

## **Department of Nuclear Science and Engineering**

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

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

### **Faculty and Administration**

Anne White was promoted to the rank of associate professor without tenure.

Bilge Yildiz was promoted to the rank of associate professor with tenure.

Ronald Ballinger continues his service on the MIT Committee on Academic Performance and the MIT ROTC Oversight Committee.

Ian Hutchinson continues to serve on the MIT Committee on Academic Performance.

Mujid Kazimi continues as director of the Center for Advanced Nuclear Energy Systems (CANES) in the department. He also continues as director of the Kuwait-MIT Center for Natural Resources and the Environment (KUMIT).

Richard Lester, who is department head, continues to serve as faculty chair of the MIT Industrial Performance Center. He is also a member of the management board of the MIT Press.

Dennis Whyte serves as the chair of the department's undergraduate program. He also served during the past year as the department's ABET (accreditation) review coordinator.

## Research Highlights

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

NSE is one of the 10 founding members of the Consortium for Advanced Simulation of Light Water Reactors (CASL), the US Department of Energy (DOE) Nuclear Energy Innovation Hub led by the Oak Ridge National Laboratory. CASL has focused on the simulation of the light water reactor (LWR) core, with simultaneous neutronic, thermal, hydraulic, and fuel materials considerations. Professor Kazimi serves as the principal investigator of the CASL–MIT project with Professor Buongiorno as co-principal investigator. Professor Emilio Baglietto serves as the national deputy leader in the area of fluid flow and heat transfer. Professor Kord Smith is a member of the scientific council. Six other professors from MIT are also involved in the project.

NSE is also an important part of the US Department of Energy's Center for Exascale Simulation of Advanced Reactors (CESAR), a DOE Office of Science Co-design Center. Professors Kord Smith and Benoit Forget, who lead the department's computational reactor physics group, are investigating new ways to improve algorithm performance on modern computing architectures. They and their students have pursued the development of high-fidelity open source software. The flagship code is OpenMC, a general geometry Monte Carlo neutron transport code designed specifically for leadership-class computing. OpenMC is being leveraged by both the CASL and CESAR initiatives. A newer code also leveraged by CESAR is OpenMOC, a two-dimensional deterministic-based neutron transport code that is being used for performance analysis on innovative computing platforms. Both codes are gaining a wide user base in universities and industry worldwide. Recent highlights include novel parallelization of a method-of-characteristic neutron transport solver on multi-core central processing units and general-purpose computing on graphics processing units, as well as efficient domain decomposition algorithms for full-core Monte Carlo simulations.

In other research, professor Benoit Forget has developed a novel technique for treating nuclear data temperature dependence that substantially reduces the memory footprint and improves simulation performance. This technique is being used to perform hot full-power analysis of a full-core pressurized water reactor for comparisons with real plant data.

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

Professor Kazimi and Drs. McKrell, Shirvan, and Pilat continue their research program on accident-tolerant fuel. The feasibility of silicon carbide and coated zirconium alloys as cladding materials in LWRs is being investigated. Professor Kazimi, joined by Dr. Shirvan, continues his study of thermal hydraulics and fuel performance in tight-lattice boiling water-cooled high-fissile conversion, even breeding, reactors. The use of thorium oxide to burn plutonium in LWRs is also being investigated. Support for this activity is provided by DOE funding through Westinghouse, two Nuclear Energy University Program (NEUP) projects, and Lockheed Martin.

The fluoride salt-cooled high-temperature reactor (FHR) project (sponsored by DOE and led by principal research scientist Dr. Charles Forsberg) has developed a new strategy to provide zero-carbon variable electricity to the electricity grid while the reactor operates at full capacity to minimize costs. The FHR is coupled to an air Brayton combined-cycle plant that is similar to a natural gas plant. The nuclear reactor, which operates as a base-load plant, achieves a thermal efficiency of 42%, with a cooling-water requirement that is 40% less than that of a LWR. Additional electricity can be generated in load-following mode by injecting natural gas into the turbine, with the possibility of more than doubling the electrical output. Because the gas acts as a peaking fuel above the lower-temperature nuclear heat, the incremental natural gas to electricity efficiency is 66%—well above the best thermal efficiency in stand-alone natural gas combined-cycle plants. This added heating raises temperatures in the power cycle and more than doubles the electricity output from the power cycle.

Professors Jacopo Buongiorno, Neil Todreas, and Michael Golay have launched a new research project to develop the concept of an offshore floating nuclear power plant that would achieve improved safety through innovative design features that avoid seismic and tsunami risks, ensure indefinite cooling of the nuclear fuel (thus reducing the likelihood of accidents with fuel damage and radionuclide release), and eliminate the need for land evacuation should such an accident actually occur. This research is a continuation of the work carried out by the NSE faculty on the lessons from the Fukushima accident. In related research, Dr. Koroush Shirvan has been exploring advances in the design of reactors anchored on the seabed, in collaboration with Professors Ballinger, Buongiorno, Kazimi, and Todreas, and Dr. Forsberg.

Professor Buongiorno and Dr. McKrell continue their studies of advanced diagnostics for two-phase heat transfer. They and their students have developed a sensor that uses a combination of selective infrared filters and two infrared cameras to measure phase and temperature simultaneously on a boiling surface. Separately, Professor Buongiorno and Dr. McKrell are studying the effects of engineered surfaces in nuclear reactors on boiling and quenching heat transfer. In collaboration with Professor Kripa Varanasi (Department of Mechanical Engineering), they have developed micro- and nano-textured coatings to enhance the critical heat flux.

Professor Ju Li's group has built liquid microelectromechanical devices for in situ transmission electron microscopy (TEM) observations of corrosion and electrochemical processes. The Li group has applied in situ TEM and atomistic modeling to study fatigue cracking and deformation-induced crystallization of metallic glasses, and they

have studied oxidative corrosion of zircalloys with and without water. They have also produced nanocomposite materials made of metal and carbon nanotubes that show superior resistance to swelling under ion irradiation.

Professor Ballinger and his students have developed a probabilistic model for the prediction of environmental degradation of iron-based alloys. The model has been applied to the prediction of degradation of submarine propeller shafts to allow extension of the inspection interval. As a result of the model predictions, a new program has been initiated to develop a new shafting system to eliminate the degradation problem. The same modeling framework is being applied to the prediction of the lifetime of used nuclear fuel dry-storage canisters.

In his first year on the NSE faculty, professor Michael Short is focusing his research in two main areas: the prevention of corrosion and fouling and the development of new methods for simulating and characterizing radiation damage in structural materials.

Professor Scott Kemp has established the Laboratory for Nuclear Security and Policy to study research problems where science-based analysis can inform the development of nuclear-related public policies. Projects are under way on open-source analysis of nuclear proliferation activities, the redesign of naval-propulsion reactors to use fuel other than weapons-grade uranium, the development of two different systems to verify nuclear-warhead dismantlement to support international arms-control treaties, and the design of international institutions to address nuclear-fuel supply risk. In related research, NSE senior research scientist Dr. Richard Lanza is developing a novel approach to the active detection of shielded nuclear materials while in transit with an easily relocatable low-dose system involving the use of monoenergetic high-energy gamma rays for transmission imaging.

Professors Neil Todreas and Ronald Ballinger are evaluating the potential for aggressive power uprates for nuclear power plants as part of life-extension programs for operations beyond 60 years. An integrated decision analysis methodology has been developed, based on analysis of the performance, safety, and economics associated with plant performance at the added capacity afforded by the adoption of high-performance fuels. Emeritus Professor Michael Driscoll, working with professors Baglietto, Buongiorno, and Lester and with several students, continues his research on the disposal of used nuclear fuel and high-level waste in deep boreholes. Analytic modeling has confirmed that thermal-hydraulic stability should prevail and protect against advective escape of water-borne radionuclides. A CFD computer program has been developed and successfully tested against an eclectic ensemble of older national laboratory codes. Materials down-selection for downhole features, supported by laboratory tests carried out with the help of Dr. McKrell, have provided increased assurance of effective confinement. This research is being carried out in collaboration with Sandia National Laboratories and is supported by a three-year DOE Nuclear Energy University Program (NEUP) grant.

Professor Bilge Yildiz's research is concerned with the development of advanced materials for energy applications in harsh environments. Her group combines in situ

experimental surface science techniques with first principles calculations and advanced atomistic simulations to address fundamental problems in solid state electrochemistry that affect the behavior of protective and functional metal oxides. Her research focuses on electrochemical–mechanical interactions at material interfaces with broad relevance to corrosion and environmental degradation generally.

Professor Paola Cappellaro’s Quantum Engineering Group investigates the dynamics and control of quantum systems with the goal of building computational and measurement devices that exceed the power of their classical counterparts. To accomplish these objectives, the group follows two directions: a bottom-up approach based on single electronic spins in diamond, and a top-down approach of studying large nuclear spin systems with solid-state nuclear magnetic resonance techniques.

Professor Cappellaro’s group also investigated a strategy for indirect control of the nuclear spin, using the electronic spin qubit as an actuator. A key result, obtained using algebraic methods, was to find the time-optimal control solutions for the most general qubit control problem and to derive stricter bounds on the time and number of switches required to engineer desired qubit gates via the actuator control. This work is supported by a National Science Foundation grant.

Professor Ian Hutchinson’s computational plasma physics research is aimed at developing a comprehensive understanding of the interaction of flowing plasmas with solid objects. An important application is the performance of Mach probes in the edge of magnetic confinement fusion experiments. A new discovery has emerged in the past year from this computational research: the plasma wake of Mach probes has been shown to be unsteady under some conditions. It is as yet unknown what effects the instability of the wake has upon the measurements, but it may have important consequences for understanding tokamak edge plasmas.

Professor Anne White’s research focuses on the study of turbulent transport in fusion plasmas, with the goal of controlling the transport and so improving the performance of tokamaks. Her group develops new measurements, such as correlation electron cyclotron emission diagnostics and a fast two-color interferometer, and designs experiments to collect data for validation of advanced simulations of turbulent transport. Research highlights include new observations of reduced electron temperature fluctuations during improved confinement regimes, such as I-mode, H-mode, and the saturated ohmic confinement regime. The changes in turbulence are not correlated with changes in intrinsic plasma rotation, indicating that these two transport channels can be separated and, perhaps, separately influenced to improve confinement.

Professor Dennis Whyte continues his research on the formation of energy transport barriers and temperature pedestals in the boundary region of magnetic fusion devices. These pedestals establish a large pressure-gradient region in the outer perimeter of the fusion plasma, helping to make fusion devices small enough to be practical for energy production. However, the formation of such pedestals is most often accompanied by both energy and particle barriers, and the latter makes control of the fuel and its purity much more difficult. Professor Whyte’s research on the C-Mod experimental tokamak

has revealed a regime, called “improved” I-mode, where an energy barrier in the pedestal could form without a particle barrier. This regime, which appears to be self-regulating through a benign high-frequency instability, also avoided damaging instabilities that typically occur in the pedestal barrier. This research could have significant implications for future burning-plasma devices such as ITER and fusion reactors.

## Education

A total of 111 students pursued graduate degrees in nuclear science and engineering this year. Sixty-one percent of these students worked in the fission energy field, 21% in fusion and plasma physics and 18% in other nuclear science and technology applications. The department awarded 13 SM degrees, 19 PhD degrees, and 3 ScD degrees. Twenty-two students entered the graduate program in fall 2013.

A total of 25 students were enrolled in the undergraduate program during the past year, including 8 sophomores, 10 juniors, and 7 seniors. Seven students completed the requirements for the bachelor’s degree in nuclear science and engineering from September 2013 through June 2014.

The department introduced a new graduate core curriculum during the past year, comprising six new six-unit course modules, all of which were taught for the first time:

- Applied Nuclear Physics, taught by professor Bilge Yildiz;
- Radiation Interactions, Control and Measurement, taught by professor Dennis Whyte;
- Nuclear Energy Systems, taught by professor Michael Short;
- Materials in Nuclear Engineering, taught by professor Michael Short;
- Essential Numerical Methods, taught by professor Ian Hutchinson; and
- Nuclear Technology and Society, taught by professor Scott Kemp.

The new core curriculum is part of a major overhaul of the department’s graduate programs, which includes the most far-reaching reforms to the doctoral program in several decades. Implementation of the new doctoral program began last September.

In professional education, the department offered the Reactor Technology Course for Utility Executives, in collaboration with the Institute for Nuclear Power Operations, for the 21st year. Professor Michael Golay serves as the faculty director. The department also presented the second offering of the International Nuclear Leadership Education Program (INLEP), designed to promote the safe and responsible use of nuclear energy worldwide by bringing together senior leaders from emerging nuclear countries to study the technical and institutional requirements for successful nuclear programs. Professors Lester and Buongiorno are faculty cochairs of INLEP, and Dr. Alan Hanson serves as executive director.

## **Faculty Awards, Honors, and Activities**

In April the department held a special two-day symposium, Michael Driscoll and Nuclear Energy at MIT: Unlimited Energy Meets an Unlimited Resource, to honor Professor Driscoll, who is celebrating his 80th birthday this year. More than 20 papers were presented at the symposium, which was cosponsored by CANES. More than 100 alumni, faculty, and students were in attendance.

Emeritus Professor George Apostolakis completed his term as a member of the US Nuclear Regulatory Commission.

Professor Ballinger continues his service as a member of the US Nuclear Regulatory Commission's Advisory Committee on Reactor Safeguards. He received the Lee Hsun Lecture Award from the Institute of Metal Research, Chinese Academy of Sciences, and the Shenyang National Laboratory for Materials Science.

Professor Jacopo Buongiorno was named a MacVicar Faculty Fellow for exemplary and sustained contributions to the teaching and education of undergraduates at MIT. He served as co-chair of the 9th International ECI Conference on Boiling and Condensation Heat Transfer. He is a member of the Defense Science Study Group and a member of the Accreditation Board of the National Academy for Nuclear Training of the Institute for Nuclear Power Operations. He continues as associate director of KUMIT.

Professor Paola Cappellaro is a senior staff member of the Institute for Theoretical Atomic, Molecular, and Optical Physics at Harvard University, a member of the Center for Ultracold Atoms at MIT and Harvard, and an associate of the Program in Quantum Information of the Canadian Institute for Advanced Research.

Emeritus Professor Sow-Hsin Chen received an honorary doctorate in physics from the University of Messina.

Professor Benoit Forget continues to serve on the executive committee of the Reactor Physics Division of the American Nuclear Society.

Professor Ian Hutchinson received the Ruth and Joel Spira Award for Excellence in Teaching.

Professor Mujid Kazimi continues his service as a member of the DOE's Nuclear Energy Advisory Committee. He is also a member of the International Advisory Board on Nuclear Energy of the United Arab Emirates.

Professor Scott Kemp is a member of the Panel on Public Affairs of the American Physical Society and has served as an informal governmental advisor on the negotiations with Iran over its nuclear program.

Professor Richard Lester serves on the Board on Science, Technology and Economic Policy of the National Research Council, and is also a board member of the New England Clean Energy Council and the John Adams Innovation Institute of Massachusetts.

Professor Ju Li organized the first Elastic Strain Engineering for Unprecedented Materials Properties Symposium at the 2013 fall meeting of the Materials Research Society (MRS), and was also the principal guest editor of a special issue of MRS Bulletin (February 2014) on elastic strain engineering.

Professor Kord Smith received the PAI Outstanding Teaching Award, presented by the MIT student chapter of the American Nuclear Society.

Professor Anne White is a member of the executive committee of the International Sherwood Fusion Theory Conference. She received the 2014 Junior Bose Award for Excellence in Teaching by junior faculty in the MIT School of Engineering. She also received the 2014 American Physical Society Division of Plasma Physics Katherine Weimer Award, which was established to recognize and encourage outstanding achievement in plasma science research by a woman physicist in the early years of her career.

Professor Dennis Whyte was the lead author on a paper that received the 2013 Nuclear Fusion Journal Prize, awarded annually by the International Atomic Energy Agency.

Emeritus Professor Sidney Yip has completed a textbook, Nuclear Radiation Interactions, to be published by World Scientific Publishers in October 2014. Professor Yip has also become a member of the Visiting Committee of the Department of Nuclear Engineering and Radiological Sciences at the University of Michigan.

### **Student Awards and Activities**

Ashok Ajoy received the Manson Benedict Award for excellence in academic performance and professional promise by a graduate student in NSE.

Nicolas Lopez received the Irving Kaplan Award for academic achievement by a junior in NSE.

Jake Hecla, Stephanie Pavlick, Jasmeet Arora, and David Tran received Outstanding Undergraduate Research Opportunities Program Awards for their outstanding contributions to a research project by a freshman or sophomore in NSE.

William Boyd, Eric Forrest, Jason Hummelt, and Lulu Li received Outstanding Service Awards in recognition of their exceptional service to NSE.

Andrew Richenderfer, Michael Pantano, and Jon Walsh received 2013 NEUP Graduate Fellowships from DOE. Sophomore Vincent Kindfuller received an undergraduate NEUP Scholarship.



Shapagat Berdibek received an Outstanding UROP Award for outstanding contributions to a research project by a junior or senior in NSE.

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

Margo Batie received the Shirley Ann Jackson Award, given by the MIT Black Student Union to a senior who is reflective of Dr. Jackson and exemplifies the mission of the Black Student Union in its dedication to the MIT black community. She also received the Mens et Manus Award, given by the MIT Office of Multicultural Programs to a senior in the community who has shown a passion and affinity for diversity and inclusion work and has made a lasting impact on the community.

Lulu Li won first place in the poster session of DOE's CASL 2014 Annual Education Workshop for her research on "LOO: A Low Order Operator Acceleration Scheme."

Will Boyd was selected to attend the Machine Learning Summer School program at Renmin University of China in Beijing. He also participated in the International Conference on Machine Learning in Beijing and in the FoTEL Symposium on Clean Energy at National Tsing Hua University in Taiwan.

Brandon Sorbom received the American Nuclear Society (ANS) Outstanding Grader award, presented by the MIT student chapter of the ANS.

Jake Jurewicz received the Roy Axford Award for academic excellence by a senior in NSE.

Doctoral student Mareena Robinson and senior Margo Batie were chosen to deliver keynote speeches at the 40th annual MIT breakfast celebration of the life and legacy of Martin Luther King.

Benjamin Magolan was awarded a Rickover Fellowship in Nuclear Engineering by the Naval Reactors Division of DOE.

Mario Manuel was awarded an Einstein Postdoctoral Fellowship sponsored by the National Aeronautics and Space Administration.

MIT freshmen Stephanie Pavlick, Jasmeet Arora, and Davis Tran won the Best Undergraduate Paper Award at the 2014 American Nuclear Society Student Conference. They were mentored by Will Boyd.

Yan Chen was selected to receive a Schlumberger Foundation Faculty for the Future Fellowship. She was also one of four MIT graduate students to receive a Chinese Government Award for Outstanding Self-Financed Students Abroad.

Caleb Waugh served as president of the Graduate Student Council, and in that capacity addressed the Class of 2014 at MIT's 148th commencement ceremony.

Jacob DeWitte was named to *Forbes* magazine's "30 under 30" list in the energy sector. DeWitte, fellow NSE PhD student Joseph Yurko, and NSE alumna Caroline Cochran co-founded UPower, a company that is developing a 1.5 megawatt container-sized nuclear "battery."

Leslie Dewan (PhD '13) was named one of *TIME* magazine's "30 people under 30" who are changing the world. Dewan and graduate student Mark Massie have co-founded a company, Transatomic Power, to commercialize their design for a molten salt reactor that is optimized for waste burning.

**Richard K. Lester**

**Department Head**

**Japan Steel Industry Professor of Nuclear Science and Engineering**