

# NSE

## Nuclear Science and Engineering

science : systems : society



The students, faculty, and research staff of the MIT Department of Nuclear Science and Engineering (NSE) generate, control, and apply nuclear reactions and radiation for the benefit of society and the environment. Our mission is to help develop the next generation of leaders of the global nuclear enterprise while providing technical leadership in energy and non-energy applications of nuclear technology. Today our Department is working to make nuclear power the safest, most economical, and most environmentally benign source of energy, while also laying the foundations for exciting new applications of nuclear radiation science and technology. As one of the world's leading academic departments in our field, we also have a responsibility to inform public debates on the wise, humane uses of nuclear science and technology.

Professor Richard K. Lester  
Head, Department of  
Nuclear Science & Engineering  
rklester@mit.edu

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Department of Nuclear Science and Engineering  
Massachusetts Institute of Technology

SPOTLIGHT ON NEW FACULTY IN NUCLEAR SCIENCE AND ENGINEERING

# Emilio Baglietto: Better Reactors Grow From Better Simulations



**N**uclear fission technology is the only viable grid-scale source of continuous, carbon-free electricity available today – but realizing its potential in the fight against global climate change requires substantial improvements in both the technological and the economic performance of new-generation reactors. Over the last 15 years, computational techniques for modeling reactor behavior on both macro and micro scales have emerged as central tools in this effort, and NSE students will have the opportunity to learn about them from a growing faculty group that includes new Assistant Professor Emilio Baglietto, a pioneer in the development of computational fluid dynamics (CFD) technology for the nuclear industry.

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Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
rklester@mit.edu*



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# We need advanced simulations to play a much larger role in supporting the existing nuclear fleet and in the design and licensing of next-generation reactors.

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Baglietto comes to NSE from the engineering simulation software company CD-adapco, where he was Director of Nuclear Applications. He joins a rapidly growing group of NSE faculty working in the field of advanced computation and simulation, including Professors Kord Smith and Benoit Forget, whose research focuses on the development of computational models and simulation tools for reactor analysis, and Professors Ju Li, Bilge Yildiz, and Sidney Yip, whose fundamental computational studies of materials behavior are shedding light on the performance of materials in the extreme environments of fission and fusion reactors.

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*Written by Elizabeth Dougherty & Peter Dunn  
Photo by Justin Knight*

Baglietto's research goals include improving the effectiveness and expanding the reach of 3-D, first-principles computational tools for nuclear reactor design. He notes that this work is applicable at the micro scale, to better understand physical interactions; at the component scale, to optimize designs; and at the full-system level, to validate new designs while taking into account complex system interactions. As a result, the technology promises to be a starting point for entirely new generations of innovation in a wide range of areas.

Baglietto first became intrigued by nuclear technology when he read about fusion reactors during junior high school in his native Italy; he established his niche in computation during his studies at the Tokyo Institute of Technology, where he earned his doctorate in 2004. At the time, however, computing systems for reactor design were underpowered and CFD implementations did not have sufficient resolution, accuracy, and scale to provide useful insights into conditions inside reactors.

In his work at CD-adapco, Baglietto helped improve CFD technology and apply it to reactor core simulations, including simulations of the behavior of the fuel rods found in light-water reactor cores. The resulting insights have led to increased fuel reliability and efficiency through minimization of damage to the rods, thus extending their lifetime and improving reactor availability and safety.

One type of rod damage comes from deposition of oxides, which seep from the reactor's structural material into the core's cooling water. These deposits, known as "crud," impede cooling and can lead to fuel failures that require reactors to be taken out of service. CFD simulations of flow and heat transfer, working in conjunction with chemistry analysis tools, helped identify excessive crud deposition locations, and enabled development of new designs with improved flow and cooling.

At NSE Baglietto will work with a recently-formed industry-university innovation hub in which the Department is playing a leading role, the Consortium for Advanced Simulation of Light-Water Reactors (CASL), which is backed by \$122 million of US Department of Energy funding. The Consortium members aim to create a virtual reactor that runs predictive simulations of new reactor designs. "The project demonstrates a large-scale US-supported commitment to the ideas I've been working towards," says Baglietto. "We need advanced simulations to play a much larger role in supporting the existing nuclear fleet and in the design and licensing of next-generation reactors." ■

## SPOTLIGHT ON WOMEN IN NUCLEAR SCIENCE AND ENGINEERING

# Paola Cappellaro: A Quantum Engineer on the Frontier of Knowledge



*To learn more about NSE please contact  
Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
rklester@mit.edu*

“Quantum engineering” is not yet a household term, but its possible impact on life in the 21st Century is enormous. This emerging discipline has the potential to revolutionize computing, precision measurement, materials science, and many other fields by harnessing the complex and often-baffling properties of sub-atomic particles. Moving this technology into reality is the mission of an NSE team led by Assistant Professor Paola Cappellaro

Unlike mechanics, metallurgy, and other ancient engineering practices, quantum engineering grows not from experience, but from theory – specifically, the 20th-century development of quantum mechanics, which seeks to explain the interaction of matter and energy on the atomic and sub-atomic scale.

Created by titans like Einstein, Schrödinger and Feynman, this body of knowledge can be deeply counterintuitive, and raises challenging questions about basic mechanisms of the universe. But Paola Cappellaro says she and her team focus on a more practical question as they develop their novel experimental equipment: how can the principles of quantum mechanics be applied to real-world challenges?

The goal is daunting – gain control over individual sub-atomic quanta, and use them as functional devices, including “qubits,” or quantum representations of information. While these are somewhat analogous to the bits used in today’s electronic computers, qubit-based computing could provide an exponential increase in power over traditional computing

Achieving this will require solutions to many issues, from the basic logistics of accessing such small entities to some odd properties of the quantum world. Quantum measurements, for example, mostly give random results, and measuring a qubit changes its value.

The fundamental challenge is that we occupy a macro world of classical physics, while qubits and quanta exist in a micro world of quantum physics. When we observe or measure an object in the quantum world, we create quantum decoherence, which causes the quantum object to appear as a classical object. In the process, most of the information associated with the object is lost, and its evolution in the quantum realm is halted. Solving the decoherence problem (which can also be created by the quantum object interacting with its environment) is essential to achieving real-world quantum computing capabilities.

One line of inquiry for Cappellaro utilizes impurities in diamonds, known as nitrogen-vacancy centers. These defects provide conditions that allow room-temperature measurement and manipulation of individual electrons, including their spin. Spin, one of the properties that make up an electron's quantum state, is a central element of quantum engineering. In addition to serving as a qubit, spin is also a potential tool for measurement of extremely small magnetic fields, which could be used to monitor brain activity, investigate new materials, and develop superconductors.

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*Written by Peter Dunn  
Photo by Despoina Chatzikyriakou*

**“The interdisciplinary nature is one of the things I like best. We’re working on very complex many-body problems with so many inputs; you need to know at least a little bit of everything to make it work.”**

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Cappellaro’s second line of inquiry involves the study of large quantum systems, to explore opportunities for control and noise reduction, and address issues related to decoherence.

Her group has developed control techniques for the study of fluorapatite (FAP) crystals, using a combination of nuclear magnetic resonance techniques to align and manipulate spin. FAP’s properties make it a good test bed for the study of quantum information transfer and quantum simulation; research to date has produced new insights into the use of spin wires, and the team has also succeeded in devising a protocol for information transfer without the need to prepare the spin wire in a precise state. This latter accomplishment enables in principle the perfect transfer of information via spin wires, and plans for the coming year call for experimental implementation of the protocol – a result that would inspire further theoretical studies.

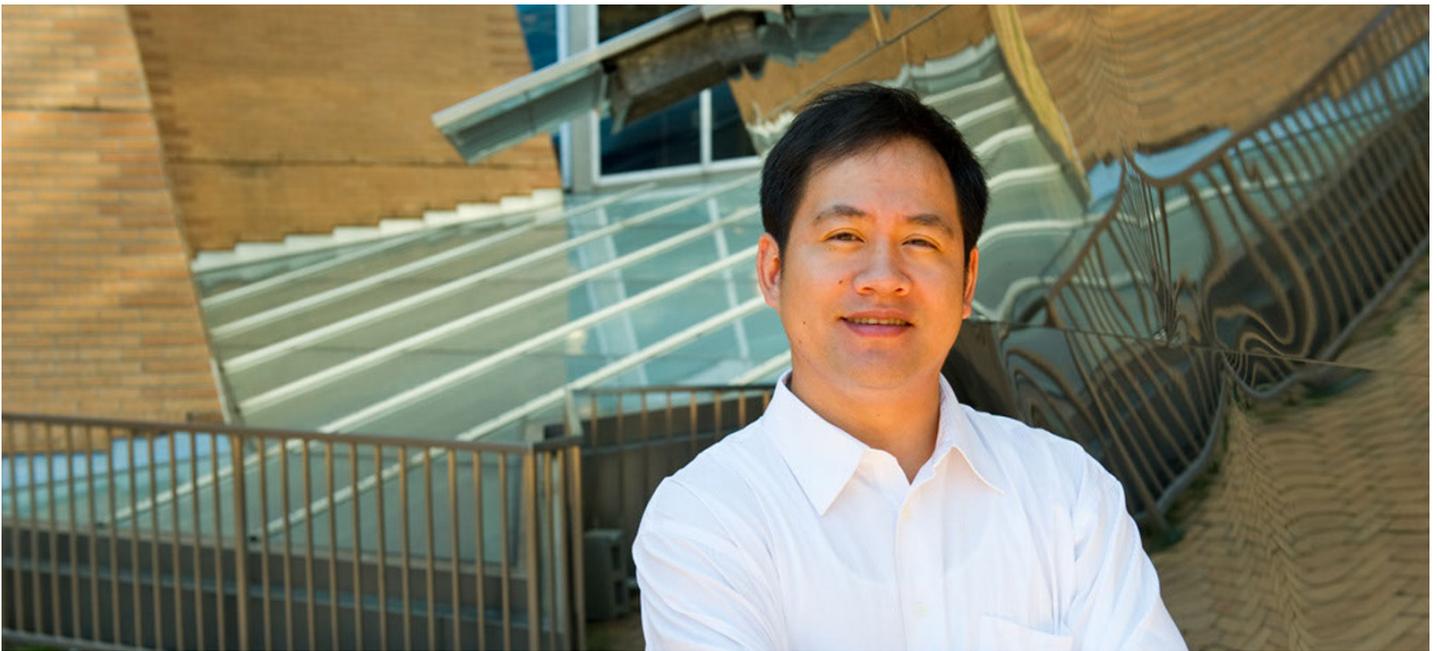
This interaction of theoretical and experimental work is at the heart of the embryonic field of quantum engineering. “You really have to start from a deep understanding of the theory...there are ideas in quantum mechanics that are very counterintuitive, so intuition can’t carry you forward,” says Cappellaro. “Then, as we try to do things that will be practical, we have to concern ourselves with experimental noise and error. Combining the two is what makes it very interesting.”

Because so much of the process is being invented in real time, Cappellaro’s group calls on resources across the Institute, from mathematicians to computer scientists to materials developers, as well as the MIT Nuclear Reactor Facility. “The interdisciplinary nature is one of the things I like best,” she notes. “We’re working on very complex many-body problems with so many inputs; you need to know at least a little bit of everything to make it work.” 

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SPOTLIGHT ON NEW FACULTY IN NUCLEAR SCIENCE AND ENGINEERING

## Ju Li: Atomic insights for new materials development



**N**uclear engineering and materials science are distinct but related fields. Newly appointed BEA Professor of Nuclear Science and Engineering Ju Li will straddle the two, as he applies his groundbreaking research into atomic-scale materials behavior to a broad range of challenges, including energy storage, waste management, and reactor materials.

To a large degree, says Ju Li, the difference between his scientific and engineering efforts comes down to time scales.

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Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
[rklester@mit.edu](mailto:rklester@mit.edu)*



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“My work involves theory and modeling of materials behavior under high mechanical stress and sometimes high temperatures,” he explains. “When you work at the scale of atoms and electrons, you think in terms of picoseconds and femtoseconds. But for engineering systems, you need to predict behavior over years, or even thousands of years for nuclear waste treatment. My primary interest is in extending the time scale of our physical models to the engineering scale.”

Over the last decade, Li has established himself as a leader in developing and applying computer simulations to gain greater understanding of fundamental nano-scale mechanical and transport properties of materials. His pioneering cross-disciplinary work has coupled continuum mechanics (in which materials are modeled as continuous masses rather than discrete particles) with meso- and atomic-scale dynamics, and has had a broad impact on the understanding of how materials behave under extreme conditions.

These scientific achievements have helped create a clearer sense of how microstructures evolve over time when exposed to stress, heat, and radiation, and have led to fundamental advances for a range of engineering challenges. These include development of new structural materials for fission and fusion reactors, better-performing battery electrodes, and improved fuel cell components. Other applications have included aerospace materials, as well as the process of vitrifying nuclear waste into a stable glass matrix.

In addition to his appointment in NSE, Li will hold a joint appointment in the Department of

## Li's pioneering cross-disciplinary work has coupled continuum mechanics with meso- and atomic-scale dynamics, and has had a broad impact on the understanding of how materials behave under extreme conditions.

Materials Science and Engineering, and will teach in both departments. He will be a key contributor to a variety of new and existing interdisciplinary materials research activities across the Institute.

After receiving his bachelor's degree in physics at the University of Science and Technology of China in 1994, Li came to MIT and earned his Ph.D. in Nuclear Engineering in 2000.

He has since held materials-related faculty positions at Ohio State University and the University of Pennsylvania, and has won many awards, including the Robert Lansing Hardy Award from the Minerals, Metals and Materials Society in 2009 and the Outstanding Young Investigator Award of the Materials Research Society (he is the first to receive this award for theory and simulation rather than experimental contributions). Li was also recently named a Chang Jiang Scholar by China's Ministry of Education.

“Ju's highly interdisciplinary approach to research is especially well-suited to MIT,” says NSE department head Richard Lester. “He will powerfully strengthen the intellectual ties between NSE and other School of Engineering departments, and his exceptional creativity, intellectual breadth, and productivity will help ensure a leadership role for the School in extreme materials research for energy and other applications.”

Li is looking forward to returning to the Institute and its intellectual climate. “There's so much going on at MIT; everybody is doing very exciting research,” he says. “That's the main draw for me.” ■

*Written by Peter Dunn*

*Photo by Justin Knight*

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Massachusetts Institute of Technology

SPOTLIGHT ON NEW FACULTY IN NUCLEAR SCIENCE AND ENGINEERING

## Kord Smith brings 30 years of simulation insight to NSE



**I**ncreasingly powerful computation technology has long been central to the advancement of reactor engineering and nuclear power generation. Few people have played a greater role in that process — or have more knowledge to share — than Kord Smith, the newly appointed Korea Electric Power Company Professor of the Practice of Nuclear Science and Engineering.

Since earning his SM (1979) and Ph.D. (1980) at NSE, Kord Smith has not only developed some of the world's most widely used software for reactor physics modeling and simulation, but also flourished in business, co-founding a successful company, Studsvik Scandpower, that supplies software for reactor core design, analysis, and operations to a majority of the world's nuclear utilities and reactor fuel vendors.

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Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
rklester@mit.edu*



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A major recognition of Smith's skills came this year when he was named chief scientist for the Center for Exascale Simulation of Advanced Reactors (CESAR), an interdisciplinary public-private effort of the Department of Energy's Office of Science aimed at creating an entirely new generation of nuclear-related computing technology. An especially interesting aspect of the program is its emphasis on parallel co-design of high performance computing (HPC) hardware and software, to ensure that next-generation HPC platforms will be ready for use in diverse disciplines such as advanced materials development, combustion engineering, and reactor simulation when machines are delivered in the 2019 time frame.

"Traditionally, hardware gets designed, and then software engineers figure out how to use it," explains Smith. "But these new machines will see a hardware paradigm shift, with massively parallel processors having much less memory per processor. With traditional methods, we might end up with a machine no one could use efficiently. So we're doing hardware and software design at the same time, and influencing each other; it's never been done on this scale before."

"It's real high-end computing, and exciting to be on the forefront, but my job is also to keep an eye on practical problem-solving, and make sure what we do can be translated into what industry needs."

That perspective will also infuse Smith's classroom work at NSE; he will leverage Studsvik's Waltham, Mass., training center to give students

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*Written by Peter Dunn  
Photo by Justin Knight*

**"If you want to do something new and unique, your credibility is helped tremendously by an understanding of how things are actually done today."**

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a hands-on feel for current industrial nuclear engineering practice. "If you want to do something new and unique, your credibility is helped tremendously by an understanding of how things are actually done today," says Smith. Students will also have the opportunity to participate in the CESAR work, and in NSE's related engagement with the DoE's Consortium for Advanced Simulation of Light Water Reactors.

"Over the last 30 years, no one has had a greater impact on the field of nuclear reactor physics than Kord Smith," commented NSE department head Richard Lester. "NSE's strategic plan calls for a new, integrated focus on advanced modeling and simulation research and teaching. Kord's arrival will help greatly in implementing that objective."

Smith, who earned his bachelor's in nuclear engineering at Kansas State University, has recently returned to the Boston area after many years living in Idaho, where he pursued mountain climbing, skiing and kayaking, and also served as a back-country and Civil Air Patrol search-and-rescue pilot. He notes, "I finally became a real engineer when I acquired a bulldozer, excavator, and compactor to construct a box-canyon airstrip at our mountain cabin." 

SPOTLIGHT ON NEW FACULTY IN NUCLEAR SCIENCE AND ENGINEERING

## Felix Parra returns to NSE's fusion program



**N**uclear fusion has tremendous potential to provide clean, safe power generation on a grand scale, but realizing that potential has challenged researchers worldwide for decades. Newly appointed NSE assistant professor Felix Parra says, however, that a convergence of theoretical insights and newly available computing power could enable significant advances towards functional fusion reactors.

Felix Parra will conduct his research in the Theory Group of the Plasma Science and Fusion Center (PSFC), home to a tokamak fusion reactor (Alcator C-Mod) and a central node of international collaboration leading towards the scheduled 2019 startup of the large-scale ITER tokamak in France. The basic challenge: achieve the elusive “burning plasma,” a stable fusion reaction that can maintain its own extremely high temperature and create more energy than it takes in.

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Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
rklester@mit.edu*

“Tokamaks should work quite well,” says Parra. “But they suffer very small-scale fluctuations in the plasma,” where hydrogen isotopes are heated and ionized to create the conditions for them to fuse and release thermonuclear energy. “While the particles should be well-confined, they tend to get pushed out, and the performance is not what we expect. The great thing is, we’ve been able to develop a simplified theory of plasma behavior, and in doing so, achieved the ability to simulate it with much less computing power.”

At the same time, new generations of computing tools are making it possible (and affordable) to run large numbers of simulations, “so we can explore physics that was hidden before,” notes Parra. “The question now is, can we use these new available tools to unravel the secrets of turbulence, and gain control over it.”

Parra earned his undergraduate degree in aeronautical engineering at Universidad Politecnica de Madrid in his native Spain, and his masters in aeronautics and astronautics at MIT. He earned his Ph.D. at the Institute’s Plasma Science and Fusion Center in 2009; his thesis (“Extension of Gyrokinetics to Transport Time Scales”) won the American Physical Society’s Marshall N. Rosenbluth Outstanding Doctoral Thesis Award. He is returning to MIT after a stint as EPSRC Postdoctoral Fellow in Theoretical Physics at Christ Church College, Oxford.

“Felix’s contributions to plasma turbulence theory are already well-known in the international magnetic fusion community,” commented

**“We can explore physics that was hidden before. The question now is, can we use these new available tools to unravel the secrets of turbulence, and gain control over it.”**

NSE department head Richard K. Lester. “He will be a dynamic addition to our outstanding program in fusion education and research.”

“MIT is an exciting place, and PSFC is one of the most exciting labs I’ve ever been to. I’m looking forward to being back with my old colleagues,” says Parra, who will teach courses in plasma turbulence and transport theory in NSE.

An early area of research will be intrinsic rotation in tokamaks. Traditionally, neutral atomic particles have been injected into tokamaks to “push” the plasma into rotation in the reactor’s toroidal (donut-shaped) chamber as part of the power-production process. But this injection requires energy; if the tokamak’s own electrical fields can be used to induce and control the rotation, it would represent another step towards the “big prize” of efficient fusion power generation. “MIT has spearheaded work in this area, and has all the tools; I’m very eager to work on it. If we could control the spontaneous rotation, we may be able to control turbulent losses,” notes Parra. ■

*Written by Peter Dunn  
Photo by Justin Knight*

SPOTLIGHT ON WOMEN IN NUCLEAR SCIENCE AND ENGINEERING

# Anne White: Solving Mysteries in the Pursuit of Fusion Power



**N**uclear fusion is perhaps the most tantalizing energy technology in development today, with the potential to completely redefine the world's energy supply system. As part of NSE's broad effort to make fusion power a reality, Assistant Professor Anne White is building new understanding of the still-mysterious conditions inside tokamaks, the experimental test beds where fusion reactions occur at temperatures exceeding 100 million degrees.

Anne White's primary workbench is NSE's Alcator C-Mod, one of three tokamak user facilities in the US and a hub of collaboration for national laboratories and international researchers as well as Institute faculty and students. Work is largely focused on the grand challenge of fusion: the need to contain an ongoing fusion reaction and capture its massive heat output for electric power generation. Success would open the door to a large-scale source of continuous power with no carbon emissions or hazardous waste problems, and fuel that could largely be extracted from ordinary seawater.

"Getting atoms to fuse is challenging — atomic nuclei carry positive charges and naturally repel one another," explains White. But at extremely high temperatures, the nuclei have enough energy that when they collide, they sometimes overcome the repulsion and fuse. The most promising candidates for power production are hydrogen isotopes deuterium and tritium — heated sufficiently, they ionize into a plasma, or charged gas; when they fuse, they create a helium isotope and a neutron, while releasing nuclear energy.

*To learn more about NSE please contact  
Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
[rklester@mit.edu](mailto:rklester@mit.edu)*

No physical container can handle the temperatures involved, so tokamaks create a “magnetic bottle” inside a doughnut-shaped chamber, using magnetic fields 100,000 times greater than the earth’s natural magnetism, says White. “The magnetic field contains the plasma by forcing the electrons and nuclei to follow spiral paths around the field lines.”

The goal (which thus far has eluded all researchers) is creation of a stable “burning plasma” that can maintain its own temperature, thus allowing the reaction to become a net producer of energy.

For over five decades, the difficulty of producing burning plasmas has driven fusion researchers to develop successively more complex and detailed theories of tokamak plasma behavior. “In the last decade, better computer simulations and diagnostic systems have helped identify plasma micro-turbulence as a primary factor in heat loss in the plasma. But there are many unsolved questions,” says White. “Our understanding of the physics of confinement is still incomplete. We need better predictions of heat and particle transport, and diagnostic systems that can directly measure turbulence.”

Building this understanding is White’s research focus. She and her team use advanced simulations to make predictions about turbulence parameters, and then compare those with experimental results to make better predictions of plasma confinement and performance. Her work was recently recognized with a Department of Energy Early Career Research Award, a five-year grant that will support the development of new plasma turbulence diagnostics.

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*Written by Peter Dunn  
Photo by Despoina Chatzikyriakou*

**“The work at Alcator C-Mod is a dance between experimentation and fundamental theory, with an exciting connection to engineering. Plasma temperatures can be 10 or 20 times hotter than the sun’s core, just three feet away from the chamber wall. The engineering challenge is huge.”**

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White notes that the work at Alcator C-Mod “is a dance between experimentation and fundamental theory, with an exciting connection to engineering. Plasma temperatures can be 10 or 20 times hotter than the sun’s core, just three feet away from the chamber wall. The engineering challenge is huge.”

Another large part of White’s work is recruiting and advising graduate and undergraduate students to work at Alcator C-Mod. “To a large extent, students run the tokamak,” she explains. “They design and lead experiments, construct diagnostics, write simulations, develop models, and find new equations to describe the tokamak plasma. Graduate student involvement is the backbone of the program.”

They are part of a global development effort that will culminate in a major milestone for fusion, and for science as a whole – the ITER tokamak, currently under construction in France. The 10 billion euro project, slated for completion in 2019, will enable much larger scale experimentation; it is designed to deliver 500 megawatts of output from 50 megawatts of input power for several minutes at a time, from a self-sustaining plasma. “If ITER works as designed and predicted, we could build a demonstration power plant about that size,” says White.

The possibility of making such a huge contribution to society’s infrastructure is appealing to White, who learned about fusion power during high school by reading science-fiction literature about interplanetary travel. “Our research is very practical; we want to build power plants. But there’s also a lot of really beautiful physics involved. When I learned as an undergraduate that I could actually work on tokamaks, I said, ‘that’s all I want to do!’” ■

## SPOTLIGHT ON WOMEN IN NUCLEAR SCIENCE AND ENGINEERING

# Bilge Yildiz: New insights into material surfaces advance energy conversion technologies



**M**aterials are key enablers in any engineering project. Bridge builders, who once worked in stone, and then in steel, can now draw on carbon fiber, polymers, and composites with outstanding strength, weight and other characteristics that extend the engineer's capabilities.

Engineers developing advanced energy technologies like fuel cells, synthetic fuel production systems, and new-generation reactors will benefit from novel materials knowledge being developed at NSE's Laboratory for Electrochemical Interfaces, headed by Bilge Yildiz, the Norman C. Rasmussen Assistant Professor of Nuclear Science and Engineering. Her team is working towards better understanding of the surface and interfacial properties of oxides, and learning to tailor the oxides' physical properties to make them highly active in fuel cell reactions, and more resistant to corrosion in reactor applications.

An especially exciting area of inquiry for Bilge Yildiz's team is the use of lattice strain (a slight displacement of the atoms in a material's lattice structure) to alter the properties and boost the performance of oxides subjected to high temperature and reactive environments in fuel cells and other nuclear energy systems.

"The purpose is to assess how strain can alter the efficiency of devices like fuel cells, or the lifetime of structural materials in reactors. We investigate how critical properties, like surface reactivity and diffusivity of oxide ions, can be controlled by strain," explains Yildiz, principal investigator at the Laboratory, which has received funding from an MIT

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Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
rklester@mit.edu*

Energy Initiative Grant, the Department of Energy (DOE) Office of Basic Energy Sciences, and a Nuclear Regulatory Commission Faculty Development seed grant.

Yildiz's work on mechano-chemical coupling in surface chemistry, reactivity, and ion conduction is also being supported by her 2011 National Science Foundation Faculty Early Career Development (CAREER) award, the NSF's most prestigious junior faculty award, which recognizes her outstanding research, excellence in education and integration of the two.

The Laboratory is probing the surfaces of solid oxide fuel cell electrodes in their reactive environments, using an array of newly developed analytical and metrology equipment, which now permits them for the first time to see into the previously unknown atomic and electronic structure of oxide surfaces at high temperatures. This includes a one-of-a-kind scanning tunneling electron microscope capable of structural and electronic interrogation at temperatures of 700 degrees C in reactive gases, coupled with an X-ray photoelectron spectrometer for chemical analysis.

This equipment, in conjunction with first-principles simulation techniques employed at the Lab, recently yielded new insights into the surface activity of solid oxide fuel cell cathodes at high temperatures and as a function of strain. "The integration of theory and experimentation is an important step towards advancing our understanding of how the surface state relates to the oxygen reduction activity on oxide cathodes," explains Yildiz. "It all leads towards a better ability to 'tune' the cathode surface behavior, by means of strain or other structural and chemical attributes."

**"In fuel cells, you want fast surface reaction and ion diffusion, so you're looking for the *fastest* strain. When you want to prevent corrosion in a reactor, you want slow diffusion. We're studying different material structures for different functions."**

Both the ion conduction and the surface reactivity are critical engineering factors, notes Yildiz. "In fuel cells, you want fast surface reaction and ion diffusion, so you're looking for the *fastest* strain. When you want to prevent corrosion in a reactor, you want slow diffusion. We're studying different material structures for different functions." Yildiz's work on corrosion activity is now also supported by the Consortium for Advanced Simulation of Light Water Reactors, the first energy innovation hub initiated by the DOE, and by the BP Materials and Corrosion Center at MIT.

By developing this molecular-level knowledge, Yildiz and her associates hope to enable new levels of control of properties in future fuel cells and reactors. The findings could enable solid oxide fuel cells to operate at lower temperatures for better economic viability, or help designers improve the corrosion resistance of structures in nuclear plants and make more accurate estimates of their lifetimes.

As Yildiz puts it, "We're developing a smaller-scale understanding of how to control material properties, which hopefully will contribute to a larger-scale enhancement of energy technology performance." ■

*Written by Peter Dunn*

*Photo by Despoina Chatzikyriakou*

SPOTLIGHT ON NSE EDUCATION

# Nuclear Security Takes Its Place In NSE's Curriculum



**W**hile virtually any scientific or engineering technology has the potential for misuse, nuclear technology is a special case, and security of materials and know-how has always been a priority in the nuclear community. In an age of rogue nations and violent sub-national organizations, the subject has even greater significance, and this is reflected in its important place in the curriculum of MIT's Nuclear Science and Engineering Department.

The attention to nuclear security is part of the Department's broader consideration of the interactions of nuclear technology with society as a whole. This is particularly important because fission reactors are emerging as the primary large-scale carbon-free energy generation method for the foreseeable future, notes Senior Research Scientist Richard Lanza.

*To learn more about NSE please contact  
Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
[rklester@mit.edu](mailto:rklester@mit.edu)*

What we need is policy that's more informed by technology, rather than the other way around. There are many protocols in place that are very prescriptive; the trouble is they were put into place 40 years ago.

"If you're going to have nuclear power, then you're going to have to deal with the issues of proliferation and safeguards," he explains. "This is a complex-systems problem, and the sort of problem MIT has addressed in the past, because we can bring together a lot of pieces."

From inside the Institute, these pieces include NSE faculty and members of other departments including Physics, Materials Science and Engineering and Political Science. Outside instructors hail from private companies and national laboratories, and government agencies like the Defense Intelligence Agency and the CIA; there is also collaboration on policy issues with Harvard's Kennedy School of Government.

In a major supplement to funding from the Departments of Defense, Energy, and Homeland Security, NSE recently received a \$2.4 million award from

the Department of Energy's National Nuclear Security Administration, under its Global Threat Reduction Initiative (GTRI). The Initiative is fostering development of a shared, five-course nuclear security curriculum at MIT, Pennsylvania State University and Texas A&M University; the materials will ultimately be promulgated to other universities.

Lanza co-teaches a course in Nuclear Non-Proliferation with Michael Hynes of Raytheon and Senior Lecturer Jacquelyn Yanch, covering a range of topics from the roots of nuclear weapons development to case studies of extremist groups (like Al-Qaeda and the Aum Shinrikyo cult) that have sought out nuclear materials and technologies on the black market. Political motivations are also explored, to help understand the nuclear aspirations of nations like Iran and North Korea.

Lanza explains that NSE leadership felt it made sense to study security in the department because "what we need is policy that's more informed by technology, rather than the other way around. There are many protocols in place that are very prescriptive; the trouble is they were put into place 40 years ago.

"There's also another aspect that's changed — nuclear technology is now worldwide. The Non-Proliferation Treaty of 1970, our principal nonproliferation agreement, recognizes five countries as having the right to possess nuclear weapons (the US, USSR, United Kingdom, France and China). These countries pledged to reduce and eliminate their reliance on nuclear weapons and promote the development of civilian nuclear power programs in other countries. The world we live in now has two more declared nuclear countries, one undeclared country, and a host of subnational groups that are seeking nuclear capability. This is a very different world than 1970."

This, says Lanza, is a primary driver behind new research into detection and analysis technologies, including the ability to track materials to their reactors of origin via their unique material "signatures," and a reactor-monitoring collaboration with Lawrence Livermore National Laboratory focused on using anti-neutrinos to detect the creation of plutonium. "As my colleague Mike Hynes has said, what we want to do is move away from the Cold War concept of mutually assured destruction, and towards mutually assured detection."

NSE's extensive work on the nuclear fuel cycle also plays a role, developing strategies for reactor design and operation that minimize production of fissile material.

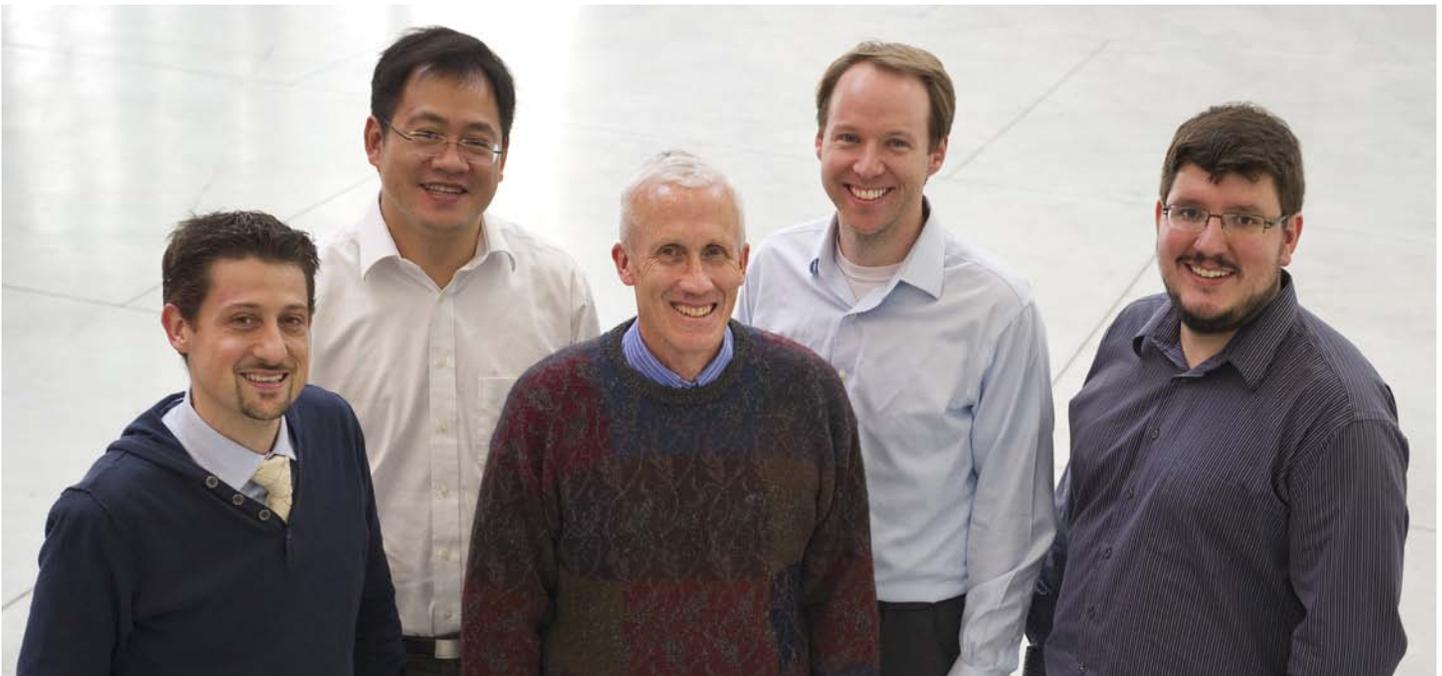
Lanza notes that there is intense interest among MIT students in security — over 50 people attended the first lecture in the nuclear non-proliferation course. "They understand that nuclear engineers are responsible for nuclear power, and if you do that, you have to be responsible for the consequences," he says. "I tell them it's their 30-year homework assignment — this isn't something we can ignore." ■

Written by Peter Dunn

Photo by Justin Knight

SPOTLIGHT ON NSE EDUCATION

# New NSE Faculty Drive Curriculum Expansion Into Computational Science and Engineering



*L to R: Emilio Baglietto, Ju Li, Kord Smith, Benoit Forget, Felix Parra.*

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*To learn more about NSE please contact  
Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
[rklester@mit.edu](mailto:rklester@mit.edu)*

Since the earliest days of science, the interplay of theory and experimentation has been the primary method of creating new knowledge. Today, the affordability of massive computing power has added a third tool to the researcher's workbench: computational modeling and simulation, which is rapidly being integrated across the NSE curriculum by a group of new faculty members with in-depth experience.

"In the past, science and engineering relied on experimentation and theory, aided by relatively simple calculations," notes Ju Li, who holds professorships in both NSE and Materials Science and Engineering, and who led the development of a newly offered course, Computational Nuclear Science and Engineering. "Now, computer

simulation has become the third leg of scientific inquiry and engineering, which supplements what we find with experimentation and theory.”

The combination of the three brings unprecedented power to bear on challenges like developing new nuclear materials, designing reactor components, and assessing complex system-level interactions, in fission, fusion and radiation technology applications.

Li notes that experimental and theoretical methods are certainly not being replaced, but that computer simulations can address some of their limitations. “Experimentation often produces only a few critical pieces of measurement, and you typically can’t have perfect initial and boundary conditions. Analytical theory gives big-picture insights, but it has to take a simplified view of the world. So in complex systems, when there are many parameters, or when systems are coupled together, it becomes intractable. Simulation is very data-rich, so one can see how internal states are coupled, and one can do parametric studies, which are sometimes difficult to do experimentally.”

The new computational science and engineering course, 22.107, will give NSE grad students what Li calls “intermediate-level proficiency” in three core skills: programming, mathematical understanding of algorithms, and construction and interpretation of models. “Our grad students have diverse backgrounds—mechanical engineering, chemistry, physics—and they will enter diverse fields after graduation. But being able to identify problems that are amenable to computer-aided solutions, and then actually implementing the programming and debugging, and interpreting the results, will all be key survival skills.”

More broadly, computational methods are already being integrated into many NSE courses, says Assistant Professor Ben Forget. “I teach reactor

## The expected result: tighter integration of computational technologies with experimentation and theory, and better odds of solving the knottiest challenges.

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physics for juniors, and we’re including some programming exercises, which provide a good introduction. And Professor Kord Smith, who leads an NSE task force on identifying new frontiers in simulation, also took the students in our reactor physics class and our class on fuel cycles to Studsvik Scandpower, a company he co-founded that makes core design software. Studsvik has been very generous, letting us use their training facilities; we’d like to continue that collaboration, and perhaps even replicate some of their training environment here at MIT.”

Forget notes that while integrated programs like MATLAB make setting up simulations very convenient, students will also be expected to build models from the ground up. “When you make the step to an industrial application, you will often need expertise in compiled languages like C++ and Fortran. We’re not teaching one language or one skill; we want students to learn to program, so they’ll be able to switch between languages without too much trouble.”

Forget adds that many newly hired department faculty, including himself, Li, Smith, Emilio Baglietto and Felix Parra, have extensive backgrounds in computational methods. “We’re building critical mass, and creating a network,” he says. “We hope to really leverage that in the next few years; there’s certainly a lot of potential for collaboration.” NSE is also seeking synergies with other Institute departments where computation is increasingly important, like aero-astro engineering, civil & environmental engineering, and mechanical engineering.

The expected result: tighter integration of computational technologies with experimentation and theory, and better odds of solving the knottiest challenges. As Li says, “Most of the problems we’re dealing with today are very difficult. To work on the border of what’s do-able, we need to couple all three together.” ■

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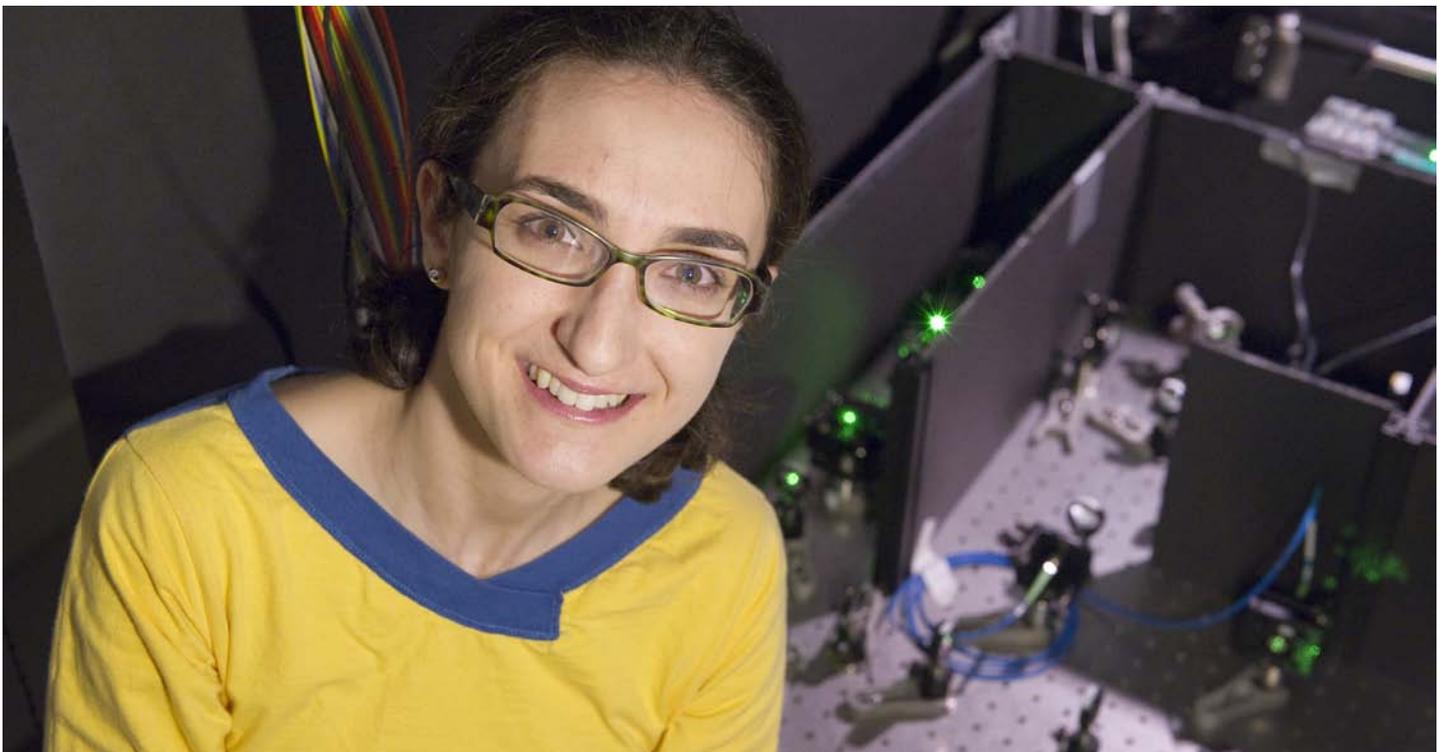
*Written by Peter Dunn*

*Photo by Justin Knight*

Department of Nuclear Science and Engineering  
Massachusetts Institute of Technology

SPOTLIGHT ON WOMEN IN NUCLEAR SCIENCE AND ENGINEERING

## Clarice Aiello: Finding quantum gold in diamond's defect



**T**he kind of diamond Clarice Aiello values does not come in a dazzling pear or square cut, swaddled in black velvet on a counter at Tiffany's. Instead, it exists as a millimeter-sized chunk on a sturdy table in a lab she built. What's more, Aiello is not searching for perfection in her rock, but imperfection of a remarkable kind: a naturally occurring defect in the diamond's lattice that, if manipulated properly, gives rise to quantum phenomena.

It is the mind-bending field of quantum mechanics that Brazilian-born Aiello has "wanted to understand more than any other thing." A fifth year Nuclear Science and Engineering (NSE) graduate student, she developed an early fascination with

*To learn more about NSE please contact  
Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
rklester@mit.edu*



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## “If you could functionalize diamonds, attach them to body cells, you could be doing fun stuff such as watching how synapses evolve or impulses work in the brain”

the field after reading Richard Feynman’s classic Caltech lectures as a freshman in college. In spite of a professed weakness in math, she pursued this branch of physics through an international education that included the Ecole Polytechnique and the University of Cambridge.

Today, Aiello is exploring new dimensions of quantum mechanics through a research project with NSE Professor Paola Cappellaro. In 2009, they set out to investigate and exploit the so-called Nitrogen-Vacancy center defect in diamond (N-V center), a routine anomaly where a vacancy is adjacent to a substitutional nitrogen atom in the carbon lattice. “We started with nothing but an empty room and had to fill it with machines,

screws, all the components that make our experiments possible,” says Aiello. Creating the lab was both arduous and gratifying, she says. “I’m not scared of building things from scratch anymore, but it takes a hell of a long time.”

Now equipped with a home-built confocal microscope, an oscillation-damping table, microwave sources, and lasers, Aiello explores some of the N-V center’s most intriguing attributes, such as its capacity to fluoresce when struck with light. But the real kicker, says Aiello, is that by carefully targeting the defect with photons, it is possible to create a quantum effect in a single electron. This is the “weird idea that an electron’s energy can be in both a 0 and a 1 state at the same time,” she explains — unlike the binary and mutually exclusive, 0 or 1, positions of an ordinary computer bit.

The quantum bit scientists generate in the N-V center may lead to a revolution in computing because “calculations are shown to speed up if your bit can co-exist in both energy states,” says Aiello. And there is another advantage: the quantum effect in diamond enabling this acceleration functions at room temperature. Aiello’s lab is currently focused on ways of controlling the environment around the defect via microwave and laser photons so that the electron lives longer than half a millisecond or so in its quantum state, potentially performing a greater number of calculations.

“Playing with the defect using photons of different wavelengths, you can sort of tell it how to behave,” says Aiello. “This is when you can start thinking about crazy things with real-life applications” — such as using the N-V defect to sense tiny magnetic fields in biological systems. “If you could functionalize diamonds, attach them to body cells, you could be doing fun stuff such as watching how synapses evolve or impulses work in the brain,” says Aiello. A nano-sized diamond probe with its capacity to measure spins — changes in single electrons -- would be significantly more sensitive than current imaging techniques, which need to read the fields of millions of spins. While Aiello’s lab is “not on the practical end of the chain,” she is “creating clever methods for people who can develop a robust, practical device.”

There are flashes of satisfaction in the “long, long” research days: “You suddenly see a quantum signal, or manipulate a quantum object, and you think, this can’t be true, it’s so delicate yet it lives in our lab.” While Aiello hopes to continue work in quantum mechanics in the next phase of her academic career, she also revels in teaching and igniting a passion for science in others. “I go crazy if I only do research,” she says, so “in the ideal world, I will find some niche solving my humble quantum mechanics problems, mixing theory and experiment, and helping students become not just accomplished researchers, but better people.” ■

Written by Leda Zimmerman

Photo by Justin Knight

Department of Nuclear Science and Engineering  
Massachusetts Institute of Technology

SPOTLIGHT ON WOMEN IN NUCLEAR SCIENCE AND ENGINEERING

## Sara Ferry: A New Generation Works To Fulfill the Promise of Nuclear Energy



**T**he world of nuclear technology is in a generational transition. Many nuclear engineers and scientists were trained between the 1950s and 1970s, but entry to the field slowed in subsequent decades; NSE Ph.D. student Sara Ferry is part of a new cadre of technologists who are working to fulfill the promise of nuclear energy in a world very different from that of their predecessors.

Ferry, who earned her 2011 SB in Physics and Nuclear Science and Engineering with a minor in French, has made nuclear metallurgy a primary focus of her work. Her research at the Institute's Uhlig Corrosion Laboratory involves "very broad

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Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
rklester@mit.edu*



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analysis of atmospheric corrosion effects on stainless steel welds, with particular emphasis on stress corrosion cracking (SCC).”

The driver, explains Ferry, is the need for longer-than-anticipated on-site storage of used nuclear fuel, due to the difficulties of starting up a centralized national storage facility. “A lot of interim storage will have to be used for a lot longer than expected,” she explains. “The evidence is that it won’t be a huge problem, but research hasn’t been done into how stainless steel storage containers will behave over an extra 50 years beyond their initial 40-year design life. We know how SCC works, but we have to look at every on-site storage facility in the country – what are conditions like, what’s in the air, especially in particularly humid and coastal environments.”

While there are existing models for how the stainless canisters behave over time, they are general and have large uncertainties. Ferry says she and her colleagues will “develop a very rigorous probabilistic model that will, given a particular type of canister in a particular type of environment, be able to estimate with reduced uncertainty how long it will take for SCC to become an issue. It sounds straightforward, but a lot of issues come in.”

Among the advanced techniques used in their experimentation is newly developed atom-probe tomography (APT), which enables the team to go atom-by-atom through their material samples, gaining new physical insights and better understanding of corrosion and cracking mechanisms, which will help reduce uncertainty in lifetime predictions. Researchers in the Uhlig lab are also using APT techniques to explore the fundamental nature of environmental degradation in other materials used in nuclear power plants.

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*Written by Peter Dunn  
Photo by Justin Knight*

## “People miss the fact that nuclear engineers, especially in our generation, are in nuclear technology because of their environmentalism”

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Long-term on-site storage is one example of how the nuclear power industry has had to adapt since its early days. Another is the need to win public trust for nuclear power in a world that is simultaneously threatened by carbon emissions and climate change and troubled by accidents at Three Mile Island, Chernobyl, and Fukushima.

“People miss the fact that nuclear engineers, especially in our generation, are in nuclear technology because of their environmentalism,” notes Ferry. “We believe it’s a very good option for right now, because it can be implemented right now. Wind and solar are wonderful parts of the energy picture, but no one thinks they will be enough. Conservation can be effective, but we can’t envision a future where we reduce electricity usage by 90 percent, which we’d have to do to cut carbon emissions to levels that the current administration advocates.”

Ferry is considering a number of options for life after her doctorate, including work in international policy or continued research. She also notes a desire to possibly return to France, where she spent several summers, including a MISTI internship at reactor developer Areva and time at Grenoble’s CEA, where she studied nanowire fabrication and the Spin Hall Effect.

But for now, she is maintaining her focus on her research, and enjoying her diverse colleagues. “The problems we deal with involve so many different resources, and I get to learn from a really wide range of people in many countries - companies that can make steel alloys, factories that can do welds, people from government, scientists at other universities and materials labs. It’s very valuable.” ■

Department of Nuclear Science and Engineering  
Massachusetts Institute of Technology

SPOTLIGHT ON WOMEN IN NUCLEAR SCIENCE AND ENGINEERING

## Ashley Finan: Developing better policy for energy innovation



**W**hen Ashley Finan receives her Ph.D. in Nuclear Science and Engineering (NSE), it won't be so much the culmination of an academic career as a milestone in a journey begun a decade ago. Finan credits some unique opportunities at MIT with setting her on a path toward a "place where it's possible to make the most positive impact" on clean energy solutions and climate change.

Finan, 27, entered MIT as an undergraduate in 2002 having "dreamt about going here since I was a little kid," she says. She arrived with an interest in physics and its practical applications, and positively disposed to nuclear energy, having grown

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Professor Richard K. Lester, Head  
Department of Nuclear Science & Engineering  
rklester@mit.edu*



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**“I have been helping develop a framework for policymakers to assess options for climate change, energy security and other energy issues, and to help identify and design better policies to encourage energy innovation.”**

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up a scant 10 miles from two Connecticut nuclear plants that seemed to her a good way to reduce dirty air emissions. “I felt strongly coal was doing a lot of damage...and that nuclear was a better source of energy.” Given her own aptitudes and interests, NSE and physics seemed a natural fit to her, and Finan leapt into Course 22.

From the beginning, she sought to balance classroom time with real-world experience, and she took every advantage of MIT’s undergraduate research program. She interned at Idaho National Laboratory, a hub for next-generation nuclear reactor research, collaborating with top-flight scientists from industry and other universities. Even while completing undergraduate requirements in reactor

design and radiation, Finan engaged in challenging research ventures. A senior design project led to an internship for a firm attempting to pair nuclear energy technology with oil sands extraction in Canada; this became the basis of Finan’s master’s degree work. It was also a turning point for her studies. She learned “how oil companies and nuclear engineering companies really work,” and how “the biggest concerns were actually economic and political.” Finan returned to MIT “with a better understanding of the issues faced by the energy industry,” she says. “This helped crystallize my interest in policy.”

With this newly refined focus, Finan devised an ambitious dissertation subject, “Energy System Transformation: An Evaluation of Innovation Requirements and Policy Options,” guided by NSE Department Head Richard Lester. She has conducted some of her research as a participant in the Energy Innovation Project, housed in MIT’s Industrial Performance Center. “I have been helping develop a framework for policymakers to assess options for climate change, energy security and other energy issues, and to help identify and design better policies to encourage energy innovation,” says Finan.

Her work shows that innovation on a massive scale will be required to manage the transformation from a high-carbon to a low-carbon-intensity energy system, and that serious funding obstacles often prevent the most promising energy innovation enterprises from reaching fruition. “There’s a valley of death between R&D and building at scale,” says Finan. Nuclear plants are one egregious example: “We’re pretty confident that they can provide power affordably once they’re built, but getting anybody to put enough capital at risk to build them is difficult. The investment required for one nuclear plant is larger than the entire balance sheet of most electric power companies in the U.S.”

Finan’s research suggests the U.S. must find a way to encourage high risk investment in energy innovation, to make public funding less vulnerable to the swings of politics, and to create an environment friendlier to private investment. Typical today are technology “push” policies that introduce a particular energy innovation, but do not create the conditions for its long-term survival. Finan prefers market “pull” policies aimed at “creating a competitive product and a flourishing market for a new technology.”

But while current political reality discourages the kind of market-based incentives she recommends, Finan can imagine an energy innovation sector that eventually resembles the IT, pharmaceutical or biology industries. After MIT-based post-doctorate work, Finan hopes to find a position where she can help bring the U.S. energy system closer to this vision. “It’s going to be very hard to leave MIT, but I really want to get to work supporting energy innovation.” ■

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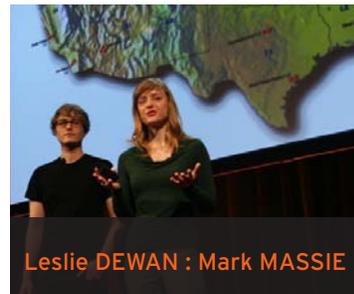
*Written by Leda Zimmerman*

*Photo by Justin Knight*

# IN + Around NSE: Meet our students

Meet our students at NSE and find out more about the Department through their stories about their experiences, their interactions with faculty and fellow students, their studies in nuclear science and engineering and how all this works with being part of the larger MIT community.

Also at [web.mit.edu/nse/inaround](http://web.mit.edu/nse/inaround)



Leslie DEWAN : Mark MASSIE



Sara FERRY



Ashley FINAN



Shawn FITZGERALD



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Tanzeer KHAN



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Professor Richard K. Lester  
Head, Department of Nuclear Science & Engineering  
Massachusetts Institute of Technology  
77 Massachusetts Avenue, 24-107  
Cambridge, Massachusetts 02139  
rklester@mit.edu  
617-253-7704

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