# Department of Nuclear Science and Engineering

At the end of my tenure as department head, it seems appropriate to provide a sober multiyear survey of the department's achievements in comparison with the strategic plan finalized in June 2004, five years ago. The first section of this report consists of this strategic "report card." In short, a large fraction of what we set out to do was achieved. Nuclear Science and Engineering (NSE) is launched on a major renewal at MIT, just as it is in the nation and the world. There are many notable achievements but many major challenges that still remain to be met.

Subsequent sections of this document provide details on faculty and student achievements and activities, which testify to the department's ongoing vitality and influence.

## Department Strategic Report Card 2004–2009

In June 2004, the Department of Nuclear Engineering finalized its strategic plan. This is a brief review, five years on, of what we said then and what we did. In italics are quoted in full the exact words from the executive summary plan of action of that document. Then follows for each topic a brief commentary on what has happened.

### Field of Activity

> *While re-energizing our historic strengths in nuclear energy engineering, we will actively position, promote and develop the Department on a disciplinary foundation of applied nuclear sciences.*

This has been the consistent position of the department in word and deed. We have substantially strengthened our external impact in fission and fusion. There is no dispute about the disciplinary principle within the department, although there has been debate about what it means. Some faculty emphasize energy applications as important distinctions. Others favor a more extended, individual-investigator perspective of the field.

> *We will change the official department name to "Nuclear Science and Engineering" as soon as the MIT formalities can be completed.*

After extensive consultations with important stakeholders, agreement was obtained and a vote of the MIT Faculty approved the name change in December 2004.

### Education

> *We will complete the transition to a graduate core curriculum structured around disciplinary fundamentals in three subjects. Additional specialist knowledge will be taught through focused courses for the areas of fission, fusion, and nuclear science and technology.*

This transition was completed essentially immediately and has effectively helped students experience cross-connections between different areas of the department. Continual refinement of the core courses has been undertaken. Suggestions for major modifications have been explored on subsequent occasions and are still under consideration, but the structure has served well.

*We will maintain approximately the current graduate student enrollment of 110 students, and continue efforts to increase recruitment of top-quality domestic students.*

The graduate enrollment in 2009 is 109, not including a few double-degree candidates counted in other programs. The number of graduate applications has increased so that the percentage of graduate student applicants admitted for consecutive five-year periods has shown increasing selectivity as documented in the following table. Domestic application numbers are strong.

**Graduate admittance rate five-year averages and spring 2009**

| Period | Total percent admitted | Percent admitted with aid |
|---|---|---|
| 1994–1998 | 57 | 35 |
| 1999–2003 | 46 | 32 |
| 2004–2008 | 40 | 27 |
| 2009 | 33 | 23 |

*We will seek to stabilize Department undergraduate enrollments at roughly 60 (20 sophomores per year) which is close to the Engineering School average per faculty at our present size. (In spring 2004, 21 freshmen declared for Nuclear, the highest number ever.)*

Our undergraduate enrollment has remained above 45 but has not quite reached the 60 target. There were 23 sophomore declarations in spring 2009.

*We will continue our wider contributions to undergraduate education through the teaching of major courses located in other departments, and joint courses.*

Twelve different department faculty have taught seven different external undergraduate courses. The Institute statistics still do not fully reflect that contribution, because a "credit follows teacher" accounting approach has not yet been implemented. NSE faculty teach a major fraction of energy courses at MIT.

## Research Thrusts

*We will enhance and develop research leadership in: advanced fission reactors and fuel cycles for economic attractiveness, safety, proliferation resistance, reduction of waste management burden, and fuel efficiency.*

Jacopo Buongiorno, an expert in reactor engineering and thermal hydraulics, joined the faculty in September 2004. Benoit Forget, an expert in computational reactor physics, joined the faculty in January 2008. A multimillion-dollar, multidisciplinary study of the nuclear fuel cycle funded by the Nuclear Energy Institute (NEI) and the Electric Power Research Institute (EPRI) was won and is nearing completion.

*—nuclear reactor materials and technology for high temperature hydrogen production, and deep space propulsion*

Bilge Yildiz, an expert in materials in nuclear reactor, hydrogen production, and fuel cell environments, joined the faculty in September 2007.

> *—application of nuclear and radiation interactions as tools for basic biology, practical realization of quantum computing, and nano-scale research*

Alan Jasanoff, an expert in contrast agents for nuclear magnetic resonance imaging of brain function, joined the faculty in September 2004. Paola Cappellaro, an expert in quantum information and quantum devices, will join the faculty in September 2009.

> *—magnetic plasma confinement physics and engineering in support of the burning fusion plasma mission and advanced plasma confinement*

Dennis Whyte, an expert in plasma materials interactions in tokamaks with strong influence in the International Tokamak Experimental Reactor (ITER) design, joined the faculty in September 2006. Anne White, an expert in plasma confinement measurements, will join the faculty in January 2010. NSE faculty and students are dominant in the MIT Alcator tokamak facility, which is a major national confinement facility (approximately $20 million per year).

> *We will seek to obtain influence within the new Idaho National Laboratory by participating in a bid for the management and operations contract. This role will bring research leadership opportunities and support for education to MIT.*

The Battelle Energy Alliance bid, in which MIT was a partner, won the management and operations contract for Idaho National Laboratory (INL) and took over in February 2005. As part of this agreement, funds for a fully endowed professorship (four million dollars) at MIT are committed and now almost all collected. In addition, research and operations funds approaching two million dollars have so far been awarded.

> *We will seek to obtain recognition and base operations funding of the MIT reactor as a key national facility for research and technology testing for the next generation of nuclear reactors and for broader nuclear science and technology.*

After protracted efforts, this plan has just begun to gain traction as well as significant funding for the MIT reactor (MITR). With the full support of INL, MITR has been designated an affiliated facility in support of the new organization of the advanced test reactor at INL. As a result, several experiments are already under development for pilot implementation at MITR.

## Faculty and Resource Development

> *Nuclear Engineering Department faculty are, on average, old. There have been major reductions in faculty numbers over the past 10 years. Probably at least four of the present Department faculty will retire in the next 5 years. To fulfill the vision and mission just outlined it is essential to renew the faculty. We propose that we should recruit at least one junior professor per year for the next five years. In view of the faculty age gap, we also anticipate recruiting one or two outstanding mid-term professionals at the tenured faculty level. Fission engineering is the highest priority area, but we plan also for hires in the fusion and wider nuclear science and technology areas.*

In addition to the two faculty (one in fission and one in nuclear science and technology) who arrived in fall 2004, the department has been accorded five faculty slots under this plan, somewhat short of the seven minimum proposed. These slots have been filled with two fission faculty, two fusion faculty, and one nuclear science and technology faculty. These recruitments have typically taken 22 months from slot award to starting teaching. This delay, though not unusual for MIT faculty hires, is longer than ideal but reflects the external realities of high demand and few outstanding candidates. One recruitment (fusion) was an associate with tenure hire, and the others were assistant professors. Professors Buongiorno and Jasanoff have been promoted to associate without tenure. Unfortunately, there have been unexpected departures in addition to those expected through retirements. Professor Jeffrey Coderre was not accorded tenure. Professor Jasanoff transferred to Biological Engineering. Professor David Cory has stated his intention to leave MIT and has gone on leave of absence. Professor Kim Molvig retired early. The active faculty in September 2009 will then be 13.5, an uncomfortably low level.

> *We will seek additional funding for first year graduate students in the form of endowed fellowships and training grants. These resources will be focused on attracting top students, and helping junior faculty establish their research. A senior faculty member will be tasked with coordinating these fundraising efforts.*

This effort has been very successful. We have the beginning of endowment of four new fellowships in the names of retiring professors in a scheme that permits us to immediately award rotating fellowships. We have enhanced the existing fellowship endowment funds, such as the McCormick and Henry fellowships. We have also raised ongoing expendable funding for four full fellowships per year from private and corporate donors. We are grateful to Neil Todreas, an emeritus professor, who has been instrumental in several of these successes, which we have devoted to attracting top students and to helping support junior faculty. We recently attracted major educational funds from the Nuclear Regulatory Commission (NRC): $400,000 over four years for fellowships, $1.35 million over three years for junior faculty development, and $300,000 over three years for Department of Energy (DOE) fellowships. A two million dollar bequest to the department has also been agreed upon as well as a one million dollar enhancement to the Rasmussen professorship, together with several other significant individual donations.

## Faculty Awards, Honors, and Activities

Professor George Apostolakis continues to serve as a member of the statutory Advisory Committee on Reactor Safeguards of the US Nuclear Regulatory Commission, where he chairs the subcommittees on reliability and probabilistic risk assessment and on digital instrumentation and control. He serves as cochair of the Peer Review Committee of the Nuclear Science and Technology Directorate, INL. He continues as editor in chief of the international journal *Reliability Engineering and System Safety* and as secretary of the International Association for Probabilistic Safety Assessment and Management. He gave invited plenary lectures at the 3rd International Workshop on Critical Information Infrastructure Security (CRITIS '08) in Rome and at the 7th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety (NUTHOS-7) in Seoul. He also gave invited seminars at the Polytechnic of Milan and Bocconi University in Milan.

Professor Jacopo Buongiorno received the 2008 American Society of Mechanical Engineers Heat Transfer Division Best Paper, September 2008 (J. Buongiorno, "Convective Transport in Nanofluids," Vol. 128, 240–250, *Journal of Heat Transfer*, 2006). He has continued to lead the International Nanofluid Property Benchmark Exercise (INPBE) effort.

Professor Sow-Hsin Chen was elected a fellow of the Neutron Scattering Society of America for "his outstanding achievements in the study of the structural and dynamical properties of water and complex fluids by neutron scattering." Professor Chen serves as a member of the International Advisory Committee of the China Advanced Research Reactor and was US chairman of the Second US–China Workshop on Scientific and Industrial Applications Using Neutrons, Muons and Protons, Dongguan, China, November 7–9, 2008.

Professor Benoit Forget served as secretary in the reactor physics division of the American Nuclear Society (ANS) and was elected treasurer for the upcoming year. He was appointed to the Rasmussen junior faculty development chair, 2008–2010, and received the PAI Outstanding Teaching Award presented by the student chapter of ANS, April 2009.

Dr. Charles Forsberg was elected a fellow of the American Association for the Advancement of Science (AAAS).

Professor Jeffrey Freidberg, in collaboration with professor Andrew Kadak, published a commentary in *Nature Physics* "Fusion–Fission Hybrids Revisited." Professor Freidberg's textbook, *Plasma Physics and Fusion Energy*, appeared in paperback form. This book is used in several MIT NSE graduate plasma physics subjects.

Professor Michael Golay served on the Energy Initiative's Education Committee. Its most important achievement has been establishment of the Institute-wide energy minor, where his new subject, Introduction to Sustainable Energy is a core component.

Professor Ian Hutchinson was 2008 chairman of the American Physical Society's Division of Plasma Physics. He presented an invited plenary talk at the 5th International Conference on the Physics of Dusty Plasmas and continued as coprincipal investigator of the Alcator C-Mod tokamak plasma confinement experiment at MIT.

Professor Alan Jasanoff gave the Issekutz Memorial Lecture at Dalhousie University and organized a session on molecular imaging at the American Chemical Society annual meeting.

Professor of the practice Andrew Kadak continues to serve on the executive committee of the Nuclear Installations Safety Division of ANS and serves on the ANS Special Committee on Nuclear Non-Proliferation. He continues to serve on the US Nuclear Waste Technical Review Board and the Rhode Island Atomic Energy Commission. Professor Kadak also serves on the editorial advisory board of *Nuclear Engineering and Design*. Professor Kadak was invited to Singapore as part of an international team of experts to advise the Singapore government on nuclear energy development and safety regulations in preparation for nuclear expansion in Southeast Asia. Professor Kadak also served as the technical cochairman of the International High Temperature Gas Reactor Conference in September 2008 in Washington, DC.

Professor Mujid Kazimi continued as a member of the board of managers of Battelle Energy Alliance and chair of its Science and Technology Committee. He served on scientific advisory committees for the International Atomic Energy Agency and for departments at Brookhaven National Laboratory, Tokyo Institute of Technology, and Jordan University of Science and Technology. He is active in ANS, where he is a member of the Honors and Awards Committee, the Publications Steering Committee, and the Steering Committee of the International Congress on Advances in Power Plants. He gave invited talks at three international meetings: NUTHOS in Seoul (Korea), Nuclear Energy in the Gulf in Jeddah (Saudi Arabia), and Energy 2030 in Abu Dhabi (United Arab Emirates). He also presented special sessions at the winter meeting of ANS and the annual meeting of AAAS in Chicago. Professor Kazimi was a guest editor for a special issue of *Nuclear Engineering and Design*. At MIT, he continued to serve as chair of the MIT Reactor Safety Committee and director of the Center for Advanced Nuclear Energy Systems (CANES).

Dr. Richard Lanza is chairman of the Institute of Electrical and Electronics Engineers Nuclear Science Symposium and Medical Imaging Conference for 2009.

Professor Ronald Parker served on advisory committees reviewing the quality of the scientific program at a number of fusion laboratories engaged in plasma research, including the Max-Planck-Institute for Plasma Physics in Garching, Germany; Princeton University's management of the Princeton Plasma Physics Laboratory; and the Atomic Energy Commission (CEA) Department of Controlled Fusion in Cadarache, France. He also served on a panel reviewing research and development and facilities needed to realize fusion energy in the European Union. The panel's conclusions provided important input to the European Commission in a planning process leading to a coherent program of European research over the next decade and beyond in support of ITER and the following step of a DEMO reactor.

Associate professor Dennis Whyte was awarded the Ruth and Joel Spira Award for Distinguished Teaching by the MIT School of Engineering. He participated in a National Research Council committee to review US science participation in the ITER project. He led the topical group on boundary interactions for the US Burning Plasma Organization, is a core member of the Divertor/SOL Group International Tokamak Physics Activity, and is a member of the steering committee on plasma-facing components research for the United States. Professor Whyte won a three-year fusion diagnostics development grant from DOE to develop the accelerator-based in situ surface diagnostics for magnetic fusion devices (see research highlights below). He presented an invited talk at the 23rd International Symposium on Fusion Engineering in San Diego, CA.

Professor Jacquelyn Yanch relocated her office and laboratory to 16-56, a move expected to facilitate her transition from research in radiation production for radiotherapy applications to research investigating the biological consequences of low-dose and low-particle fluence-rate radiation. Professor Yanch has accepted a joint appointment with the Department of Biological Engineering effective July 2009.

Professor Sidney Yip received the 2009 Outstanding Teaching Award from the Student Chapter of ANS. In September, he organized a workshop at MIT on the advocacy of computational science with support by the National Nuclear Security Agency. He was appointed to the steering committee of the MIT Center for Computational Engineering when it was established in the School of Engineering. At the Industrial Liaison Program Research and Development Conference in October, he organized a special session on multiscale modeling of materials, with six talks by faculty colleagues across the Institute. At several DOE workshops on nuclear energy, national nuclear security, and advanced modeling and simulation in 2009, he cochaired the panels on materials behavior and advanced materials design. In honor of Professor Yip, a symposium was organized by former students and colleagues. The symposium, entitled "Multiphysics Materials Modeling from Atoms to Continuum," was held at the 10th US National Congress on Computational Mechanics, Columbus, OH, in July.

## Research

### Fission: The Center for Advanced Nuclear Energy Systems

Research in fission energy is predominantly conducted through CANES, which also hosts research for nonnuclear applications using nuclear-origin methodologies. The research program covers near-term as well as long-term technology and policy options. Support is derived typically 50% from government—such as DOE, NRC, INL, and other national laboratories—and 50% from US and international industrial and private sources. The research efforts can be categorized as falling into four programs:

- Advanced reactor technology
- Nuclear fuel cycle technology and economics
- Enhanced performance of nuclear power plants
- Nuclear energy and sustainability

The MIT study on the future of the nuclear fuel cycle entered its second year. It is a multidisciplinary collaborative effort with the MIT Energy Initiative that is strongly supported by the US nuclear industry, such as EPRI and NEI. An "Update of the MIT 2003 Future of Nuclear Energy" report, which examined the changes relevant to nuclear energy since then, was issued in May 2009. In particular, the update pointed out that while the cost of all energy options has risen, nuclear energy could be competitive with coal and gas if the financing of all plants were on equal footing or if a carbon emission fee were imposed. A full report on the fuel cycle is expected by the end of 2009: the primary focus is on options to manage the spent fuel from light water reactors (LWRs) over the next few decades.

CANES entered into an agreement with AREVA to collaborate on nuclear energy research and professional education. As part of this process, new fellowships will be offered to students in NSE, and expanded opportunities for MIT students will be made available for internships at AREVA facilities.

CANES organized two symposia during this period. In January 2009, a two-day symposium on "Nuclear Hydrogen Production" was held at the Ecole Polytechnique near Paris and was organized in collaboration with CEA. Four professors and five students from MIT participated. In April 2009, a two-day symposium was organized at MIT specifically for AREVA to cover "Innovation in Nuclear Energy Technology." The program, organized by professors Ben Forget and Mujid Kazimi, surveyed several topics under development at MIT. Twelve MIT speakers and one AREVA speaker participated. Thirty-one AREVA experts attended.

Three professional short courses were offered in June 2008. Professors Michael Golay and Jacopo Buongiorno organized the 17th session of the four-week reactor technology course for utility executives, offered jointly with the Institute of Nuclear Power Operations. Also in June, professors Mujid Kazimi and Neil Todreas offered the 43rd session of the one-week summer course on nuclear plant safety, and professor George Apostolakis directed a one-week course on risk-informed operations of nuclear power plants.

CANES enhanced its international internship program by expanding the AREVA positions and initiating Electricité de France summer positions, for a total of 10 positions for NSE students. CANES continued to host summer interns, both MIT Summer Research Program and Research Science Institute, and MIT Undergraduate Research Opportunities Program (UROP) students, totaling some dozen for each of the past summers.

Highlights of some of the NSE-CANES research projects follow.

## Advanced Reactor Technology

### Advanced Light Water Reactors

An important feature of CANES research is that advanced LWR technology development as well as reactors using other coolants is being pursued. The LWR development effort involves several approaches to improving reactor economics either by raising the power density in the core while maintaining or enhancing the safety margins or by increasing the power conversion efficiency by reaching superheated steam conditions.

*High-efficiency fuel for LWRs.* The development of novel fuel geometries, instead of conventional solid cylindrical fuel, for LWRs has been pursued by professor Mujid Kazimi and Dr. Pavel Hejzlar. A DOE-supported project had concluded that core power of the pressurized water reactors can be raised while maintaining or improving thermal margins via adoption of annular fuel with internal as well as external cooling. If coolant flow is increased proportional to power, the new fuel can support a 50% increase in core power density. A project supported by the Korea Atomic Energy Research Institute is examining application of the annular fuel to Korean reactors, with limited flow increase but with lower core inlet temperature. TEPCO is supporting an investigation of the use of several advanced fuel designs to raise the power in a boiling water reactor (BWR). The project found that large assemblies with smaller pins of solid cylindrical geometry and helical cruciform-shaped (HCS) fuel, with some careful design choices, may be able to raise the power up to 30%. In addition, hydraulic tests were conducted and showed that the HCS fuel could reduce the core pressure drop below that of the current fuel, because the helical rods' contact points along the axial length eliminate the need for grids for mechanical support. In this period, an experimental facility was built to investigate the effect of the new HCS geometry on mixing between coolant channels, which will be a factor in determining the limiting (critical) power associated with this new fuel design.

Professor Neil Todreas is investigating use of the inverted fuel concept for LWRs; in this design, the fuel surrounds the coolant. The inverted core configuration uses hydride fuel in vertical hexagonal blocks (U-Th-$ZrH_{1.6}$ or Pu-Th-U-$ZrH_{1.6}$) perforated by coolant channels arranged in a triangular lattice. A cylindrical Zircaloy clad forms the wall of each coolant channel, and a liquid-metal (LM) gap separates the clad from the fuel. Each channel is provided with multiple short twisted tape inserts (TT) aimed at enhancing critical heat flux (CHF). A hexagonal duct made of Zircaloy or stainless steel surrounds each fuel prism and a LM gap separates the inner surface of the duct from the outer surface of the fuel. The inverted fuel configuration yields lower fuel temperature than a typical rodded core having the same fuel volume fraction and coolant pressure drop. Analysis of pressure drop, heat transfer coefficient, and CHF at high pressure in the presence of short TTs continues. Neutronic and structural as well as thermal hydraulic analyses will determine the extent of a possible power density upgrade. An experimental investigation of TT inserts in various configurations within the coolant channel has been initiated to confirm the pressure drop predictions.

*Nanofluids for nuclear applications.* The use of nanofluids (colloidal binary systems of water and nanoparticles) has been shown to enhance the boiling CHF, which ultimately can result in power density increases in boiling systems, such as nuclear reactors, high-power electronics, and heat exchangers. Professor Jacopo Buongiorno, in collaboration with Dr. Linwen Hu of the Nuclear Reactor Laboratory, has continued to study the heat transfer characteristics of nanofluids.

In the past year, the nanofluid research program has focused on quenching heat transfer. Quenching refers to the rapid cooling of a very hot solid object by exposure to a much cooler liquid. Quenching has many industrial applications; for example, steels can be hardened by heating and subsequent rapid cooling, a process that is done by immersion in water (hard quench) or oils (slow quench). Quenching also plays an important role in mitigating the consequences of loss-of-coolant accidents in nuclear reactors. The work in Professor Buongiorno's lab has shown that alumina, silica, and diamond nanoparticles at low concentrations (≤0.1 volume percent) greatly accelerate the quenching process. The detailed mechanisms responsible for such acceleration are being scrutinized.

Professor Buongiorno continued to lead the INPBE effort. INPBE comprises 34 participating organizations from 13 countries, which independently measured the thermal conductivity of identical control nanofluid samples and reported the data to MIT. The results have shown that the effective medium theory can predict nanofluid thermal conductivity, drawing the controversy on this topic close to an end. A paper has been submitted to the *Journal of Applied Physics.*

The nanofluid research program is sponsored by AREVA, DOE, EPRI, ABB, Saudi Arabia's King Abdulaziz City of Science and Technology, and a gift from Mr. Doug Spreng.

*LWRs with advanced economic features.* An investigation is being conducted by Professor Kazimi, Dr. Hejzlar, and Dr. Edward Pilat into the possibility of creating a very compact medium-power LWR suitable for use in conjunction with desalination plants or oil refineries. The two LWR concepts being explored are (1) an integrated reactor with the steam generator and core in the same vessel, based on the Westinghouse-led IRIS reactor, but with compact steam generators based on Heatric heat exchangers and (2) a superheat BWR that utilizes annular fuel cooled with boiling water on the outside and steam on the inside. The initial results from these efforts are promising and were reported to the ANS meeting in June 2009. Another reactor is being examined, with salt as a coolant in order to reach very high temperatures. The molten salt reactor uses UZrH as fuel. This project is supported by the Masdar Institute of Science and Technology.

*Multiphysics modeling.* The next generation of reactors will require a true multiphysics approach to correctly account for the feedback effects that these reactors will possess. This project, led by Professor Benoit Forget and funded by INL, introduces a framework that facilitates the coupling of different physical phenomena needed to simulate a nuclear reactor. This work uses a novel coupling approach for reactor physics based on the bond graph formalism. Bond graph formalism, originally developed at MIT in the 1950s, relies on using several basic elements to describe the energy flow of the system by dividing any power flow between two ports into two components: effort and flow. In the initial ongoing phase of this project, heat conduction is coupled to neutron diffusion on a simple one-dimensional problem. The one-speed neutron diffusion equation was described according to the bond graph formalism and was coupled to the already well-known heat conduction bond graph through information bonds that transfer heat generation and temperature between two elements.

*Stability of advanced BWRs.* Professor Mujid Kazimi and his students have been examining the potential for density wave oscillations in advanced boiling water-cooled reactors. The stability against coupled nuclear and thermal oscillations in a core cooled by natural coolant convection, in symmetric and asymmetric forms, was analyzed by frequency-domain methods. It was concluded that a naturally cooled core, such as the economic simplified BWR (ESBWR), can be stable by appropriate selection of core height and inlet orificing. This reactor would be more sensitive to changes in power and flow conditions than is typical of current BWRs at their rated conditions. However, at lower powers, where a current BWR will operate in natural convection, the ESBWR-like reactor has better stability margins. The time-domain stability limits are also being investigated by using the TRACE code. The code was examined against experimental observations. The code is being used to assess the impact of multidimensional representation of the nuclear reactions on the predicted stability conditions.

### Advanced Gas-Cooled Modular Pebble Bed Reactors

The Next Generation Nuclear Plant (NGNP) has been proposed for construction at INL as part of the US effort to demonstrate non-$CO_2$-emitting methods to produce hydrogen. CANES continues to work on developing the pebble bed reactor, which is one of the two high-temperature reactor concepts being considered for the NGNP. As a follow-up to last year's successful experiment on air ingress mitigation conducted by two students working with professor Andrew Kadak, detailed computational fluid dynamics modeling of the experiment continued to provide an analytical benchmarked tool for future applications. If it proves to be valid for larger reactors, this injection system could avoid a major safety challenge of high-temperature gas reactors. Another student is working on benchmarking air ingress accident experiments conducted in Germany in 1984 with computational fluid dynamics tools to support data mining to allow for the development of simpler algorithms that can be used in faster-running systems analysis tools such as MELCOR. This work is supported by a NRC grant.

Professor Kadak is supervising an experiment to reduce the bypass flow in a pebble bed reactor by using smaller central graphite reflector pebbles, which preferentially increases the flow in the fueled annular core. If this experiment is successful, the use of a dynamic reflector may be enabled, greatly simplifying the design of future pebble bed reactors while maximizing power capability and increasing overall safety.

A key technical question regarding pebble bed reactors is determination of the peak power density and temperatures in the 400,000-pebble core. Because of the unique reactor configuration, in which pebbles are moving through the core and refueling it during operation, placing neutron instrumentation in the pebble bed is not possible. This requires a good analytical understanding of the reactor physics and heat transfer in the core. During operation of the AVR reactor in Germany, metal melt wires were used to check peak temperatures and were found to exceed predicted maximums. With Professor Forget, a UROP student is using MCNP for modeling a matrix of pebbles of varying burnup and graphite reflector boundary conditions to simulate the reactor.

An SM thesis supervised by Professor Kadak demonstrated that a pebble bed reactor core could be designed to fit within a reactor vessel outer diameter of 14 feet 3 inches, which is the largest size that can be transported by train. The power level of 250 MWth would be capable of producing approximately 100 MWe, considered an appropriate size for developing nations. This design is built on a modularity principle, which enables building the plant in modules at factories to be shipped to the plant site by train or truck, greatly expanding application to noncoastal or river sites.

CANES continues collaborations on the Chinese pebble bed project sponsored by the Institute of Nuclear Engineering Technology of Tsinghua University. Also, Professor Kadak collaborates with the South African Pebble Bed Modular Reactor Project and the Westinghouse design team for the NGNP.

### *Advanced Fast Reactor Systems*

*Risk-informed balancing of safety, nonproliferation, and economics for the sodium-cooled fast reactor (SFR).* This three-year research project is supported by the Nuclear Energy Research Initiative of DOE. Its objective is to develop risk-informed design development and evaluation tools that take into account safety, economics, licensability, and proliferation resistance. These tools are applied to a number of design alternatives to identify opportunities to reduce the cost of the SFR while maintaining a high level of safety and proliferation resistance. The intent is to assist DOE in developing technical requirements to be imposed on the industrial design organization, in identifying research needs, and in assessing the technology risk of alternatives.

The work is led by MIT and includes Idaho State and Ohio State Universities. Professor Apostolakis is the principal investigator. Professors Michael Driscoll, Michael Golay, Andrew Kadak, and Neil Todreas are leading individual tasks and contribute to the overall direction of the project. A review group consisting of senior representatives from General Electric Company and Argonne, Idaho, and Lawrence Berkeley National Laboratories provides guidance and access to relevant information.

Progress is being made in the following areas:

- *Enhanced SFR efficiency:* Options for increasing efficiency are being examined. The S-$CO_2$ cycle has an efficiency benefit over the Rankine cycle in the temperature range considered. Eliminating the intermediate loop is also effective in increasing efficiency.
- *Transient response:* Failure frequencies and conditional failure probabilities in the PRISM (power reactor inherently safe module) and ALMR (advanced liquid metal reactor) probabilistic risk assessments (PRAs) are being examined. A probabilistic model for eutectic formation was created to model the failure probabilities correctly.
- *Self-actuated shutdown systems (SASS):* A ranking methodology is being developed to rank SASS designs according to their performance characteristics. Based on the preliminary rankings, curie point latches appear to be the best choice for increasing scram reliability.
- *Probabilistic risk assessment:* NRC's technology neutral framework (TNF) is used to evaluate SFR designs. An informative importance measure was developed, called the limit exceedance factor, for the margin each system has in reduction of reliability before the TNF limit of $10^{-8}$ per reactor year for large releases (greater than 500 rem of radiation) would be exceeded. This factor would identify candidate systems, structures, and components for simplification.
- *Safety analysis:* Argonne National Laboratory has provided input for SAS4A-based loss-of-flow safety analyses for the ABR-1000 design to use as the reference case for metal-fueled transient analyses.
- *Improved SFR economics:* ALMR design alternatives were considered and a few were in detail. The most complete of these design alternatives was the manufacture of certain components, such as the steam generator, as nonsafety grade instead of safety grade.
- *Enhanced proliferation resistance:* The applicability of a risk-informed and performance-based regulatory approach is assessed. Constructing a probabilistic security assessment tree, named success tree, leads to quantification of metrics (proliferation success probability), which allows for framing the security problem similarly to standard risk analyses (PRA).

*Fast reactor fuel modeling.* Professor Buongiorno led development of the fuel engineering and structural analysis tool code to predict the irradiation performance of metal and oxide fuel pins in sodium-cooled fast reactors. Both steady state and transients are modeled. The metal fuel code raised significant interest, resulting in a new research contract from TerraPower, a venture capital company developing a new fast reactor concept and another contract from INL. A PhD student supervised by Professor Buongiorno and Dr. Hejzlar examined several options for novel fuel elements to help reach high burnup in sodium fast reactors. The work resulted in new capability for thermal analysis of coolant in subchannels surrounding fuel rods using the RELAP code.

*Fast reactor blankets.* A group led by professor Benoit Forget and professor Mike Driscoll is studying optimal ways to reintroduce blankets in fast reactors. Studies have focused on the design of proliferation-resistant blankets that produce denatured plutonium that is still usable for reactors. Additional work has also investigated optimizing the transmutation of used nuclear fuel by introducing neutron spectrum optimization routines that will select ideal blanket compositions that will minimize certain isotopes in the discharged fuel (i.e., waste) while still addressing proliferation and safety concerns.

*Advanced gas-cooled fast reactors.* Work was completed in September 2008 on a multiyear project supported by DOE to evaluate a gas-cooled fast reactor employing a direct cycle supercritical $CO_2$ Brayton power conversion system. The most important findings were (1) the concept could be capital-cost competitive, but startup fuel cycle costs are penalized by the low core power density, limited largely to satisfy the goal of postaccident passive natural convection cooling; (2) active decay heat removal is preferable as the first line of defense, with passive performance in a backup role; (3) an innovative tube-in-duct fuel assembly, vented to the primary coolant, appears to be practicable; and (4) use of the supercritical $CO_2$ gas-cooled fast reactor to support hydrogen production is possible, as sufficient energy can be recuperated from the products $H_2$ and $O_2$ to allow the electrolysis cell to run 250°C hotter than the reactor coolant, and the water boilers can be used for reactor decay heat removal. Increasing core power density is identified as the top priority for future work.

*Supercritical $CO_2$ power cycle.* Also completed during the past year was our decade-long effort, primarily supported by DOE via Sandia, to establish sound technical grounds for acceptance of the supercritical $CO_2$ power conversion system as a recognized contender for advanced nuclear reactor applications. A final set of papers were presented at the supercritical $CO_2$ Power Cycle Symposium held at Rensselaer Polytechnic Institute in April 2009. Some half dozen programs worldwide have now initiated follow-on efforts to bring this technology to fruition.

*Corrosion-resistant, functionally graded composite material for Pb-Bi-cooled reactors.* Professor Ronald Ballinger's group has been developing a composite structural alloy that will be resistant to corrosion in high-temperature liquid Pb and Pb-Bi eutectic to temperatures as high as 700˚C. A new corrosion-resistant alloy, developed by Professor Ballinger's group, is being applied as a cladding layer to both the inside diameter of grade T91 pipe and the outside diameter of grade T91 fuel cladding. The project is in its third year, and the final product will be completed and corrosion tested. Separate effect studies to explore the evolution of the interface between the corrosion-resistant and structural layers have shown that little dilution will occur over the expected life of either pipe or fuel cladding. Successful completion of the project will result in technology that will enable viability of the Pb-Bi system from a materials standpoint and allow higher temperature operation. Higher temperature operation will greatly improve the overall economics of the Pb-Bi system.

*Corrosion of materials in supercritical $CO_2$.* A program is under way in Professor Ballinger's group to explore the corrosion of materials in supercritical $CO_2$ over the temperature range 650–800˚C and the pressure range 12.5–25 MPa. A wide range of materials are being studied initially. Once initial results are obtained, the matrix will be narrowed and the temperature–pressure range as well as the length of exposure will be expanded. Professor Ballinger's laboratory (H.H. Uhlig Corrosion Laboratory) is the only university laboratory with this capability. A detailed analysis of the corrosion process is being carried out with a goal of optimizing performance through material and processing/heat treatment control.

### MIT Reactor Upgrade

*Use of low-enrichment fuel in the MIT research reactor.* The use of highly enriched uranium in research reactors has facilitated high neutron fluxes for use in many scientific disciplines. Last year, Dr. Tyler Ellis, working with Dr. Thomas Newton, professors Mujid Kazimi and Benoit Forget, and Dr. Edward Pilat, developed a design for a fast-flux booster for the new MIT reactor core. The new core has a candidate design using monolithic 20% enriched uranium and 7% molybdenum (U-7Mo) fuel and maintains acceptable thermal and fast neutron fluxes within the confines of the existing core structure by using a plate-type fuel similar to but thinner than the current fuel elements. The fast flux booster relies on a liquid metal-cooled fueled insert at the center of the core and is able to increase the flux by a factor of 1.6. Dr. Linwen Hu and Professor Kazimi engaged in an effort to qualify the methods used for thermal-hydraulic analysis of the coolant flow in the core. Issues of transition core with part old and part new elements were also assessed.

*Enhanced computational reactor physics.* A group led by professor Benoit Forget has developed a code package for performing detailed fuel management studies at the MIT reactor that is easy to use and is based on state-of-the-art computational methodologies. A wrapper was written that enables fuel management operations to be modeled using MCODE, a code developed at MIT that couples the reactor physics code MCNP to the point-depletion code ORIGEN. To explicitly model the movement of the control blades in the MIT reactor as the core is being depleted, a criticality search algorithm was implemented to determine the critical position of the control blades at each depletion time step. Additionally, a graphical user interface (GUI) was developed to automate the creation of model input files. The fuel management wrapper and GUI were developed in Python, with the PyQt4 extension being used for GUI-specific features.

### Nuclear Fuel Cycle Technology and Economics

*The future of the nuclear fuel cycle.* MIT received a grant from NEI and EPRI to conduct a three-year study on the nuclear fuel cycle to provide a deeper understanding of the credible options for managing the spent fuel from a growing nuclear energy deployment. The emphasis is on meeting US energy needs but within a global context. This study, patterned after the 2003 MIT study on the future of nuclear energy, has a multidisciplinary team across the Institute and is led by professors Ernest Moniz and Mujid Kazimi. Other NSE faculty involved include professors George Apostolakis, Michael Driscoll, Andrew Kadak, and Michael Golay. Faculty members from other departments include Stephen Ansolabehere, John Deutch, Thomas Eagar, and John Parsons. Dr. Charles Forsberg is executive director of the study. An external advisory committee chaired by the Honorable Phillip Sharp has been active in reviewing the study's progress.

An "Update of the 2003 Future of Nuclear Power" report was issued. It lays the context for a large study that will include fuel cycle economics, uranium resources, alternative nuclear fuel cycle options with different nuclear growth scenarios, technological readiness, public acceptance of repositories, spent fuel storage options, waste management options (borehole waste disposal and new waste forms), and nonproliferation. "The Future of the Nuclear Fuel Cycle" study will be completed near the end of 2009. The study will offer an assessment of various options and identify critical questions for nuclear fuel cycle research in the following few years.

*System analysis of fuel cycle options.* Professors Kazimi and Forget and Dr. Hejzlar and their students are investigating thermal and fast-spectrum closed fuel cycles compared with the open fuel cycle regarding spent fuel management economics and proliferation resistance. In addition, the nuclear fuel cycle simulation code CAFCA system dynamics version was upgraded to allow for a larger number of reactor options and several models for characterizing the waste burden and economics of the fuel cycle. The validation of CAFCA against other system codes, such as DANNESS of Argonne National Laboratory, VISION of INL, and COSI of CEA has been concluded. A report was issued that shows the comparison of results for four reference scenarios. It was concluded that, provided care is used to harmonize the assumptions about the technology options and industrial conditions, the codes by and large lead to similar results. However, each code utilizes different built-in assumptions and default conditions, which can lead to variations in the dynamics of the simulated system.

*Flexible conversion ratio fast reactors.* A group led by professor Neil Todreas and Dr. Pavel Hejzlar evaluated flexible conversion ratio fast reactor systems for time-dependent management of both fissile inventories and higher actinides within a DOE-sponsored project. The focus of the design effort is on reactor core designs having two conversion ratios: (1) near zero to transmute legacy waste and (2) near unity to operate in a sustainable closed cycle. Three liquid reactor coolant core candidates—sodium, lead, and liquid salt (as distinguished from molten salt containing molten fuel)—and supercritical carbon dioxide gas were selected for cross-comparison. The gas coolant core results from another completed MIT project and sodium results from Argonne National Laboratory work were selected for comparison with the lead and liquid salt coolant core results developed in this project. The feasibility of the lead-cooled and liquid salt-cooled reactor concepts has been established for both conversion ratios. The liquid salt-cooled concept was found to be more challenging to develop and required innovative features to overcome neutronic and thermal hydraulic challenges. All liquid-cooled concepts can be designed to passively accommodate the unprotected limiting accidents. Comparison among all four coolant concepts confirmed superiority of the sodium approach regarding achievement of desirable large power density and specific power ratings, which points to the ability to achieve reduced capital and fuel cycle costs.

*Proliferation resistance of the fuel cycle.* Methods for assessing the nuclear weapons proliferation resistance of different nuclear fuel cycle proposals are under study by professor Michael Golay. He emphasizes the use of risk assessment techniques for evaluation of the success probability of a potential proliferator, considering utilizing a reactor/fuel cycle facility for diverting fissile material for use in nuclear explosive devices. Professor Golay and his students developed such methods in projects as varied as assessment of the proliferation potential of the gas-cooled pebble bed reactor, the sodium-cooled fast reactor, and associated fuel cycle facilities (with support from DOE). This work has been the subject of three recent or current PhD theses, one SM thesis, and one SB thesis. This method was also featured in a Generation IV International Forum project on development of techniques for assessment of proliferation resistance and physical protection. Professor Golay has also pioneered the use of Bayesian estimation techniques for evaluation of proliferation behavior on both national and facility-specific scales. This work has been the subject of two recent SM theses and has been funded by INL.

*Deep boreholes for waste disposal.* Work has continued at a modest level under supervision by professor Mike Driscoll on the evaluation of deep boreholes for disposal of high-level radioactive nuclear waste. The recent focus has been on highly secure and irretrievable entombment of the minor actinides and troublesome fission products such as I-131 and Tc-99. A master's thesis and several student project reports were completed. This work has taken on added significance in view of the recent federal decision to move away from Yucca Mountain as the legally designated US repository.

*Cement for nuclear waste confinement in a repository.* The higher-level goal of this project is to attain a special chemistry of cement that can trap $Cl^-$ ions on its surface, defined by nano-sized calcium-silica-hydrate (C-S-H) particles, to evade localized corrosion of the spent nuclear fuel cask proposed for repositories. The specific objective of this study is to understand the mechanism of $Cl^-$ binding onto the surface of the calcium silicate hydrate (C-S-H) lamella in cement. This is a complicated problem, particularly because of the gel-like and not-well-known structure of amorphous C-S-H and its surface. At this early stage of the project, Professor Yildiz's group in collaboration with Professor Yip started using a recent atomistic model to understand the surface chemistry of cement. This is important not only for avoiding the corrosion of internally embedded metals but also for trapping radionuclides leached out from the spent nuclear fuels in a repository.

*Intergenerational ethics of nuclear waste management.* Professor Kadak sponsored a summer visit by a PhD student from the Delft University of Holland to study the role of intergenerational ethics in waste management policy decisions. An interesting finding of this research, which reviewed options relating to closing the fuel cycle, is that based on a risk model of the Yucca Mountain repository, current generations will be bearing a greater risk than future generations in the management of this nation's high-level waste. Professor Kadak sponsored a four-day engineering ethics workshop during Independent Activities Period with Behnam Taebi of Delft University as the lead lecturer. The goal was to have students appreciate the theory and practical issues of ethical challenges that one might experience in the workplace.

### *Enhanced Performance of Nuclear Power Plants*

*Risk-informed design.* In the early phases of advanced systems design, information is scarce. The technologies, components, and processes to be used have not been specified adequately or are not well understood and uncertainties are very large. We are developing a methodology that assists the designers at these early phases.

It is based on the analytic-deliberative decision-making process (ADP), which brings together multiattribute decision theory with the analytic hierarchy process to create a dialogue among stakeholders. ADP identifies and prioritizes attributes relevant to a decision problem and supports the formulation of metrics to measure the performance of different design options. It allows stakeholders to quickly identify crucial parameters and uncertainties and to rank alternatives, and it provides the information necessary to work toward consensus. ADP is a scalable methodology that can be refined as a system evolves to incorporate information that is more detailed and stakeholder preferences that are better developed. Professor Apostolakis and his students have applied the methodology to the selection of a technology for a decay heat-removal system in a lead-cooled flexible conversion ratio reactor that was designed at MIT.

Professor Golay examined the use of probabilistic evaluation of the effectiveness of passive safety features in reducing risks. This work emphasized the roles of functional failures, those involving intact, but inadequate, systems attempting to perform essential safety functions. This work was the subject of one recent PhD thesis and two SM theses.

*Advanced methods for probabilistic risk assessment.* The objective of this activity is to develop advanced modeling and computational PRA methods and tools appropriate for specified classes of risk-informed regulatory decision making. Professor Apsotolakis and his students are examining surrogate models, also known as meta-models, which represent approximations to the true system model that allow for quick simulation, making uncertainty propagation tractable, especially for models that present a prohibitive computational burden. Such models are frequently used for design optimization purposes and to some extent have made their way into the field of reliability assessment for complex systems. Numerous approaches to meta-model development have been proposed in the literature, most of which are regression-type models, such as linear regression or locally weighted polynomial regression. Perhaps the most familiar such method is the response surface methodology. All these methods consist of running model evaluations a predetermined number of times for specified input values and fitting a simplified model to the results. The question of how many evaluations need to be performed, as well as what input configurations should be evaluated, remains unanswered and to a large extent relies on the analyst's expertise. A more systematic method of answering these questions is being investigated.

Another meta-modeling technique that is being investigated is artificial neural networks (ANNs). ANNs are similar to the other methods in that they consist of a set of assumed functions (basis functions) with unknown parameters that are fit to the output of the model. The fitting process is referred to as training in the ANN literature. ANNs have been demonstrated to be quite robust, and a single network topology can be trained to predict a variety of model outputs. However, the ability of an ANN to be trained to predict a set of data relies on the number of available data as well as the assumed topology of the network.

*The effect of thermal aging properties on stainless steel weld metals.* The effect of thermal aging on the environmentally assisted crack growth is being explored by Professor Ballinger's group. While the initial thrust of the program focused on static (stress corrosion crack growth) crack growth, the program has now added a task exploration of a newly identified emerging issue that has been termed "environmental fracture." This phenomenon, identified and formally characterized for the first time in Professor Ballinger's laboratory, manifests itself as a large reduction in resistance to unstable crack propagation and fracture when a material is exposed in high-temperature water (~300˚C) for periods that exceed approximately 2,000 hours. Factors of more than 50% reduction in fracture toughness have been observed. The program focuses on environmental fracture of welds in the current program.

*Environmental degradation of materials in LWR environments including irradiation effects.* Professor Ballinger has become actively involved with INL in the areas of LWR materials degradation. His group has initiated a joint project with INL to develop capabilities for testing materials in LWR environments and to include irradiated materials. Testing is being done (crack growth and fracture toughness) on high-strength materials at MIT. Capability is being constructed for both unirradiated and irradiated materials at INL with the goal of performing irradiations at the advanced test reactor and then testing at the INL facilities. Professor Ballinger's group is supplying engineering and software for the INL facilities.

*Interfaces of structural alloys in stress corrosion cracking.* Degradation of alloy materials (cladding and structural materials) is of key concern for the longer lifetimes required for advanced nuclear reactors. A major challenge in the degradation of nuclear materials has been stress corrosion cracking (SCC) in the presence of an extreme temperature, radiation, and stress environment. SCC is an electrochemical and reactive transport phenomenon at the surfaces and has not been resolved at a fundamental level. Micro- and macro-modeling and simulation and advanced interface-sensitive experiments need to be pursued to enable advances in SCC resistance of alloys—namely, their surfaces and grain boundaries. Professor Yildiz's goal is to improve the fundamental understanding of how the alloy interface crystallographic structure and strain state control the microchemistry, corrosion, and crack initiation. For this purpose, she is pursuing three research projects: (1) correlations of structural, chemical, and mechanical properties of face-centered cubic (fcc) Ni-Cr-Fe alloy grain boundaries, using transmission electron microscopy and nanoindentation; (2) the role of strain in initiation of oxidation on the body-centered cubic (bcc) Fe-Cr surface, using first principles simulations; and (3) the evolution of self-interstitial defects in bcc Fe, using atomistic scale simulations. One journal paper has been accepted in this topic, and two are in the preparation stage.

*Advanced materials degradation simulation.* Professor Sidney Yip has maintained his industrial collaborations on materials simulation research with projects on steel, glass, and polymers.

### *Nuclear Energy and Sustainability*

*Nuclear energy for electricity, hydrogen, and drinkable water.* Hydrogen production and use to manufacture transportation fuels have become a national priority. The department is uniquely positioned to participate in this exciting new area because of the experience it has in high-temperature reactor design and analysis. A new project was started for examining various designs of nuclear power plants to address future needs of electricity, drinkable water, and hydrogen through a highly efficient and environmentally friendly reactor (HEER). HEER will emphasize minimum production of spent fuel and waste. Three advanced reactors are being examined: (1) an innovative fuel design to enable efficient (high burnup) fuel utilization and heating the coolant in an LWR to a higher temperature through implementation of annular fuel in the pressurized water-cooled integrated reactor IRIS, (2) the design of a superheat LWR, and (3) a molten salt reactor with a thermal spectrum and advanced energy conversion system. The two-year project is supported by the MASDAR group of Abu Dhabi and is supervised by Professor Kazimi and Dr. Hejzlar.

*High-temperature solid oxides for electrocatalytic production of electricity and/or fuels.* Among the various types of fuel cells, the solid oxide fuel cell (SOFC) is particularly attractive given its fuel flexibility and high conversion efficiencies, enabled by its relatively high operating temperature. SOFCs can work in a reversible mode. Coupled to a nuclear plant, they can produce hydrogen or syngas ($H_2$ and CO) for liquid fuels synthesis or combine the hydrogen and oxygen to produce electricity. Key barriers to widespread use of SOFCs thus far are materials degradation over time at high operating temperatures and poor conductivity of the electrolyte and poor activity of the cathode (the oxygen electrode) at lower temperatures. Advances in materials are needed to significantly decrease the operating temperature, which would reduce materials degradation, extend the lifetime of reversible SOFC systems, and reduce cost. To realize this, improved fundamental understanding of the atomic and electronic structures that control transport behavior at the interfaces is needed. For this purpose, Professor Yildiz is investigating the interface reactivity of SOFC oxygen electrode materials in three projects: (1) correlating electronic and chemical states and electrocatalytic activity on dense thin-film oxygen electrode surfaces, (2) understanding the role of lattice strain and defect chemistry on the oxygen vacancy migration at hetero-interfaces, and (3) degrading the oxygen electrodes driven by high fluxes of charge carriers and poisoning chemical species. Her approach to elucidating these questions, from micro-scale to atomistic levels, involves a multidisciplinary framework with new in situ spectroscopic techniques, analytical theory, and simulations. One journal paper and two conference papers have been accepted in AY2009, and several are in preparation.

*Nuclear power container ships.* Professor Andrew Kadak and a graduate student from Ocean Engineering have designed a nuclear-powered container ship. While not a new idea, since the Savannah was a commercial nuclear ship that operated from 1962 to 1971, current demands for new ships require higher speeds and power levels. The objective was to design twin reactors with 10-year lifetimes between refueling using low enriched LWR cores for duty cycles demanded for economic operation. While the design achieved these objectives, it is currently not an economic alternative.

*Fusion–fission hybrid.* Professors Kadak and Freidberg are engaged in research that blends the fusion and fission technologies in potentially useful applications in the nearer term than pure fusion for electric production. By utilizing a fusion device with Q factors slightly greater than one, the challenge of building such a device becomes much less. The fusion machine can produce high-energy neutrons, which can be used in a fission blanket for breeding plutonium from U-238, breeding U-233 fuel from thorium, or transmutating actinides for waste management along with the possibility of generating electricity. In essence, the fusion device becomes a neutron source for fission applications. While this idea was originally proposed in 1957, technology has advanced to a point where it can be realized. Initial studies are aimed at better understanding of fusion as a neutron source, including both magnetic and inertial confinement and better understanding of the fission technology challenges associated with such a blanket application. Additionally, the economics of such a blend of technologies will be compared with conventional fission applications for the same missions.

*Use of nuclear energy to replace conventional fossil boilers as a heat source.* Professor Kadak is exploring the application of smaller high-temperature pebble bed reactors to replace fossil boilers in older conventional fossil boilers as part of his studies on sustainable energy systems. Older fossil boilers are the least efficient and most polluting of fossil power plants. These plants are also sited closer to population centers. Pebble bed reactors with their high-temperature outputs may be a suitable replacement for the boiler while maintaining the steam power conversion system. The use of pebble bed reactors is possible due to their inherent safety and an assumed 400-m emergency planning zone, which is within the property lines of most power plants.

## Nuclear Science and Technology

Professor Sow-Hsin Chen is an expert in the applications of scattering to characterizing the structure and dynamics of soft and porous mater. He and his students have recently observed key signatures of a second critical point of water. This work will have wide significance including understanding function in biomolecular systems.

### *Discovery of the Second (Liquid–Liquid) Critical Point of Heavy Water at Critical Pressure = 2,250 ± 250 Bars and Critical Temperature = 195 ± 5 K by Neutron-Scattering Experiment*

Water, the matrix of life, displays exceptionally rich phase behavior with at least 15 crystalline forms. It is the first example of a pure substance that exhibits polyamorphism, the existence of two distinct glass forms: low-density amorphous (LDA) ice and high-density amorphous (HDA) ice. Moreover, its thermodynamic response functions, such as the isobaric thermal expansion coefficient $\alpha_p$, show a tendency to diverge on approaching a deeply supercooled temperature ($T_s$ = 228 K) at ambient pressure. One possible explanation of this anomalous behavior rests on the hypothesis that at the supercooled temperatures water is composed of a mixture of two structurally distinct liquids, the low-density liquid (LDL) and the high-density liquid (HDL). They are, respectively, the thermodynamic continuation of the LDA and HDA into the liquid state. Thus, in this deeply supercooled state, there is a coexistence line between LDL and HDL, which should end at a second liquid-liquid critical point (LLCP) at some elevated pressure. Above the LLCP temperature, in the one-phase region, there is an imaginary line of the maximum correlation length, called the Widom line. The divergent behavior of the thermodynamic response functions can be attributed to crossing the Widom line. Although a series of molecular dynamics simulations support this hypothesis, definitive experimental evidence of the existence of the LLCP in water is so far lacking. We use neutron scattering to directly measure the density of supercooled heavy water confined in mesoporous silica material as a function of temperature and pressure $\rho(T, P)$—namely, the equation of state. The combination of the measured isobaric density profile and the evaluated isobaric thermal expansion coefficient allows us to identify the Widom line and locate its end point, the LLCP. Consequently, a coherent picture of the phase behavior of supercooled and glassy water now emerges.

### *New Measurement of Dynamic Susceptibility of Supercooled Water to Find Its Relation to the Dynamic Crossover Phenomenon*

We measured, for the first time, the dynamic susceptibility $\chi_T(Q, t)$ of deeply supercooled water by means of quasi-elastic neutron scattering. We show an increase in the peak height of $\chi_T(Q, t)$ as the temperature is lowered toward the dynamic crossover temperature $T_L$. Below $T_L$, the peak height decreases steadily. We attribute this phenomenon to the change in slope of the Arrhenius plot of the translational relaxation time at $T_L$.

### *Proteins Remain Soft at Lower Temperatures Under Pressure*

The low-temperature behavior of proteins under high pressure is not as extensively investigated as that at ambient pressure. We study the dynamics of a hydrated protein under moderately high pressures at low temperatures by using the quasi-elastic neutron-scattering method. We show that, when applying pressure to the protein–water system, the dynamics of the protein hydration water does not slow down but instead becomes faster. The degree of "softness" of the protein, which is intimately related to the enzymatic activity of the protein, shows the same trend as its hydration water as a function of temperature at different pressures. These two results taken together suggest that, at lower temperatures, the protein remains soft and active under pressure.

### *First Measurements of Phonon-like Low-Energy Excitations of Protein Molecules by Inelastic X-Ray Scattering*

Molecular dynamics simulations and neutron-scattering experiments have shown that many hydrated globular proteins exhibit a universal dynamic transition at $T_D = 220$ K, below which the biological activity of a protein sharply diminishes. We studied the phonon-like low-energy excitations of two structurally very different proteins, lysozyme and bovine serum albumin, using inelastic x-ray scattering above and below $T_D$. We found that the excitation energies of the high-Q phonons show a marked softening above $T_D$. This finding suggests that the large-amplitude motions of wavelengths corresponding to this specific Q range are intimately correlated with the increase in biological activities of the proteins.

### *Phase-Contrast Imaging*

Phase-contrast imaging, under investigation by Richard Lanza, is an approach to x-ray and neutron imaging that uses the refraction of x-rays to examine small differences in materials that are not discernible with conventional absorption imaging. This work formed the PhD thesis of Antonio Damato, who showed the criteria for source coherence required to use this technique. Current x-ray sources are near their flux limit for this application and a new approach based on coded sources was developed. If brought successfully to a practical stage, this technique could reduce patient dose by an order of magnitude. Berthold K.P. Horn of Electrical Engineering and Computer Science (EECS) and the Computer Science and Artificial Intelligence Laboratory (CSAIL) was also involved in this work.

### *New Approaches to Borehole Logging*

Borehole logging refers to the collection of techniques used in the oil industry to investigate the properties of subsurface features so as to more reliably predict the outcome of drilling for oil. Erik Johnson (PhD 2009) examined a new approach to this problem using high-energy photons in the 7- to 9-MeV range. The advantage of his method is to extend the distance from the borehole that is investigated, thereby lessening the effect of wall irregularities and exploring considerably larger volumes of space. The work was done under the supervision of Richard Lanza and in collaboration with Brad Roscoe and Darwin Ellis of Schlumberger.

### *Long-Distance Passive Imaging of Radionuclides*

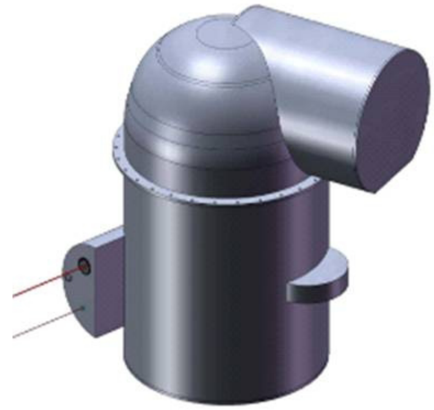
Long-range (100 m) detection of radioactive sources is a problem that has both security and environmental consequences. In earlier work, Richard Lanza and coworkers showed that the combination of small signals and widely distributed background made detection while in motion difficult unless spatial resolution and imaging were used. This project developed a large mobile imager that combined active mask coded aperture imaging and Compton imaging to produce reliable detection of radioisotopes in the 40- to 3,000-MeV energy range. Traditional coded apertures use passive masks whose performance degrades at high energy while Compton imaging is a gamma imaging technique that degrades at low energy. We devised a new method in which the elements of the coded aperture mask were themselves detectors that could also be used as part of a Compton imager. The two methods were combined by using a new dynamic imaging technique to produce high-quality detection even at relatively high speeds for the system. This work was a large collaboration with Raytheon, Los Alamos National Laboratory, and Bubble Technologies. Berthold Horn of MIT EECS and CSAIL was also a collaborator.

### *Dynamic Reconstruction*

Reconstruction methods traditionally use detectors and collimators (or coded apertures), which operate in a "staring mode" in which the system is static long enough that images may be built up before reconstruction. Richard Lanza and collaborators developed a new approach to imaging that builds up images on a photon-by-photon basis, even when the geometries of detector and collimators are changing significantly between individual photon events. The result is a whole new generalized approach to imaging that can incorporate three-dimensional imaging and computed tomography imaging as subsets of this approach. Lanza has applied this approach to long-distance passive imaging as well as to imaging of x-ray backscatter for the detection of improvised explosive devices. This work was part of the SM thesis of Jayna Bell (SM 2009). MIT collaborators included Berthold Horn (EECS and CSAIL) and Gordon Kohse (MIT Nuclear Reactor Laboratory) and the work was carried out with American Science and Engineering under Defense Advanced Research Projects Agency sponsorship.

### *Superconducting Cyclotrons*

Cyclotrons have been in use for almost 80 years and are a well-proven technology. The volume (and mass) of a cyclotron decreases inversely with the cube of the magnetic field. Advances in superconductive magnet design and cryogenics have produced transformational changes in this technology. By going to fields that are factors of four or five greater than conventional resistive coil machines, Richard Lanza and collaborators have designed a series of machines that are almost two orders of magnitude smaller than these conventional machines, while reducing costs. One example is the design for a 12- to 16-MeV proton cyclotron that is completely self-contained with a total mass of ~600 kg and a diameter of 70 cm. Such machines essentially make accelerators "components" and, for applications such as security and medical isotope production, make such systems portable and much lower in cost. This work is a collaboration with Timothy Antaya of the MIT Plasma Science and Fusion Center (PSFC).



*Design drawing for a self-contained 10-MeV superconducting proton cyclotron. The entire system, including cooling and controls, is less than 1 m high, is 50 cm in diameter, and weighs approximately 200 kg.*

### *Quantum Information Processing*

Quantum mechanics provides a fundamentally new approach enabling us to build devices that exceed the performance of any possible classic device. Quantum mechanics poses the fundamental physical limits to information processing; by building quantum sensors, actuators, secure communication channels, and computers we effectively reach the limits in power and accuracy allowed by the laws of physics. The challenge to utilizing quantum mechanics is to control a large enough system so that the efficiency gains offered by quantum mechanics outweigh the technical challenges. Professor Cory and his colleagues have demonstrated control over quantum devices that are so large they cannot be simulated classically. They are working to turn these quantum systems into practical quantum devices. The program has two stages: the first stage is directed at laboratory-scale devices for characterizing and controlling magnetization, transport, and chemistry. These devices will be enabling for advancing nano- and quantum technology. The second stage aims to construct devices that can operate outside the laboratory and yet still demonstrate the efficiencies achieved uniquely through quantum mechanics. Professor Cory and his students approach quantum information processing through collaborations with Dr. Chandrasekhar Ramanathan (NSE); professor Seth Lloyd (Mechanical Engineering); Dr. William Oliver (Lincoln Laboratory); Dr. Mohamed Arif (National Institute of Standards and Technology); professor Mikhail Lukin (Harvard University); Dr. Paola Cappellaro (Harvard University); professor Lorenza Viola (Dartmouth University); and professor Raymond Laflamme, professor X.W. Tang, professor Jonathan Baugh, and Dr. Joseph Emerson (all at the University of Waterloo). A few of the highlights from last year are briefly described below.

Ms. Cecilia Lopez has developed a unifying description of approaches to efficient error finding. A challenge in quantum computing is that to achieve fault tolerance requires some knowledge of the error model. Since the number of terms in a generic error model grows exponentially with the number of qubits, directly measuring all possible errors is not an option. The efficient error-finding schemes that have been developed through collaborations between MIT and the University of Waterloo parameterize reasonable physically relevant models from a polynomial number of measurements.

Mr. Troy Bornamann has taken a different approach to dealing with errors. He has demonstrated a quantum code that protects coherent information even in the presence of large experimental errors in implementing the code. He is now working to demonstrate this finding experimentally.

Dr. Chandrasekhar Ramanathan has reported on a series of experiments that use nuclear magnetic resonance (NMR) to simulate multibody dynamics. One finding has been to show that even in a dipolar coupled spin chain information can be efficiently transported. Applications include using spin chains as channels for quantum information and creating highly polarized spin systems as potential transducers.

Dr. Jonathan Hodges has implemented a new series of optically detected magnetic resonance experiments based on the nitrogen/vacancy defect in diamonds. He has demonstrated that quantum information can be manipulated between electron and nuclear spins and that the contrast of electron spin readout can be improved by considering the nuclear spins as a quantum resource. This work is in collaboration with Professor Lukin's laboratory at Harvard University.

Mr. Fei Yan has started a project to use optimal control theory to improve the coherent control over persistent current flux qubits patterned from superconductors. In this collaboration with Dr. Will Oliver and professor Terry Orlando, we have used the enhanced control to obtain an improved model of the noise, which currently limits the applications of superconducting quantum systems.

Ms. Clarice Aiello and Mr. Mohamed Abutaleb have continued to develop pulsed electron spin resonance as a testbed for coherent control of quantum information. They have developed new instrumentation to enable studies at cryogenic temperatures with optimal control pulses and demonstrated a new approach to control where there is a finite bandwidth on the control parameters.

Mr. Kevin Kruslich has initiated a study to directly observe spin injection into superconductors via magnetic resonance. He has implemented NMR studies at controlled cryogenic temperatures and demonstrated that he can develop control methods that work in metallic samples. Note this situation is extreme since the skin depth of metals dictates that the necessary radio-frequency fields drop off exponentially as they move into the sample.

Ms. Sarah Sheldon has developed the theory, numerical simulations, and experiments to extend the liquid state NMR testbed to decoherent processes. She has used this procedure to demonstrate the loss of information associated with the Overhuaser enhancement and has developed means of controlling it.

Dr. Dmitry Pushin is building the new neutron interferometer geometry that he described last year. This novel approach employs quantum error correction to suppress noise from vibrations (which is the greatest experimental challenge to using neutron interferometry). We anticipate that this improvement will permit broader applications of neutron interferometry and enable communities of condensed matter scientists and biochemists to access the instrument.

Alan P. Jasanoff gave the Issekutz Memorial Lecture at Dalhousie University and organized a session on molecular imaging at the American Chemical Society annual meeting, among other professional activities. He codeveloped a course, Neuroimaging Cells & Circuits, which had a successful debut in the fall term. Research highlights included publication of a new genetically encoded magnetic resonance image sensor for kinase activity and demonstration of in vivo sensing by a novel engineered protein sensor for neurotransmitter release in intact animals.

### *Patient Dose in Diagnostic Radiology*

Jacquelyn Yanch and collaborators have quantified the increase in radiation dose experienced by the overweight and obese from diagnostic radiological exams. For the moderately overweight, the dose is increased by a factor of two to five over the dose a lean patient experiences. However, this dose increase jumps to factors of 10–40 times the doses to lean patients for the very overweight and obese, depending on the distribution of body fat. The orientation of the patient in the x-ray beam has a significant impact on the dose received. The Boston University Medical Center has begun implementing Yanch et al.'s published recommendations for dose reduction based on patient positioning as part of their routine clinical practice.

### *Low-Dose-Rate Irradiations*

Jacquelyn Yanch is investigating the effects of varying the radiation dose rate delivered to cells and animals to examine the impact of environmentally relevant and societally relevant radiation exposure rates. At the doses we encounter (from the environment, from the nuclear fuel cycle, from radiological terrorism, and during space travel), it is the rate of delivery and not the total dose that is most relevant. Animals and cells given doses that are lethal when delivered all at once show little to no noticeable effects when delivered over extended periods. Yanch and collaborators from Biological Engineering are investigating a range of biological responses, with the goal of identifying quantifiable markers of radiation history in both mammalian cells and small animals.

### *Synergistic Effects of Radiation and Partial Gravity in Space*

Radioisotope foils available in Jacquelyn Yanch's laboratory generate radiation with dosimetric characteristics similar to the radiation emitted during a solar particle event (SPE), an event of potentially significant hazard for astronauts. Since the timing of SPEs is unpredictable, experiments on the International Space Station (ISS) aimed at understanding the synergistic effects of both radiation and microgravity are possible only if the irradiations are performed on earth, the cells are frozen for transport, and they are then thawed once the experiment has been transferred to the ISS. Yanch and collaborators from the Harvard Medical School are irradiating osteocytes to examine the effects of radiation on bone density and bone formation with the ultimate goal of examining the radiation/microgravity synergy using these isotope foils on the ISS.

## Fusion and Plasma Physics Overview

NSE departmental research in fusion and plasma physics is primarily carried out through the MIT PSFC.

The Alcator C-Mod tokamak is the experimental centerpiece of NSE research. Alcator C-Mod is one of three major national facilities for fusion research in the United States based on the tokamak confinement concept. The MIT PSFC was awarded a new five-year cooperative agreement and research grant to operate the Alcator C-Mod tokamak through October 2013. The Alcator C-Mod project was funded at a level of approximately $25 million in FY2009. The Alcator team, with heavy involvement from NSE faculty, put forward an extensive and exciting research proposal for the next five-year contract period, with particular emphasis on supporting the ITER international fusion experiment starting construction in France. Alcator C-Mod has unique contributions to make to ITER due to its compact design with a magnetic field that matches ITER, unique worldwide for the divertor tokamak design of ITER. In addition, the very high power density of Alcator makes it relevant to studying energy exhaust at levels commensurate with those expected in fusion reactors. The C-Mod proposal received excellent reviews by a panel of outside experts chosen by DOE in May 2008 during an on-site visit.

The NSE fusion faculty are strongly involved in Alcator C-Mod: Professor Hutchinson is coprincipal investigator of the Alcator C-Mod tokamak project, professor Ron Parker leads the lower hybrid radio-frequency heating experimental team, Professor Freidberg is associate director of PSFC, and associate professor Dennis Whyte leads the fusion materials analysis accelerator laboratory while being heavily involved in boundary, materials, and disruption research on Alcator C-Mod. There are approximately 30 NSE graduate students in fusion and plasma physics, making up nearly half of the approximately 60 PSFC students. There are also alternative confinement, exploratory fusion/plasma experiments at the PSFC, such as the levitated dipole experiment.

Below we give a few illustrative highlights of fusion and plasma research involving NSE students and faculty. The PSFC report to the president and the C-Mod five-year proposal can be consulted for further details of the research accomplishments and plans.

### *Alcator C-Mod Inspection and Recommissioning*

A complete inspection of the Alcator C-Mod experimental facility was carried out in 2008–2009. It involves a complete disassembly of the tokamak and auxiliary components. This process is necessary due to the unprecedented electromagnetic stresses placed on C-Mod components during operation at its high field. The disassembly began in June 2008. Reassembly and successful plasma operations recommenced in June 2009.

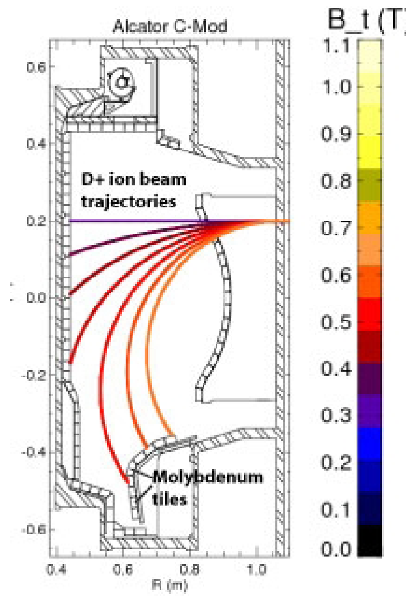
In general, the inspection was very positive, with no major issues found in the complex magnet and vacuum system of Alcator. However, after a routine inspection of the alternator in summer 2008, the original equipment manufacturer recommended that the generator rotor not be returned to service. The alternator is necessary to provide the large amounts of pulsed power for magnetic coils operation in Alcator C-Mod. The C-Mod team then embarked on a process to reevaluate the rotor's fitness for service. This process has involved multiple steps: a complete nondestructive evaluation (NDE) reinspection, including boresonic ultrasound imaging, visual inspection, and surface eddy current probing; removal of two bore sample rings; extensive materials testing of the bore samples, including chemical analysis, tensile, fracture toughness, and crack growth measurements; and microstructure and fractographic analysis. Two outside companies, experts in the field of generator rotor safety evaluation for the electrical utility industry, were contracted to examine all the data (both NDE and from the materials samples) and to give their independent recommendations with regard to fitness for service of our rotor. All materials tests showed that the rotor steel has good properties, well beyond the “conservative” assumptions normally used by industry consultants in the absence of actual measurements on a specific rotor. NSE faculty were heavily involved in assessment of the rotor, including professor Ron Ballinger as a materials expert, professor George Apostolakis as a risk assessment expert, and professor Ian Hutchinson as coprincipal investigator of Alcator C-Mod. A group of outside expert companies certified that the rotor was fit for continued service, with large margins of safety. A panel of experts assembled by MIT’s vice president for research has concurred with these findings and recommendations, and in April 2009 the MIT vice president endorsed return to service for the alternator. Reassembly of the alternator was successful, allowing C-Mod plasma operations in June 2009.

### *Computational Modeling of a New in Situ Diagnostic for Plasma-Facing Components in Fusion Devices*

The field of plasma surface interactions (PSI) seeks to understand the coupled system that forms between magnetically confined plasmas and the material boundary surfaces, known as plasma-facing components (PFC). In future steady-state or long-pulse devices, such as the ITER tokamak, PSI processes are expected to cause severe, large-scale modifications of PFCs, resulting in operational limits and shortened device lifetimes. Concurrent with the large-scale PFC modifications, it is well established that the properties of the material surface play a critical role in setting the properties of the thermonuclear plasma used for fusion; the PFCs can be considered to set the “boundary condition” of the plasma. Consequently, comprehensive diagnosis of PSI issues presents a critical challenge to ensure the success for the next generation of magnetic fusion devices; however, while diagnostics and experimental procedures to measure PSI-relevant plasma parameters are well established in magnetic fusion devices, there currently exists no in situ, routine diagnosis of PFC surface conditions, severely hindering the progress of PSI science.

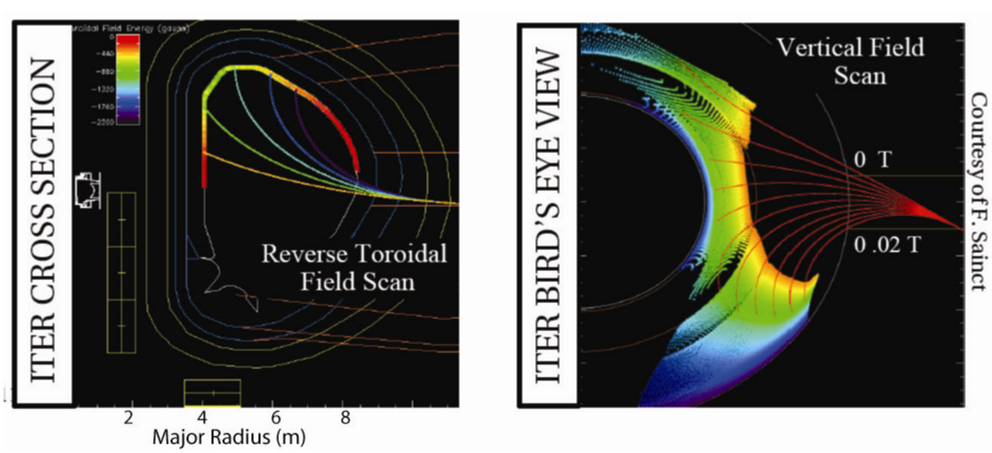
To address the critical lack of in situ PFC surface diagnostics, professor Dennis Whyte’s group is adapting ion accelerator-based materials analysis techniques, collectively known as ion beam analysis (IBA), to the Alcator C-Mod tokamak. Ex situ IBA has been the “gold standard” for quantifying PFC surface modifications such as hydrogen fuel retention, net erosion and deposition, and isotope impurity discrimination; however, by performing in situ IBA, we are maximizing the PFC surface areas that can be analyzed and enabling IBA techniques to be used in studying the time evolution of these PFC modifications, allowing the correlation of local and global PFC surface properties with plasma conditions. In addition, in situ IBA could greatly facilitate isotope tracer identification for particle transport studies in the boundary region. Ultimately, the diagnostic goal of the project is to obtain measurements of PFC surface modifications on a shot-to-shot timescale with ~1 cm spatial resolution and submicron depth resolution over a large portion of the PFCs inside the Alcator C-Mod tokamak.

The key feature of the diagnostic is exploiting the toroidal and poloidal magnetic fields of the tokamak in between plasma shots to electromagnetically steer an ion beam to PFC surfaces of interest for analysis by nuclear reaction product detection. For the prototype diagnostic on Alcator C-Mod, a compact, radio-frequency quadrupole linear accelerator will be installed on one of C-Mod's radial ports and a high-current 0.9-MeV deuteron ion beam will be injected into the vacuum vessel, where they will be steered by the magnetic fields to PFC surfaces. The deuteron ions will induce high-Q nuclear reactions with retained isotopes in the PFCs (notably, deuterium and other low-Z nuclei). The energetic-neutral reaction products (neutrons and gamma rays) can be measured by protected detectors hidden in the C-Mod superstructure, yielding information about the PFC materials.




*Example trajectories in the poloidal plane of 1-MeV deuteron ion beam steered to various plasma facing component tiles in the Alcator C-Mod tokamak by varying the toroidal magnetic field. Note that surfaces without line of sight to the beam entrance can be accessed due to the radially varying magnetic field.*

Because of the unprecedented nature of the diagnostic and its innovative IBA techniques, preliminary diagnostic development research of NSE graduate student Zach Hartwig has focused on the development of advanced computational simulation tools to function as a complete start-to-finish "synthetic diagnostic." The simulations are being used to optimize installation of the radio-frequency quadropole accelerator and particle detectors, to guide detector design and requirements, and will be used to interpret data once the diagnostic is operational. In addition, the numerical models have been adapted to examine the possibility of using the same technique in ITER. The study was the focus of visiting student Florent Sainct of Ecole Centrale Paris. He showed that a 10-MeV deuteron beam could be used to provide in-vessel detection of radioactive



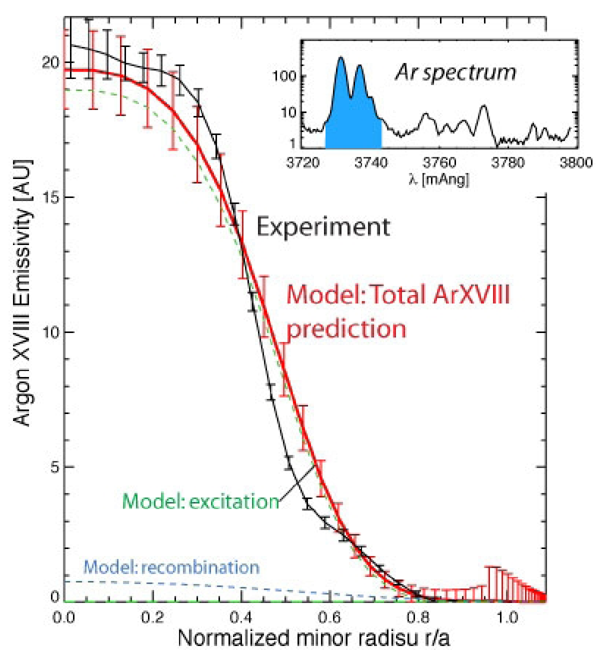

*Trajectories of a 10-MeV deuteron ion beam in ITER. Location of interception with plasma facing components (PFCs) are color coded to magnetic field strength. Tritium content can be monitored at each location by using the neutrons from D-T fusion reactions in the PFC. (Left) Coverage in the poloidal plane. (Right) Top view of ITER showing coverage in the toroidal direction. Note that nearly full coverage of half the ITER PFC surface can be achieved.*

tritium fuel in plasma-facing components, thus possibly providing a major upgrade to the operational and safety diagnostics for ITER.

The project involves Professor Whyte, senior scientist Richard Lanza, NSE graduate students Zach Hartwig and Harold Barnard, and visiting student Florent Saint from Ecole Centrale Paris.

### *Insights into Atomic Physics Processes Using Alcator C-Mod Plasmas*

The atomic physics properties of high-Z (i.e., high atomic number) impurities are very important in understanding tokamak fusion plasmas. High-Z impurities are expected in these hot plasmas because they will comprise the boundary materials (e.g., molybdenum and tungsten in C-Mod and reactors), and noble gases (e.g., argon) will be used to provoke line radiation for power dispersion in ITER and reactors. For instance, knowing the exact radiation power losses and ionization state balance of these impurities will be critical to predicting power balance. However, because of the extreme temperatures of fusion plasmas, direct laboratory testing of high-Z atomics physics in highly ionized states is generally absent. The Alcator C-Mod tokamak and its superb set of radiation diagnostics, part of an MIT/Princeton Plasma Physics Laboratory collaboration, has been used to probe and verify atomic physics calculations. The research, led by NSE graduate student Matt Reinke and supervised by professor Ian Hutchinson, focused on plasmas in Alcator that were intentionally seeded with large amounts of argon impurities to produce plasmas dominated by the impurity radiation, thus allowing for quantitative comparison with calculated rates for argon. Details of the line emissions from highly ionized argon (one or two bound electrons) showed fair agreement with modeling. However, it was found that overall radiative power losses did not agree across the entire plasma profile—that is, at regions of the plasma of different temperature. The research showed that this discrepancy arises from the coupled uncertainties in the atomic physics ionization rates and the impurity transport. Enhanced diagnostics tools were identified that could resolve these issues. The research results were reported in an invited talk, "Analyzing the Radiation Properties of High-Z Impurities in High Temperature Plasmas" by NSE graduate student Matt Reinke at the 16th International Conference on Atomic Processes in Plasmas held March 2009 in Monterey, CA.




*Hydrogen-like argon ($Ar^{+17}$) emissivity as a function of minor radius in the Alcator C-Mod plasma. Note the excellent agreement between model predictions and experiment. (Insert) Argon spectrum.*

*Basic Physics of Plasma Interactions with Absorbing Objects*

As an outgrowth of his studies of electric-probe diagnostics, basic plasma research on the interaction of flowing plasmas with spherical objects is being conducted by Professor Hutchinson and his student Leonardo Patacchini. This work combines computational simulation with a specifically developed particle-in-cell code, SCEPTIC, and analytic theory to interpret and compare with the computations. A major scientific breakthrough in understanding magnetized probe behavior has resulted from their realization that cross-field drifts, rather than small-scale turbulence, are the dominant perpendicular transport mechanism. The drift model leads to a three-dimensional fluid formulation that has been solved analytically for an arbitrarily shaped object. This remarkable achievement replaces prior heuristic analyses with a rigorous ab initio calculation and enables us to understand how the current collection depends on the surface orientation of a probe in a strong magnetic field. We thus obtain calibration of the performance of Mach probes (used in many magnetic confinement devices to diagnose plasma flow) including the effects of diamagnetic drifts. The calculations help to explain recent puzzling experimental results. This fluid theory has been extended to incorporate a kinetic-theory calculation of the full parallel ion distribution function and compare it with the results from the newly developed three-dimensional version of SCEPTIC. The excellent agreement in the relevant regimes validates both theory and simulation and has led to several major journal publications. The National Science Foundation (NSF)/DOE grant for this research has been renewed for a further three years.

## Student Awards and Activities

Robert Block received the Irving Kaplan Award for outstanding academic performance by a junior.

Matthew Denman won Best Presentation in Advanced Reactors at the ANS Student Conference.

Antoine Cerfon received an award for the best graduate student presentation at the 2009 International Sherwood Fusion Theory Conference/American Physical Society, April 2009.

Jake DeWitte was elected student representative to the ANS board of directors and is also chair of the Nuclear Engineering Student Delegation to Congress.

Paolo Ferroni received an outstanding teaching assistant award.

Craig Gerardi received the Manson Benedict Fellowship Award.

Mark Massie received the Department of Energy Advanced Fuel Cycle Initiative Fellowship.

Anna Nikiforova received an ANS Graduate Scholarship Award.

Anna Nikiforova, Paul Romano, and Tim Lucas received awards for their outstanding contributions to the department and MIT.

Bren Phillips was awarded the NSF Graduate Research Fellowship. He was also selected for the Admiral Hyman Rickover Fellowship Program in Nuclear Engineering (although he turned it down in favor of the NSF fellowship).

Paul Romano received the Roy G. Post Foundation Scholarship and 2nd Best Student Paper at Advances in Nuclear Fuel Management IV.

Kathreen Thome won Best Presentation in Fusion Energy at the ANS Student Conference.

Bao H. Truong received a 2008–2009 graduate scholarship award for a graduate student pursuing nuclear science and engineering studies.

Daniel Zaterman received the Roy Axford Award for outstanding academic performance by a senior.

**Ian H. Hutchinson**
**Department Head**
**Professor of Nuclear Science and Engineering**

*More information about the Department of Nuclear Science and Engineering can be found at http://web.mit.edu/nse/.*