pulsed-power facility in the world, with around 250 experiment days per year, of which 10 are made available to external users through the Z Fundamental Science Program. As such, these experiments provide a unique opportunity to study magnetic reconnection on Earth at the conditions found in extreme astrophysical environments, such as black hole coronae. In support of PUFFIN and MARZ, Professor Hare's group has been running simulations using the GORGON 3D magnetohydrodynamics code, augmenting the simulation capability present in the Center of Excellence headed by Richard Petrasso at the PSFC.

Professor Michael Short's group made two major discoveries this year worth mentioning, both relating to direct measurement of radiation damage through stored energy fingerprints. First, the direct energy signature of radiation damage in neutron-irradiated metals from the MIT reactor was successfully measured, most notably from materials irradiated at reactor conditions. Second, the group successfully showed that they were able to determine the amount of uranium-bearing gas enriched in centrifuges, based on changes in phase transformation enthalpies in PTFE (Teflon)—a gasket material used in enrichment centrifuges.

Charles Forsberg is developing two large-scale heat storage technologies to address the challenges of a low-carbon economy and the addition of wind and solar to the electricity grid that creates volatile wholesale electricity prices with times of near-zero electricity prices and times of high prices. The Firebrick Resistance Heated Energy Storage system uses conductive firebrick developed by us to convert low-price electricity when available into stored high-temperature heat at temperatures from 1,000°C to 1,600°C. The high-temperature heat is delivered as hot air, when needed, for use in industry and gas turbines. Patents have been filed and a startup company has been formed to commercialize the technology. The second technology is the Crushed Rock Ultra-Large Stored Heat system to provide 100 GWh of storage at capital costs of $2–$4/kWh, a factor of 10 under existing heat storage technologies. Heat provided by nuclear or concentrated solar power plants is stored at times of low electricity prices to produce peak electricity at times of high prices. The very low cost (50 times less than batteries) may enable daily to weekend/weekday energy storage.

As principal investigator, Forsberg is building a forced circulation, liquid-salt loop at the MIT reactor that includes heating the salt to 700°C, irradiating the salt, and cooling it. The loop will simulate behavior of salt coolants in a fluoride-salt-cooled, high-temperature reactor with clean salt and solid fuel; a molten salt reactor with fuel dissolved in the salt; and a salt blanket in a fusion reactor. The general-purpose test loop will investigate corrosion, tritium, and fission product transport and be a test bed for instrumentation and salt cleanup systems. It's the first such loop to be built in over 50 years in the United States.

Professor Emilio Baglietto co-founded the University Consortium extending the DOE national Center of Excellence (COE) for Thermal Fluids Applications. The consortium is led by the Penn State Department of Nuclear Engineering; it partners with the COE and industry members to accelerate the deployment of advanced nuclear reactors. The grant, awarded by the US Department of Energy, funds collaborative work with scientists from the Massachusetts Institute of Technology, the University of Michigan, Texas A&M University, North Carolina State University, Liberty University, Kairos Power, Westinghouse, General Atomics, and TerraPower, as well as Idaho National Laboratory and Argonne National Laboratory. Professor Baglietto leads the focus area on thermal striping of reactor internals, one of the four challenge problems selected by the consortium. The hybrid turbulence modeling and turbulence uncertainty quantification methods developed by Professor Baglietto's group are the central technology to advance the thermal-hydraulic modeling and simulation of leading-edge reactor designs, leveraging collaboration with the consortium members to extend the validation and best practice creation for the advance simulation methods.

In a project focused on developing high-fidelity digital twins for the critical systems in advanced nuclear reactors, Professor Baglietto, supported by Professor Koroush Shirvan, is collaborating with researchers from GE Research and GE Hitachi to assemble, validate, and exercise high-fidelity digital twins of the BWRX-300 systems. The GE

Hitachi BWRX-300, a small, modular reactor designed to provide flexible energy generation, is a promising concept that aims to be competitive with natural gas to realize market penetration in the United States. Digital twins address mechanical and thermal fatigue failure modes that drive operations and maintenance activities well beyond selected BWRX-300 components and extend to all advanced reactors where a flowing fluid is present. The role of high-fidelity resolution is central to the approach, as it addresses the unique challenges of the nuclear industry. Professor Baglietto is leveraging the tremendous advancements that his team has achieved in recent years to accelerate the transition of the nuclear industry toward high-fidelity simulations in the form of computational fluid dynamics (CFD).

Baglietto's group, under the now completed Consortium for Advanced Simulation of Light Water Reactors program, has considerably advanced the capability of predicting heat transfer in multiphase flow systems, up to its critical condition. The modeling approach has demonstrated the essential ability to extend its application to include the effects of varying heater and coolant evolution, which is becoming relevant to support life extension of both the light water reactors as well as CANDU reactor fleets, and extends well beyond the nuclear industry. Since 2020 NASA has provided continued and growing support to leverage the modeling techniques advanced in Professor Baglietto's group as part of the new Lunar and Mars Exploration programs, where a key concern is related to the long-term storage and transfer of fuels in a cryogenic state—on the lunar surface and in orbit. Two projects have been funded to first assemble the boiling closure as part of the NASA CFD simulation tools, and further to produce new closure models for cryogenic fluids in collaboration with the experimental team of Matteo Bucci. A third project has been funded to perform reduce gravity tests in parabolic flights, starting in fall 2021. The program will continue to expand to extend the model applicability into the NASA simulation tools and later to extend its applicability to a range of cryogenic fluids.

Assistant Professor Matteo Bucci is expanding his research activities in two-phase heat transfer. His laboratory, known as The 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 the understanding and enhancement of the boiling performance.

The team is leading many projects aimed at elucidating the mechanism of boiling heat transfer and the boiling crisis. In fact, despite decades of research, the 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 as diverse as space vessels and high-power electronic devices. The team is currently leading two projects sponsored by the Department of Energy through the Nuclear Energy University Programs and the Versatile Test Reactor (VTR) programs, two projects sponsored by the Nuclear Naval Laboratory, two projects sponsored by NASA, and one project sponsored by the National Science Foundation.

In 2020, Professor Bucci received an award from the National Science Foundation to study the fundamentals of boiling heat transfer. In particular, his team will explore "the percolative scale-free nature of the boiling crisis." This is a new fundamental theory put forward in a 2018 paper by Professor Bucci, published in *Physical Review Letters*, and recently corroborated by new results published in *International Journal of Heat and Mass Transfer*. The team is currently preparing another publication discussing the presence of a unifying principle of the boiling crisis, which can be deducted mathematically through continuum percolation models, and supporting this conclusion with experimental data obtained on a plethora of boiling surfaces and several operating conditions.

Artificial intelligence has changed the research landscape in many areas of science and engineering. However, its application to two-phase heat transfer research has been marginal so far and practically limited to the interpolation of experimental data. Professor Bucci's team is leading efforts at the intersection of experimental research, advanced diagnostics, and artificial intelligence. 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 (i.e., the post-processing). In 2020, Professor Bucci has expanded the use of machine learning capabilities to the boiling crisis, demonstrating that it is possible to make online predictions of the margin to the boiling crisis and elucidating the physical parameters controlling this phenomenon. All these developments will be integrated to develop an autonomous heat transfer lab. In January 2021, the team started a research project sponsored by the Nuclear Naval Laboratory aimed at developing an experiment run autonomously by artificial intelligence without any operator control.

Professor Bucci also started, in collaboration with Professor Baglietto, an experimental project sponsored by NASA as part of the new Lunar Exploration program. The Red Lab team has developed high-resolution diagnostics and run experiments to study the boiling of cryogenic fluids. These experiments will inform the development of models in Professor Baglietto's group. In fall 2020, the team received an award to study these phenomena in microgravity conditions.

Assistant Professor Koroush Shirvan has initiated a project supported by Fortum (a Finnish energy company), in collaboration with MIT's Concrete Sustainability Hub, to create an open-source advanced nuclear cost model. The focus of the work will be near-term, small modular reactors. The work will focus on quantifying risk and uncertainties in nuclear technology cost calculation and aims to draw insights on key pathways and innovations that can effectively support nuclear energy deployment.

Professor Shirvan continued his work on light water reactor (LWR) sustainability by improving LWR safety and economic efficiencies supported by DOE in collaboration with nuclear utilities and vendors. This past year, he developed multitude advanced methods to assess performance of near-term accident tolerant fuels (ATFs) and high burnup fuels. The US nuclear industry plans to adopt high burnup fuel and selected near-term ATFs by 2025 to improve safety and reduce nuclear fuel cycle cost. Professor Shirvan is also continuing his work with the company Free Form Fiber to additive manufacture an optimized fuel form.

During the past year, Professor Shirvan has formed a strong, advanced non-water cooled reactor research program to support the future of nuclear technology. He led concept and team development of three successful NSE proposals to the U.S. Department of Energy's Advanced Research Projects Agency's program, Generating Electricity Managed by Intelligent Nuclear Assets, aimed to significantly reduce operation and maintenance cost of advanced nuclear technologies through digital twining. He led the only successful university led proposal for the Advanced Reactor Demonstration Program as part of the US government effort to demonstrate advanced nuclear technologies before 2035 based on a high-temperature-reactor concept that can more flexibly provide carbon-free energy for non-electricity applications.

In addition, Professor Shirvan has initiated nuclear space research and development in the department. An innovative, high-performing nuclear fuel technology based on thorium received the best paper award at the Nuclear Enabling Technologies for Space conference. He has also been leading the development of a test bed for accelerated deep space nuclear qualification at the MIT reactor to support NASA's deep space missions, particularly the human mission to Mars.

Professor Shirvan has made progress on the application of artificial intelligence (AI) to nuclear reactor core design. The work is being performed in collaboration with the MIT Quest for Intelligence and funded by Exelon, the largest nuclear plant operator in the United States. The AI technology based on reinforcement learning has shown promise and great efficiency in replicating the complexities of real-life nuclear fuel engineering. The first version of the AI software was successfully installed on Exelon computer systems in September 2020. The team plans to fully deploy the technology for Exelon candidate reactors by the end of 2021.

Professor Paola Cappellaro's Quantum Engineering Group focuses on developing novel quantum devices by engineering quantum systems and their control. The research activities span the control of small quantum systems optimized for specific tasks, such as quantum sensing, and of larger, many-body systems that provide a platform to study quantum simulation and more broadly, limits on the control and coherence of scalable quantum systems.

Among key results, the Quantum Engineering Group found novel control sequences to increase the coherence time of spin qubits and allow vector magnetometry with single spins (while most previous schemes only allowed scalar magnetometry). The exquisite control on such systems also enables using them for quantum simulations of exotic matter states, such as tensor monopoles and time symmetries. By advancing the control of many-body systems with analytical and machine learning optimization, they could explore the Floquet prethermalization regime (a robust phase that emerges under periodic driving of many-body quantum systems) and the rate at which this quasi-equilibrium phase will eventually thermalize—an important benchmark in the quest to control ever-larger quantum systems.

Professor Ju Li's group continued to develop radiation and helium tolerant materials for fission and fusion energy. Neural network interatomic potentials were developed for FLiBe and NaCl molten salts, and the effects of hydrogen/tritium valence on its bonding and transport in molten salts were studied. A universal neural network interatomic potential inspired by iterative electronic relaxations called TeaNet was developed by So Takamoto when he visited Ju Li's group, covering the first 18 elements on the periodic table (hydrogen to argon). TeaNet has been shown to be robust and can be used to describe C-H molecular structures, metals, amorphous silicon dioxide, and water. Continued development of TeaNet has led to the commercial software, Matlantis™, a cloud-based atomistic simulator, by Preferred Networks, and ENEOS Corporation, that can now describe arbitrary combinations of the first 55 elements on the periodic table, with more being added. A fundamental study of radiation polarization and interstitial-vacancy imbalance in ion-beam irradiation was published in *Computational Materials*. In addition, advances were made in elastic strain engineering of diamond and metallic glasses, as well as development of first-principles machine-learned constitutive relation for deep elastic strain engineering.

Professor Mingda Li and his research group focus on designing next-generation materials measurement methods, augmenting state-of-the-art materials measurement techniques, and performing unconventional uses of existing techniques to acquire key information on quantum materials that had been considered not measurable or not readily measurable before. Gaining such knowledge is valuable to boost fundamental advancement and to support practical applications of quantum technology.

During the past year, Professor Mingda Li showed that nontrivial electronic topology can leave hallmark traces in lattice degrees of freedom, breaking new ground on detecting topology; the group also showed that the thermoelectric energy conversion power factor can be enhanced by a factor of 10 by using a newly established physics law. Beyond that, using symmetry-preserved neural networks, Professor Mingda Li and his group have shown that it is possible to predict the density-of-state of phonons—a key property that governs thermal transport process—with comparable accuracy to finest calculation but with two-to-three orders of magnitude lower computational cost; lastly, in a more recent report, Professor Mingda Li and his group showed that, for the first time, an exotic dynamic quantum phase can be observed in solid-state systems. These works have been highlighted by the DOE Office of Science Highlights and in the following MIT News stories:

- "Newly Observed Phenomenon Could Lead to New Quantum Devices"
- "A Cool Advance in Thermoelectric Conversion"
- "A Streamlined Approach to Determining Thermal Properties of Crystalline Solids and Alloys"

Research Scientist Richard Lanza continued his work with the World Federation of Scientists (WFS) on infrastructure security and nuclear arms control. The infrastructure work focused on linkages between electric grid and gas pipeline infrastructure. The initial conclusions and recommendations were published in *US Infrastructure: Challenges and Directions for the 21st Century*. This work was prescient in view of the events in Texas in the winter of 2021 when the electric system and the natural gas distribution system both failed and resulted in a major power outage.

During the current year, the group has taken on a new area of interest: Can Joint Risk Analysis and Cooperative Risk Mitigation Help Advance Nuclear Arms Control? The WFS, an international group of nuclear and risk experts, has begun exploration of the application of state-of-the-art risk sciences to arms control issues. The findings and recommendations were driven primarily by lessons learned from the exercise.

Quantitative concepts are essential in risk assessment, such as probabilistic risk assessment, but precise measurement is seldom available in negotiations, necessitating more subjective judgments as to whether the significance of a particular action is positive, negative, or basically neutral. Furthermore, in a confrontational environment, depending on how the parties play the game, working side by side with formal risk assessment methodologies on technical issues as well as on national defense and arms control considerations may or may not enhance dialog, help develop trust, or facilitate some mutually acceptable solutions forward. Although the results are not yet clear, preparing formal risk analysis with the prospect of engagement may at least enhance the understanding of each party of its own risk horizon.

In collaboration with colleagues in Electrical Engineering and Computer Science, Mechanical Engineering, and at Massachusetts General Hospital's Radiology department, we have continued our work in developing an X-ray imager for imaging with a 3D resolution of 10 nm and below. This work is the subject of two patents that were recently approved: "Nanoscale X-ray Tomosynthesis for Rapid Analysis of Integrated Circuit (IC) Dies," US Patent 1,115,213,0B2; and "System and Method for Nanoscale X-ray Imaging of Biological Specimen," US Patent 1,114,543,1B2. The former is a technique for inspecting integrated circuit dies for defects and possible clandestine changes while the latter is aimed at imaging structures within individual cells. The overarching goal of the cellular imaging is to enable routine, direct visualization of interactions between an agent (i.e., a drug or biologic) and cell surface or intracellular receptors. Ultra-high resolution X-ray images will complement the information obtained by DNA sequencing and provide a more complete picture about the ultra-structure of the cell surface and cytoplasm of the altered DNA. The ability to rapidly determine the ultra-structural details of the cell surface, particularly receptors, will allow a more robust response to drug resistance and therapy selection and will provide an understanding of the mechanism of drug resistance and significantly reduce the risk of drug resistance.

For initial tests, we used a conventional scanning electron microscope (SEM) to simulate the multibeam source. The beam size of the SEM can be adjusted down to 10 nm or less and will be used to demonstrate absorption and phase contrast imaging at 30 nm.

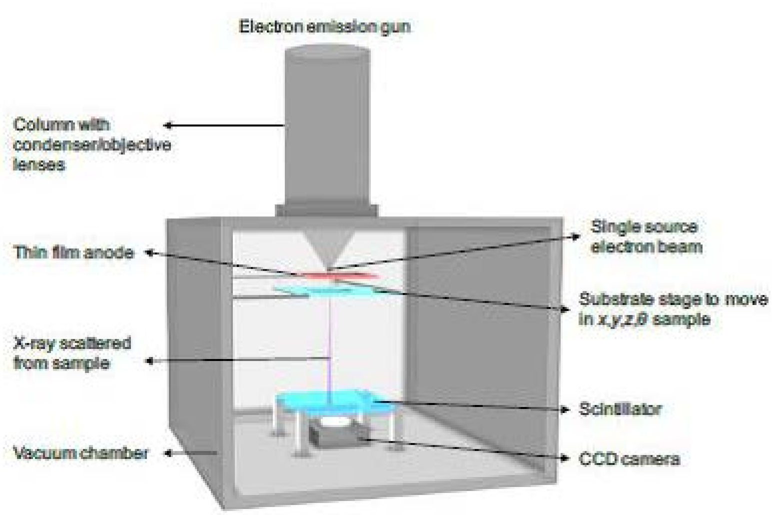


*Figure 1: Proof of concept of X-ray nanoscope platform built by modifying an SEM.*

Professor Emeritus Sidney Yip continued his professional activity as an emeritus member in the department and at MIT on two levels. He has completed a collaboration with Wanda Andreoni at the Swiss Federal Institute of Technology of Lausanne in which they served as co-editors in chief of the *Handbook of Materials Modeling*, second edition, published in six volumes in 2020 by Springer-Nature. In addition, Yip is writing a research manuscript called *Molecular Mechanisms in Matter*. The work will be composed of 15 scientific essays each of which will be focused on a stand-alone, specific topic in materials research. Collectively the essays present an extended perspective on integrating theory, modeling, experiments, and simulations to exploit the opportunities and challenges of bridging computer and computational science.

Professor Emeritus Neil Todreas continued his work on the thermal hydraulic behavior of wire wrapped rod bundles for sodium fast reactor application with Professor Shih-Kuei Chen of the Institute of Nuclear Engineering and Science, National Tsing-Hua University (NTHU) Taiwan. They were invited by Julio Pacio of the Belgian Nuclear Research Centre at Mol to advance their published methodology for the Belgium MYRAHH project for its licensing application to Belgium regulatory authorities. The MYRAHH is an accelerator-driven system cooled by lead- bismuth eutectic. During this period, the necessary technical modeling steps were identified, documented, and published in *Nuclear Engineering and Design*, and the methodology was updated to include an existing fluid bundle mixing mechanism. Future work will finalize the numerical model and verify it based on the extensive internationally available database.

Professor Todreas also initiated work on assessing and advancing application of the consequence-based methodology for physical security of microreactors. A methodology is being sought nationally for micro-reactors that will provide the necessary physical security without the need for continuous presence of an armed security force. Steps have been taken in the United Kingdom to define the consequence-based methodology. The US commercial nuclear program and the Canadian program have yet to confirm a definitive statement of the physical security methodology that will be utilized. In our work, we have formulated a definition of physical security methodology for micro-reactors and tested its resiliency through application to two small reactor types, a liquid metal–cooled fast reactor concept (under commercial development) and the MIT research light water-cooled reactor.

The assumption is that an attacker is in control of the facility and thus can disable any security element or system that they have the technical ability to interdict. Then the worst-case scenario consequences that their attack can cause are determined. This approach does not take credit for interdiction by any security systems at the facility or intervening actions by onsite staff. Instead, the analysis focuses on only the inherent features of the plant: what are likely to be the targets of an attack and characteristics of the plant that inherently prevent, diminish, or delay these attacks. Note that once the unique consequences of the facility attack are enumerated, these consequences are examined in terms of radiological dose to the public and plant workers to determine whether or not they are acceptable. If the consequences are significant and have an adverse effect on public health and safety, then security systems must be designed and implemented to prevent such consequences from occurring. The analysis results identified what appeared to be the most limiting events for each reactor. However, the final step of computing the radiological dose at the site boundary that could impact a public member and a plant worker remains to be done in a rigorous manner.

## Education

A total of 95 students pursued graduate degrees in nuclear science and engineering. Of these students, 35% worked in the fission energy field, 26% in fusion and plasma physics, 17% in materials, and 22% in other nuclear science and technology applications, including nuclear technology management and policy, nuclear security, and quantum engineering. The department awarded four SM degrees and 16 PhD degrees. In fall 2020, 16 students entered the graduate program.

Twenty-two students were enrolled in the undergraduate programs during the past year: Course 22, three sophomores, three juniors, three seniors; Course 22-ENG, eight sophomores, two juniors, and three seniors. From September 2020 through June 2021, five students completed the requirements for the bachelor's degree: one in nuclear science and engineering, and four in engineering as recommended by the Department of Nuclear Science and Engineering.

As most on-campus activities remained restricted, the NSE Communication Lab (Comm Lab) found different ways to support students and postdoctoral researchers with their technical communication needs by offering pre-pandemic services remotely, strengthening online resources, and adding new programming around community outreach and engagement. Under the management of Marina Dang, six graduate students served as Communications Fellows and held 214 one-on-one coaching sessions with 78 unique clients (compared to 225 sessions and 69 unique clients last year). Roughly 47% of NSE graduate students and 68% of NSE undergraduates used the resource. The most common reason for using the Comm Lab was slide presentations (30%), though we also noticed a jump in appointments for graduate school and fellowship applications (23%) compared to the previous year (15%). The client return rate remained high (62%), and only 18% of tasks were class related, suggesting students are seeing the value of effective communication in their academic and professional development.

In addition to coaching sessions, the Comm Lab offered both regular and new NSE-specific workshops and panels, published CommKit articles, and collaborated with instructors from six undergraduate and graduate courses. To match evolving needs, new content included science video creation, digital posters on Zoom, and remote slide presentations. The Comm Lab also helped with departmental events, such as the NSE Winter School, the NSE Graduate Research Expo, and the first UROP Summer Research Festival.

The Comm Lab also invested in multiple community-building initiatives. Within the Department of Nuclear Science and Engineering, Marina Dang and the fellows coordinated writing communities (Informal Writing Group, PHinisheD), created a way for students to receive feedback faster (Quick Takes), and launched a blog to disseminate communication tips from students, postdocs, and faculty. Dang supplemented the traditional Communications Fellow training with DEI-minded (diversity, equity, inclusion) guidelines and active bystander practice sessions. Beyond NSE, the Comm Lab collaborated with Career Advising and Professional Development, the Teaching and Learning Lab, the Writing and Communication Center, and the MIT Libraries, as well as offering customized support to students from underrepresented minority groups through the MIT Summer Research Program and the Laureates and Leaders program.

The Nuclear Winter School is an opportunity for current undergraduate students to explore the Department of Nuclear Science and Engineering and MIT. This initiative seeks to promote the value of graduate education in nuclear science and engineering, to increase the number of women and students from underrepresented minority groups in nuclear science and engineering research, and to demystify the graduate student application process and lived experience once at MIT. Undergraduate students of color, women, and those from historically underserved groups are especially welcome. Due to Covid-19, the January event was held virtually.

## Awards, Honors, and Activities

### Faculty Activities and Honors

Professor Jacopo Buongiorno is a member of many scientific committees, including Commissariat a l'Energie Atomique, Nuclear Energy Division, Scientific Advisory Committee; SEAB Space Working Group, Department of Energy; National Academy for Nuclear Training, Institute of Nuclear Power Operations Accreditation Board; Steering Committee, International Congress on Advances in Nuclear Power Plants, American Nuclear Society; MIT Reactor Safeguards Committee; Committee on Sexual Misconduct Prevention and Response; Oak Ridge National Laboratory, Nuclear Science and Engineering Directorate Advisory Committee; Khalifa University of Science and Technology, Nuclear Technology Research Center Advisory Board; and the Nuclear Innovation Alliance, Advisory Committee.

Professor Buongiorno presented numerous invited lectures and seminars during the reporting period, including the following:

- "Nuclear Energy: The Opportunities for Radical Innovation," roundtable, Global America Business Institute, May 25, 2021
- "How to Facilitate Commercialization of New Nuclear Technologies," 2021 Multilateral Nuclear Energy Dialogue, Global America Business Institute, May 19, 2021
- Panelist on the Role of Nuclear Energy in a Clean Energy Future, University of Illinois at Urbana-Champaign, May 6, 2021
- Panelist at the webinar on Climate Crisis: Alternatives to a Carbon-Based Economy, University of Massachusetts at Amherst, April 22, 2021
- "Nuclear: A Versatile and Clean Energy Source for the 21st Century," presentation to Dutch Members of Parliament, e-Lise Foundation and Liberal Friends, March 15, 2021
- "Nuclear Energy in a Low-Carbon World: Essential Tool or Relic of the Past?" workshop at NTHU, Taiwan, March 10, 2021

- "Nuclear Energy: The Need for Radical Innovation," panel on Roundtable on Nuclear Frontier Issues: At the Interface between Technology and Societies, Belfer Center for Science and International Affairs, Harvard University, March 5, 2021; also presented at the University of Illinois at Urbana-Champaign, online lecture, February 9, 2021; Sustainable Nuclear Energy Technology Platform webinar, February 3, 2021; Yale University, online lecture, November 12, 2020; and University of California at Berkeley, online lecture, October 10, 2020
- "Can Nuclear Batteries Be Economically Competitive in Large Markets," Fission Battery Workshop Series, INL, January 27, 2021
- "Nuclear Energy: A New Beginning?" Naval Nuclear Laboratory's Knolls Atomic Power Laboratory, January 5, 2021
- "New Nuclear: Much More than Just Electricity," Spanish Nuclear Society Annual Meeting, online presentation, November 17, 2020
- "Nuclear: A Versatile and Clean Energy Source for the 21st Century," online presentation to the Dubai Nuclear Energy Committee, July 21, 2020

Professor Ju Li was elected a fellow of the American Association for the Advancement of Science (2020), and included in Webometrics h > 100 Highly Cited Researchers list (global rank: 3,383 March 2021).

Professor Mingda Li received a 2021 Early Career Research Award by the DOE Basic Energy Sciences Program for his work in machine learning-augmented multimodal neutron scattering for emergent topological materials. He also received the Ruth and Joel Spira Award for Excellence in Teaching.

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

Professor Michael Short was one of 12 winners of the 2021 Teaching with Digital Technology Awards. He also was named a 2021 MacVicar Faculty Fellow.

Professor Emeritus Neil Todreas published the third edition of his textbook *Nuclear Systems*, vol. 1, *Thermal Hydraulic Fundamentals*, originally written with Professor Mujid S. Kazimi in 1990, and which has been adopted extensively over the last 30 years by US and international universities for the study of nuclear heat transfer and fluid flow applications. The preparation of the second edition of the companion volume (*Elements of Thermal Hydraulic Design*) has also been completed and is in the proofing and printing process.

Professor Anne White was appointed School of Engineering Distinguished Professor of Engineering. This professorship was established to recognize outstanding contributions in education, research, and service. Professor White's appointment recognizes her exceptional leadership, innovation, and accomplishments in education and research.

## Student Awards and Activities

Rachel Sophia Bielajew, Zoe Fisher, Richard Ibekwe, Erica Salazar, and William Robert Stewart received the award for Outstanding Student Service for exceptional service to the department.

Bodhi Bodhisatwa Biswas won second place in the Advanced Reactor Systems category of the Innovations in Nuclear Technology R&D Awards Program for 2021, awarded by the US Department of Energy.

Florian Chavagnat received the AY2021 MathWorks Engineering Fellowship and an award of $79,000.

Zoe Fisher received the Irving Kaplan Award for academic achievement by a junior in Nuclear Science and Engineering.

Leanne Galanek received the outstanding UROP Award for outstanding contributions to a research project by a junior or senior in Nuclear Science and Engineering.

Ethan Klein was awarded Outstanding Grader of the Year, presented by the student chapter of the American Nuclear Society.

Artyom Kossolapov received a 2020 American Nuclear Society Young Professional Thermal Hydraulics Research Award when attending the ANS winter meeting virtually in November 2020.

Miriam Kreher won two American Nuclear Society graduates scholarships: ANS Pittsburgh Local Section Graduate Scholarship and the John and Muriel Landis Scholarships.

Peninah Levine received the Roy Axford Award for academic achievement by a senior in Nuclear Science and Engineering.

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

Samuel McAlpine was awarded the first place prize in the Innovations in Nuclear Technology R&D Awards sponsored by the US Department of Energy, Office of Nuclear Technology R&D. McAlpine's award is in the Open Competition in the category of Advanced Reactor Systems.

Lucio Milanese was awarded the prestigious Schwarzman Scholarship to spend one year at Tsinghua University in Beijing. Milanese, along with three others from MIT, will pursue master's degrees in global affairs and leadership training at Tsinghua University in Beijing.

Natalie Montoya was part of a team that won the Environmental Justice Challenge at the 2020 MIT Policy Hackathon. The challenge was to design a cumulative impact assessment for Massachusetts that used specific criteria, including climate change indicators, to identify environmental justice communities. Montoya also received the AY2022 James C. Gaither Junior Fellowship in the Nuclear Policy Program at the Carnegie Endowment for International Peace.

Lucy Nestor and Katherine Zhao received the outstanding UROP Award for contributions to an NSE project by a first-year or sophomore in Nuclear Science and Engineering.

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

Erica Salazar received the Outstanding Student Service Award in NSE this year. Erica also received the MIT Energy Initiative Fellowship and received a Women in Innovation and STEM Database at MIT fellowship.

Cong Su won the department's 2020 Del Favero Thesis Prize for their paper, "Atomic Engineering—Controlling Atoms with Electron Irradiation for Quantum Devices."

Amelia Trainer and Evan Leppink received the outstanding Teaching Assistant and Mentorship Award for exceptional contributions to other students in the department.

Jiayue Wang won the Best Oral Award at the 2021 Materials Research Society (MRS) Spring Meeting and the MRS Graduate Student Award.

Yang Yang began a tenure-track assistant professor position in the Department of Engineering Science and Mechanics at Pennsylvania State University.

Christian Yoo received a fellowship from the National Science Foundation Graduation Research Fellowship Program.

The two best poster winners at the NSE 2021 virtual Research Expo were:

- Judges' Selection: Isabel Naranjo De Candido—"Flexible Siting Criteria and Staff Minimization for Micro-Reactors: Staff Minimization Strategy," Professor Jacopo Buongiorno (advisor)
- Attendees' Selection: Guoqing Wang—"Quantum Information Applications Based on Modulated Quantum Control," Professor Paola Cappellaro (advisor)

## Staff Awards and Activities

For the first time, the department awarded the Michael Driscoll Award for Unique and Unwavering Dedication to the Department. It was given to a member of the NSE support staff for their efforts in supporting the department during the Covid pandemic. The recipients were Rob Allison, Heather Barry, Rachel Batista, Carolyn Carrington, Anne Dulong, Patricia Glidden, Nancy Iappini, Lisa Magnano-Bleheen, Kristi Stone, and Laura Guild.

Brandy Baker received the Outstanding Staff Award, presented by the student chapter of the American Nuclear Society.

Majdi Radaideh received the Postdoctoral Service Award for exceptional service to the department, MIT, or the world at large through activities outside the lab.

Nouf Mousa AlMousa received the Postdoctoral Outstanding Research Award for research of outstanding academic quality.

**Anne E. White**
**Department Head**
**School of Engineering Distinguished Professor of Engineering**