Department of Nuclear Science and Engineering

The MIT Department of Nuclear Science and Engineering (NSE) celebrated its 50th year in 2008. Based on the discipline of nuclear and radiation interactions, it continues both to expand the knowledge of the scientific foundations of the subject and to develop important practical applications and the related engineering. Our involvement in the increasingly urgent national debate about sustainable energy options is a key part of MIT's impact in the energy arena. Such diverse basic and applied studies as quantum information processing, nanofluids, atomistic materials simulation, fusion plasma physics, and probabilistic risk analysis are burgeoning areas in which NSE is a major MIT contributor.

As part of its jubilee celebrations, the department hosted Susan Eisenhower, who presented the Rose Lecture on the topic "Atoms for peace, past, present, and future" in which she combined insightful policy analysis with some personal reminiscences of childhood days in the Eisenhower White House. Continuing the combination of prospect and retrospect, an anniversary symposium was held that included some of the students and faculty from the department's earliest days and also seminars about the work of the newest arrivals in the department. Industrial participants in the symposium announced initiatives to fund multiple graduate fellowships in the field, a welcome addition to the financial strength of the department. At the closing dinner-dance, many other development gifts were announced, including million-dollar-plus pledges and bequests and a major collective gift from four retirement-stage professors. The Department commissioned a 25-minute video documentary on the history of the department, which proved to be highly successful, informative, and entertaining.

Undergraduate enrollment continued strong, at approximately the target envisioned in our strategic plan. A major review of the curriculum was undertaken this year to reinvigorate the course offerings, improve coordination with other departments, and reemphasize the priority of undergraduate teaching. Graduate enrolment fell slightly, in part because of the effects of retirement of senior faculty.

Two new junior professors were recruited this year. Bilge Yildiz is a former NSE student specializing in materials in harsh environments such as nuclear reactors, fuel cells, and hydrogen generators. Benoit Forget is a nuclear reactor physicist whose research involves high-fidelity large-scale computational studies of neutron dynamics and fuel interactions. These recruitments are a critical part of the ongoing renewal of department faculty. Additional faculty searches are continuing. Two NSE professors were promoted to associate professor this year: Jacopo Buongiorno and Alan Jasanoff.

Nuclear fission energy in the United States is continuing on a track toward major expansion. Nine applications for licenses for new reactors have been officially submitted to the Nuclear Regulatory Commission (NRC). The NRC, like most nuclear agencies and industrial participants, is hiring large numbers of nuclear engineers and NSE students are in great demand. Several large contracts for reactor construction have been signed.

A major MIT interdisciplinary study of the nuclear fuel cycle, initiated by NSE as part of the Energy Initiative, has begun. The activities in boron neutron capture science and therapy have decreased substantially because of funding reductions and faculty departures. However, the MIT reactor has been designated by the Department of Energy (DOE) and the Idaho National Laboratory (INL) as a part of the national nuclear reactor research facilities surrounding the Advanced Test Reactor. This development, proposed originally as part of the INL management and operations contract in which MIT participates through NSE, promises to enhance the research utilization of the MIT reactor and provide opportunities in support of current and next-generation reactors and wider applications.

Department activities in neutron scattering, neutron interferometry, and quantum information technology have achieved notable successes. Several accelerator-based research initiatives have begun.

The Alcator tokamak project submitted its renewal proposal for the next five-year period; it was very favorably reviewed. This national facility for fusion research is extremely well placed to contribute to addressing the challenges faced by the International Tokamak Experimental Reactor (ITER) for which the international agreements were legally completed during the past year. The US omnibus budget zeroed the US funding for ITER construction in FY2008; so all is not political plain sailing for ITER; however, US and MIT activities continue in strength. NSE professors and students were leading participants in the ITER technical review.

As we look toward the next 50 years of NSE at MIT, priorities are to build renewed faculty strength to exploit the strategic strength of the department in areas of technical opportunity and vital national interest.

Undergraduate Program

Undergraduate enrollment continues above historical levels for the department. Twenty students declared nuclear science and engineering in fall 2008 (entering sophomore class fall 2008). Forty-six students were enrolled in the undergraduate program during the past year, including 15 sophomores, 9 juniors, 19 seniors, and three fifth-year students. Fourteen students completed requirements for a bachelor's degree in nuclear science and engineering in 2007.

Graduates of the NSE program choose a wide range of careers, including advanced study in nuclear engineering or physics, law and medical school, consulting and financial services, and industrial engineering. The fact that the NSE program is broad based enables these transitions. Some of the strengths our program provides are a unique introduction to nuclear engineering and low-energy nuclear physics, a strong foundation in physics and math, extensive hands-on experiences in laboratory courses, and senior-level design and thesis work. This past year we reviewed the program and are enhancing the hands-on component by adding two half-semester sophomore year courses: one on numeric methods for nuclear engineers and a projects-based learning course. This projects-based course will provide access to radiation systems early in the undergraduate program and will help students see the results of practical nuclear engineering and their contributions to it. This first year, the students will design and build a lead monitor based on X-ray fluorescence with potential applications to testing for lead paint in toys.

Undergraduate Research Opportunities Programs (UROPs) are a signature aspect of the NSE undergraduate experience. In addition, there is great demand from industry and research organizations for summer internship participants. A number of our students accept internships overseas, which is an important way to obtain global experience.

Graduate Program

Twenty five students entered the graduate program in fall 2007. The graduate program totaled 96 students: 46% are working in fission and energy studies, 24% specializing in nuclear science and technology, and 28% specializing in fusion. The department awarded 22 master of science degrees, 11 doctoral degrees, and 1 nuclear engineering degree during the academic year.

Faculty Awards, Honors, and Activities

Professor George E. Apostolakis gave the keynote speech at the International Conference on Probabilistic Safety Assessment and Management (PSAM 9) in Hong Kong. He continues 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 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 an invited lecture at the Greek Atomic Energy Commission in Athens.

Professor Ronald Ballinger received a Certificate of Appreciation for Patriotic Civilian Service from the Department of the Army for exceptional meritorious service as an advocate of our Reserve Officers' Training Corps programs.

Professor Jacopo Buongiorno received the Best Paper Award at the 1st ASME Micro/Nanoscale Heat Transfer International Conference, Tainan, Taiwan, January 2008. He received the School of Engineering Junior Bose Award for Excellence in Teaching. He was appointed to the Carl Richard Soderberg professorship of power engineering, 2007–2010. Professor Buongiorno launched and has been coordinating the international nanofluid property benchmark exercise (INPBE) with 24 participating organizations from eight countries. He led Track 3 at the American Nuclear Society International Congress on Advances in Nuclear Power Plants 2008. He cotaught the French Atomic Energy Commission (Commissariat à l'Energie Atomique, CEA) summer doctoral course "LWR Thermal-Hydraulics and Fuel Modeling" in Saclay, France, Jul 30–Aug 3, 2007. Professor Buongiorno became a member of the editorial board of the journal *Advanced Sciences Letters*.

Professor Sow-Hsin Chen received the 2008 Clifford G. Schull Prize at the American Conference on Neutron Scattering for "seminal contributions to understanding the dynamical properties of supercooled and interfacial water using neutron scattering techniques, and for an exceptional record of training young scientists in the use of scattering techniques to solve topical interdisciplinary problems in complex fluids and soft matter," in Santa Fe, NM, May 2008. He was also elected a fellow of the Neutron Scattering Society of America. Professor Chen has served as a member of the Beam Instrument Advisory Committee of the newly constructed Australian medium-flux research reactor in the Australian Nuclear Science and Technology Organisation nuclear center in Sidney, Australia, in Feb 2007.

Professor Benoit Forget was elected secretary in the reactor physics division of the American Nuclear Society (ANS).

Professor Jeffrey Freidberg was named an American Association for the Advancement of Science fellow for "distinguished contributions to research and teaching in the areas of theoretical plasma physics and magneto-hydrodynamics as applied to problems in magnetic fusion." Also, his recent textbook, *Plasma Physics and Fusion Energy*, is scheduled to appear in paperback form in summer 2008. This book is used in several MIT graduate plasma physics subjects.

Professor Ian Hutchinson served as chairman of the American Physical Society's Division of Plasma Physics and member of DOE's Fusion Energy Sciences Advisory Committee. He continues on the international advisory board of the journal *Plasma Physics and Controlled Fusion* and was a guest editor of an edition of the journal *Physics of Plasmas*.

Professor Alan Jasanoff was honored by the National Institutes of Health (NIH) for "exceptionally innovative" research. He was awarded a 2007 NIH Director's New Innovator Award, a highly competitive $3.5 million grant. Professor Jasanoff was promoted to associate professor without tenure.

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*. He is chairman of the International Nuclear Societies Council, which represents most of the professional nuclear societies in the world. He served as a technical cochairman of the HTR-2008 conference on high-temperature gas reactors. Professor Kadak continued as the chair of the National University Consortium of the Battelle Energy Alliance, which operates INL.

Professor Mujid Kazimi continued to be a member of the board of managers of Battelle Energy Alliance and assumed chairmanship of the Science and Technology Committee of the board. He served on scientific advisory committees for departments at Brookhaven National Laboratory, Tokyo Institute of Technology, and Paul Scherrer Institute. He joined the Honors and Awards Committee and continued to serve on the steering committee of the International Congress on Advances in Power Plants for ANS. Last summer he cotaught the one-week course "LWR Thermal-Hydraulics and Fuel Modeling" in Saclay, France, for PhD students in Europe organized by the CEA.

He was a guest editor of a special issue of *Nuclear Technology* on annular fuel for light water reactors (LWRs). At MIT hee continued to serve as chair of the MIT Reactor Safety Committee and director of the Center for Advanced Nuclear Energy Systems (CANES).

Professor Ronald Parker is serving on a panel reviewing the research and development and facilities needed to realize fusion energy in a European demonstration fusion reactor in a time frame of 30–35 years. He also serves on advisory committees reviewing the quality of the scientific program at a number of European laboratories engaged in plasma research, including the Max-Planck-Institute of Plasma Physics in Garching, Germany, the FOM Institute for Plasma Physics in Rijnhuizen, Netherlands, and CEA's Department of Controlled Fusion Research in Cadarache, France. He also served in the past year on the search committee for the new director of the Princeton Plasma Physics Laboratory.

Associate professor Dennis Whyte participated as a US delegate of the Scientific and Technical Advisory Committee for ITER. He was appointed to 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 US.

Professor Bilge Yildiz received the PAI Outstanding Teaching Award presented by the student chapter of ANS, April 2008.

Professor Sidney Yip has become increasingly engaged in synergistic activities on the advocacy of computational science (modeling and simulation) as an approach to solve fundamental problems across disciplinary boundaries. He serves on advisory boards at Lawrence Livermore National Laboratory and INL.

Research

Research Funding

Volume administered directly by the department decreased substantially once again from FY2007 to FY2008, from about $5.2 million to $4.6 million, roughly an 11% decrease in funds expended. The main sponsors whose volume dropped significantly were L3 Communications ($469,000, prime sponsor Defense Advanced Research Projects Agency), The Space and Naval Warfare Systems Center (SPAWAR $260,000), and the Army Materiel Office ($188,000). This and other sponsor decreases were offset to some extent by increases in expenditures of funds from DOE, American Science and Engineering Inc., and Alfaisal University. The research landscape continues to change, partly due to departing faculty and less active emeriti; this change is offset by increased activity by new and existing faculty.

Two projects on imaging for security sponsored by the Department of Homeland Security (via L3 Communications) and SPAWAR under the direction of Dr. Richard Lanza came to an expected conclusion in mid-FY2007, with some of that volume replaced by a project from American Science and Engineering, Inc.

Some DOE fission research programs had their funding shifted to the NRC. The few existing projects we have from those programs continue for another year or two. We have applied for and received some funding from the NRC for faculty fellowships and student support, but the change of focus means a basic source of funding for our faculty has significantly changed character. The new NRC projects have not yet been awarded but will generally favor our junior faculty.

DOE continues to be our single most important sponsor, but support for university research continues to be turbulent. Through the DOE offices and labs, and subawards from other universities, we received more than two million dollars last year, about 40%, of our primary department research funding. This is consistent with the past four years, although before that the percentage has been as high as 60%.

We established new contracts with American Science and Engineering Inc., Argonne National Laboratory, Schlumberger Corporation, Dynamic Dinosaurs B.V. (a Shell Corporation investment company), and Raytheon.

The "nuclear renaissance" has not yet substantially strengthened the amount or nature of funding provided through the federal government. Some of our corporate relationships have yielded research funds, but basic research on the next generation of fission reactors will be through DOE, if the past is any indicator, and funding from that agency is down from a high water mark in FY2004, when expenditures in NSE were almost $2.9 million.

Faculty-led research funding though interdepartmental centers such as the Plasma Science and Fusion Center, Bitter Magnet Lab, and MIT Energy Initiative (MITEI) was strong. These centers are financially dominant in our research activities and we continue to provide faculty leadership and strong student engagement there.

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, with support from DOE, the NRC, INL, and national and international companies. The research efforts can be categorized as falling into five programs:

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

The research generally involves the integration of science and engineering to develop designs of economic and reliable advanced reactor and fuel cycle systems. Among the important features is that LWR development is being pursued as well as reactors using other coolants. 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. This includes pursuing different fuel geometries, such as annular fuel and twisted cross-shaped fuel by professor Mujid Kazimi and Dr. Pavel Hejzlar and an inverted fuel element design by professor Neil Todreas. An alternative approach is the effort by professor Jacopo Buongiorno and Dr. Linwen Hu to reach enhanced critical heat flux of water by the addition of nanoparticles in small fractions (less than 0.1% by volume). Additionally, enabling a higher coolant exit temperature is being investigated to improve the efficiency of thermal-to-electrical power conversion. This may require a different cladding material, such as SiC composites. This effort involves professor Ron Ballinger, Dr. Gordon Kohse, and Dr. Thomas McKrell as well as the aforementioned professors.

A significant new development is initiation of an examination of the future of the nuclear fuel cycle, a multidisciplinary collaborative effort with the MITEI that is strongly supported by the US nuclear industry, such as the Electric Power Research Institute (EPRI) and the Nuclear Energy Institute (NEI). This three-year project will provide an updated version of the 2003 MIT report "The Future of Nuclear Energy" but will focus on options to manage the spent fuel from LWRs over the next few decades. New faculty and research staff members having analytical or industrial expertise relevant to fuel cycle development have joined the department with this effort in mind. A full-time research scientist (Charles Forsberg) joined MIT to become the executive director of the study. A part-time scientist (Monica Regalbutto) was appointed to cover the chemical aspects of reprocessing. On the neutronics side, a junior faculty member (Ben Forget) was hired by the department and started in January 2008.

CANES organized two symposia during this period and was largely responsible for the department's 50th anniversary symposium. In July 2007, a three-day symposium on "Innovation in Nuclear Power Technology" was held in Japan in collaboration with the Center for Research into Innovative Nuclear Energy Systems at Tokyo Institute of Technology. Five professors and nine students from MIT participated. In November, a workshop on opportunities for fundamental research and breakthrough in fission was held at MIT. The program was organized by Dr. Pavel Hejzlar in collaboration with Stanford University's Project on Energy. Speakers from universities, national laboratories, and industry participated. About 70 people attended. Details can be found on our web page. The 50th Anniversary Symposium was held at the Boston Museum of Science and included highlights of NSE history, present activities, and future directions.

Three professional short courses were offered. In June 2007, professors Michael Golay and Jacopo Buongiorno organized the 16th 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 a reformatted form of the 42nd session of the summer course on nuclear plant safety, and professor George Apostolakis directed a one-week course on risk-informed operations of nuclear power plants

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

Advanced Reactor Technology

Advanced Light Water Reactors

High-efficiency fuel for light water reactors. The use of advanced fuel instead of conventional solid cylindrical fuel in LWRs has been under investigation by professor Mujid Kazimi and Dr. Pavel Hejzlar. A DOE-supported project investigated the ability to raise the core power of the pressurized water reactors (PWR) while maintaining or improving thermal margins via adoption of annular fuel with internal cooling. A special issue of *Nuclear Technology* was devoted to the results of this effort in Nov 2007. A new project supported by the Korea Atomic Energy Research Institute was started to examine application of the annular fuel to Korean reactors. The effort included assessing the shutdown margin and effects of partial blockage of the internal coolant due to crud. TEPCO supported a scoping analysis of the use of several advanced fuel designs to raise the power in a boiling water reactor (BWR). The project investigated smaller pins of solid geometry, annular fuel, twisted cross-shaped fuel, and the use of uranium hydride instead of uranium oxide as fuel. The three approaches, 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 twisted cross-shaped fuel could reduce the core pressure drop below that of the current fuel, because the twisted rods' contact points along the axial length eliminate the need for grids for mechanical support. The current focus is on determining the design of an experiment to determine the critical power associated with this new fuel design.

Professor Neil Todreas is investigating the use of the inverted fuel concept for LWRs. In a typical fuel-rodded design, the fuel rods are surrounded by coolant, whereas in this design the fuel surrounds the coolant. Hence, the designation inverted fuel concept. The inverted core configuration uses hydride fuel in vertically oriented 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 walls 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. However, the addition of TTs reduces this temperature difference, by an extent that depends on the TT geometric characteristics. Prediction of pressure drop, heat transfer coefficient, and CHF at high pressure in the presence of short TTs is under investigation. Neutronic and structural analyses as well as the thermal hydraulic ones will determine the extent of possible power density upgrade.

Stability of advanced BWRs. Professor Mujid Kazimi and his students examined the implications of the coolant density change across the core to density wave oscillations in advanced 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. It was concluded that it is possible to design a core, such as the economic simplified BWR (ESBWR), to 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 even a current BWR will operate in natural convection, the ESBWR-like reactor has better stability margins. Furthermore, with an expanded model that allows for the possibility of water flashing, the stability at low-pressure conditions was shown to be attainable when appropriate steps in pressure ascendance were taken during the start up of such a reactor.

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, heat exchangers, etc. In the past year, professor Jacopo Buongiorno and Dr. Linwen Hu's research program on nanofluids has focused on studying the detailed features of nanofluid boiling. The work is enabled by the deployment of a unique pool boiling facility equipped with infrared thermography, which allows for acquisition of the two-dimensional time-dependent temperature distribution on the boiling surface. Traditional hard-to-measure parameters such as bubble frequency, departure diameter, and nucleation site density are accurately obtained with this facility and can reveal the subtle differences between nanofluid and water boiling behavior. Data interpretation is under way.

An experimental investigation of nanofluid convective heat transfer in the turbulent and laminar flow regimes was completed and revealed that, if the measured properties of the nanofluids are used in defining the governing dimensionless groups, the traditional correlations/models accurately reproduce the heat transfer and viscous pressure loss behavior of the nanofluids. This finding is significant because controversial abnormalities in nanofluid heat transfer had been reported previously in the literature.

At the first scientific conference entirely dedicated to nanofluids (*Nanofluids: Fundamentals and Applications*, September 16–20, 2007, Copper Mountain, CO), it was decided to launch an international nanofluid property benchmark exercise (INPBE) to validate nanofluid property measurements (particularly of thermal conductivity) performed with various experimental methods and to generate a reliable database of nanofluid properties. Twenty-four organizations from the US, UK, France, Switzerland, South Korea, India, China, and Singapore participate in the exercise, which is coordinated by professor Jacopo Buongiorno. More information on INPBE is available at http://mit.edu/nse/nanofluids/benchmark/index.html.

The nanofluid research program is in collaboration with the MIT Nuclear Reactor Laboratory and is sponsored by AREVA, DOE, EPRI, Saudi Arabia's King Abdulaziz City of Science and Technology and a generous gift from Mr. Doug Spreng.

Advanced Gas-Cooled Modular Pebble Bed Reactors

The Next Generation Nuclear Plant (NGNP) is being 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 reactors being considered for the NGNP. This year two students in the Department of Aeronautics and Astronautics completed an air ingress

Air ingress experiment (from left to right: Professor Andrew Kadak, with undergraduate students Joseph Yurko and Katrina Sorensen)

experiment as part of their year-long design project under the supervision of professor Andrew Kadak. The students successfully demonstrated that injecting very small amounts of helium in the top of the reactor vessel upon a break in one of the primary pipes could delay if not prevent the onset of natural circulation. If this proves to be valid for larger reactors, this injection system could avoid a major safety challenge of high-temperature gas reactors.

An additional experiment completed by one of Professor Kadak's undergraduate students was a pebble flow experiment to address bypass flow through a central dynamic graphite reflector. The issue is with a large column of pure graphite pebbles in the center of the reactor; a considerable amount of flow that is not heated would bypass the fueled region, requiring operation at higher temperatures since the helium coolant is eventually mixed in the lower portion of the reactor. This initial test was to show that if smaller central graphite pebbles were used compared with the outer fuel pebbles, the laminar flow paths previously demonstrated would be maintained with the different-sized pebbles. The result was that the mixing did not occur, allowing for the next flow tests, which are being designed by another UROP student.

Progress also continues on modularization of pebble bed reactor designs with Professor Kadak. A student completed a thesis validating that the approach is practical by working with General Dynamics Electric Boat, one of the two builders of the US nuclear submarine fleet. Electric Boat pioneered the modular integrated engineering, design, and fabrication of submarines. Additionally, a master's thesis is being completed on optimizing the size of the reactor vessel from a core physics standpoint so that the vessel can be readily shipped by train to locations that are not near coastal regions to allow for a broader application of this technology to support the "Lego" construction of this plant. CANES continues collaborations on the Chinese pebble bed project sponsored by the Institute of Nuclear Engineering Technology of Tsinghua University. Professor Kadak participated in an International Atomic Energy Agency meeting in October 2007 on high-temperature reactor safety in Beijing. He also collaborates with the South African Pebble Bed Modular Reactor Project and the Westinghouse design team for the Next Generation Nuclear Plant.

A consortium of universities has been established with MIT as the technical lead to develop an understanding of the behavior of alloys proposed for use in high-temperature gas-cooled reactor (HTGR) heat exchangers that will operate at temperatures as high as 950°C. Professor Ron Ballinger is the MIT principal investigator. The partner universities are the University of Nevada, Las Vegas, Boise State, and the University of Illinois, Urbana–Champaign. INL is also participating. The team is exploring the mechanical behavior of alloys 617 and 230 over the temperature range 450°C–950°C. Properties being evaluated include creep, creep-fatigue, creep crack growth, fatigue, and static crack growth in prototypic HTGR environments. Initial results indicate that in some temperature ranges there will be a significant environmental effect when the oxygen potential becomes comparable to the equilibrium potential for the metal-oxide.

Advanced Fast Reactor Systems

A 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 sodium-cooled fast reactor while maintaining a high level of safety and proliferation resistance. The intent is to assist DOE in its planning purposes, 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 project is led by MIT and includes Idaho State and Ohio State Universities. Professor George Apostolakis is the principal investigator. Dr. Pavel Hejzlar and 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 from Argonne, Idaho, and Lawrence Berkeley National Laboratories provides guidance and access to relevant information.

Corrosion-resistant, functionally graded composite material for Pb-Bi cooled reactors. Professor Ron 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. Thomas Newton, working with professor Mujid Kazimi, professor Benoit Forget and Dr. Edward Pilat, developed a design of the MIT reactor core using monolithic 20% enriched uranium and 7% molybdenum (U-7Mo) fuel that maintains acceptable thermal and fast neutron fluxes within the confines of the existing core structure by using plate-type fuel with the same dimensions as the current fuel elements. This year, they engaged in an effort to qualify the methods used for thermal-hydraulic and neutronic safety evaluations of the new core and in examining a code from Argonne National Laboratory to do fuel management studies more quickly.

Increasing the Si irradiation capability at MIT reactor (MITR). As part of professor Andrew Kadak's design course, a conceptual design was developed for increasing the capability of the MITR to irradiate larger silicon ingots. The current capability is limited to 4- and 6-inch ingots with a market demand for larger 8-inch ingots. The students developed an innovative design that used an existing 12-inch beam port in a nonconventional way to allow for the insertion and removal of ingots without requiring a redesign of the reactor support structure. The students also reviewed the existing irradiation facility and proposed modifications that would improve throughput and reduce occupational exposure. This project prompted interest by a commercial firm to take the next steps in design to implement such a system.

Enhanced computational reactor physics. Professor Benoit Forget has been establishing a computational reactor physics group since his arrival in January 2008. He and a graduate student are working on developing a Monte Carlo fuel cycle code that will support the MITR conversion. This code enables fuel shuffling and fuel management capabilities to MCNP/MCODE and will be extended to other reactor types beyond the MITR. He is also looking to establish methodologies that will increase the fidelity of current simulations of nuclear reactors by improving and transforming the current modeling and simulation approach.

Advanced 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 with an emphasis on what to do with the spent fuel. This study is patterned like the 2003 MIT study on the future of nuclear energy with a multidisciplinary team across the Institute involved. The study 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 S. Ansolabehere, S. Bowring, J. Deutch, T. Eagar, and J. Parsons. Dr. Charles Forsberg was hired as executive director of the study, and Dr. Pavel Hejzlar is in charge of the fuel cycle system simulation effort. An external advisory committee with professor Phillip Sharp chairing has been constituted.

The objective of this multiyear study is to provide a deeper understanding of the credible options for managing the spent fuel from a growing nuclear energy deployment, considering not only reactor technologies but also the entire fuel cycle: uranium resources, alternative fuel cycles with and without separation of various elements for recycling fissile fuels, and waste management. The study explicitly considers a range of nuclear energy deployment rates, with a high end sufficiently large to meet a major fraction of the US energy demand and address climate change concerns. The emphasis is on meeting US energy needs but within a global context. Factors being considered in the study include economics, risk, nonproliferation, institutional structures, and technology readiness. The first year's activities include a metastudy that will help frame critical questions for research in the following years.

System analysis of actinide transmutation options. Professors Andrew Kazimi and Neil Todreas and Dr. Pavel 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. Their work has shown that thermal reactors can be applied to the reduction of actinide accumulation by transmutation of transuranics (TRUs), provided that suitable nonfertile materials are developed to host the TRU elements. The nonfertile fuel rods could replace 20% of a LWR assembly uranium dioxide (UO_2) fuel rods, and that would lead to net destruction of TRUs. However, recycling of TRUs may need cooling intervals of about 20 years to limit the spontaneous fission neutrons during fuel manufacturing. In addition, the use of thorium hydride to host the actinides in PWRs is being investigated. The nuclear fuel cycle simulation code CAFCA has been upgraded with a more user-friendly acceptance of alternative advanced reactor options and also has been equipped with a more robust numerical scheme to estimate the appropriate rate of addition of advanced reactor capability. A system dynamics version was created to allow for built-in treatment of uncertainties. Work this year enlarged the number of fuel cycle options that can be simulated, including high burnup fuel and mixed oxide recycling in LWRs as well as fast reactors with different conversion ratios. The validation of CAFCA against other system codes, such as DANNESS of Argonne National Laboratory, VISION of INL, and COSI of CEA is being pursued.

Flexible conversion ratio fast reactors. A group led by professor Neil Todreas and Dr. Pavel Hejzlar is developing within a DOE-sponsored project a flexible conversion ratio fast reactor system for time-dependent management of both fissile inventories and higher actinides. 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. Two liquid reactor coolant core candidates are selected for development and cross-comparison. The coolants are lead and liquid salt (as distinguished from molten salt containing molten fuel). Gas coolant core results from an ongoing MIT project and sodium results from Argonne National Laboratory work will be evaluated in comparison with the lead and liquid salt coolant core results. The feasibility of the lead-cooled reactor concept has been established for both conversion ratios, and the design of liquid salt-cooled cores is under development. The liquid salt-cooled concept was found to be more challenging to develop and required some innovative features to overcome neutronic and thermal hydraulic challenges. A patent application for the conceptual design of a liquid salt-cooled reactor that overcomes these challenges was submitted in June 2007.

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 in 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. This methodology has been applied to the selection of a technology for a decay heat-removal system in a lead-cooled flexible conversion ratio reactor concept under study at MIT.

Reliability of passive safety systems. A comprehensive risk-informed methodology for passive safety system design and performance assessment has been completed and demonstrated on the flexible conversion ratio reactor. First, the methodology provides a framework for risk-informed design decisions and as an example two design options for a decay heat removal system are assessed and quantitatively compared. Next, the reliability of the system is assessed by quantifying the uncertainties related to system performance and propagating these uncertainties through a response surface using Monte Carlo simulation. Finally, a sensitivity study is performed to measure the relative effects of each parameter and to identify ways to maintain, improve, and monitor system performance.

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.

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 International Reactor Innovative and Secure, (2) the design of a superheat LWR, and (3) a molten salt reactor with a thermal spectrum and advanced energy conversion system. The 2-year project is supported by the MASDAR group of Abu-Dhabi NS and is supervised by professor Kazimi and Dr. Hejzlar.

Developing an economic high-temperature solid oxide electrolyzer. Professor Bilge Yildiz and her group are examining the design of a solid oxide electrolysis cell (SOEC) of steam to increase the durability of the electrodes. They are examining the choice of oxide materials as well operating temperature and pressure to optimize the performance of the SOEC for production of hydrogen and oxygen. Electrochemical modeling and experiments are being pursued with support from INL and the MITEI.

Nuclear power container ships. Professor Andrew Kadak and a graduate student from the Navy are working on the design of 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 is to design twin reactors with 10-year lifetimes between refuelings using low enriched cores for duty cycles demanded for economic operation. Safety of floating nuclear plants will be reviewed as a part of the design project. Challenges that will be addressed beyond the technical are licensing and operations in world ports. The economics of nuclear-powered commercial ships will be addressed as a function of rising fuel costs.

Application of Risk Assessment to Non-nuclear Systems

Risk-informed decision making. One critical objective of the Domestic Nuclear Detection Office (DNDO) is to provide effective systems for radiological screening at US shipping ports and border crossings, which it currently does with simple plastic scintillators. In September 2005, DNDO initiated a solicitation process for new detection systems that use passive gamma-ray spectroscopy to replace the outdated systems. In attempting to decide among different system designs and deployment options, DNDO has performed a cost–benefit analysis (CBA) that includes value judgments on the relative importance of the goals of the program such as minimizing cost, maximizing detection capability, and minimizing the impact on stream of commerce among others. The results of the CBA have been questioned because several critical inputs to the analysis are very difficult to quantify in terms of dollars and require broad assumptions.

The objective of this work is to propose the use of the analytic-deliberative process (ADP) as an alternative to CBA for selecting and deploying radiation portal monitors at shipping ports and border crossings. The two decision frameworks yielded similar final decision option preferences. The greatest strength of the ADP revealed by this research was the effectiveness of the deliberation after completion of the analysis. Five major points of disagreement among the stakeholders were easily identified and discussed. Four of the disagreements were the results of misunderstandings between the stakeholders about facts regarding the case study. The deliberation allowed these misunderstandings to be identified quickly and remedied, which led to good agreement between stakeholders who disagreed initially.

Nuclear Science and Technology

Faculty and students in the nuclear science and technology (NST) program are concerned with developing new methods and applications for radiation science. Some common themes that run through NST are the development of radiation measurements as precise and quantitative markers of structure and function and the engineering of radiation systems to elicit a specific transformation. Our advances connect to a wide variety of applications including those in biology, neuroscience, medicine, chemical/materials science, remote sensing, and information science. As one would expect for such a program, we benefit from many cross-disciplinary collaborations across MIT and throughout the local community. In particular, about a third of the graduate students in the program are currently connected with studies in area teaching hospitals. The following brief project descriptions are organized by principal investigator and show some of the recent advances and plans for the NST program.

Nuclear Magnetic Resonance Imaging for Brain Science

The Jasanoff laboratory continued to make progress in the development of magnetic resonance imaging (MRI) contrast agents for molecular imaging of brain activity. Work on an MRI dopamine sensor is now being completed by graduate student Mikhail Shapiro and postdoc Gil Westmeyer, including in vivo studies that are among the first to demonstrate real-time noninvasive monitoring of dopamine transport in living animals. The next steps will use the sensor to examine patterns of dopamine released during rewarding stimulation in animals. A zinc sensor developed last year in collaboration with Steve Lippard's laboratory is being applied to detect labile zinc distributions in mice; ongoing work being performed by postdoc Xiao-an Zhang may ultimately allow functional imaging of neuronal activity using sensors of this family. Much of the newest work of the lab now concentrates on genetically encoded contrast mechanisms. These methods will allow functional imaging of targeted neuronal elements. A recent step toward this goal has been the creation of ferritin-based protein contrast agents sensitive to neuronal signal transduction pathways (work of Mikhail Shapiro).

Neutron and X-Ray Scattering

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 water at P_C = 1,550 ± 50 bars and T_C = 200 ± 5 K by quasielastic neutron-scattering experiment

By confining water in nanopores of silica glass MCM-41-S, one can bypass the crystallization and study the pressure effect on the dynamical behavior in deeply supercooled state by using neutron scattering. Professor Chen's group has observed clear evidence of a fragile-to-strong dynamic crossover (FSC) temperature T_L in the average translational relaxation time versus 1/T plot. They have shown that the crossover temperature T_L decreases steadily with increasing pressure, until it intersects the homogenous nucleation temperature line of bulk water at a pressure of 1,600 bars. Above this pressure, it is no longer possible to discern the characteristic feature of the FSC. They have identified this end point with the possible second critical point of water. This scenario has been confirmed by molecular dynamics simulations using several phenomenological models of water.

Discovery of FSC temperature, T_L ≈ 220 K, in hydration water of protein, DNA, and RNA at ambient pressure by quasielastic neutron scattering

At low temperatures, proteins exist in a glassy state, a state that has no conformational flexibility and shows no biological functions. In a hydrated protein, at temperatures ≥ 220 K, this flexibility is restored, and the protein is able to sample more conformational substates, thus becoming biologically functional. This "dynamical" transition of protein is believed to be triggered by its strong coupling with the hydration water, which also shows a similar dynamic crossover. Professor Chen's group has experimentally demonstrated that this sudden switch in dynamic behavior of the hydration water on lysozyme occurs precisely at 220 K and can be described as a FSC. At the FSC, the structure of hydration water makes a transition from predominantly high-density (more fluid state) to low-density (less fluid state) forms derived from the existence of the second critical point at an elevated pressure. They have performed similar experiments to show that the glass transitions of these biopolymers are triggered by the FSC of their hydration water.

Observation of a dynamic crossover in water confined in double-wall carbon nanotubes

High-resolution quasielastic neutron-scattering spectroscopy was used to measure H_2O hydrated double-wall carbon nanotubes. The measurements were made at a series of temperatures from 250 K down to 150 K. They have observed clear evidence of a FSC at T_L = 190 K in the confined water. Comparing the result with that obtained from the confined water in hydrophilic porous silica material MCM-41, they experimentally demonstrated that water confined in a hydrophobic substrate exhibits a lower dynamic crossover temperature by $\Delta T_L \approx 35$ K.

Discovery that the temperature derivative of the density of D_2O confined in MCM-41-S with 19 Å pores shows a peak at T_L = 235 K at ambient pressure

This fact gives decisive evidence of the existence of a Widom line (with a Widom temperature of T_L = 235 K) emanating from the second critical point of the confined water. In this experiment, Professor Chen's group also reports that D_2O confined in hydrophilic pores of MCM-41-S with a pore size of 19 Å has an 8% higher density than the bulk D_2O at room temperature. Small-angle neutron scattering (SANS) is used to measure the absolute density of water contained in 1-D cylindrical pores of silica material MCM-41-S with pore diameters of 19 and 15 Å. From a combined analysis of SANS data from both H_2O and D_2O hydrated samples, Chen's group has determined the absolute value of the density of 1-D confined water. They have found that the average density of water inside the fully hydrated 19 Å pore is 8% higher than that of the bulk water at room temperature. The temperature derivative of the density shows a pronounced peak at T_L = 235 K, signaling the crossing of the Widom line at ambient pressure and confirming the existence of a liquid-liquid critical point at an elevated pressure. Pore size and hydration level dependences of the density are also studied.

Theory and Simulation of Materials

Professor Sidney Yip continued pursuing research in theory and simulation of materials, mostly collaborative work involving graduate students, postdoctoral research associates, and faculty colleagues at the Institute and elsewhere. Additionally, he has become increasingly engaged in synergistic activities on the advocacy of computational science (modeling and simulation) as an approach to solve fundamental problems across disciplinary boundaries. Besides serving on advisory boards at two national laboratories, he is organizing a workshop at MIT on university-lab collaboration in mentoring future generations of computational scientists and coordinating a set of faculty presentations on multiscale materials simulation at the upcoming Industrial Liaison Program Research Directors Conference.

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 David Cory and his colleagues have demonstrated control over quantum devices that cannot be simulated classically. They are working to turn these quantum systems into practical quantum devices. The program has two stages: the first is directed at laboratory-scale devices for characterizing and controlling magnetization, transport, and chemistry. These 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 and Dr. Sergio Valenzuela (NSE); professor Seth Lloyd (Department of Mechanical Engineering); Dr. Will Oliver (Lincoln Laboratory); Dr. Mohamed Arif (National Institute of Standards and Technology); professor Mikhail Lukin and Dr. Paola Cappellaro (Harvard University); professor Lorenza Viola (Dartmouth University); and professor Raymond Laflamme, professor X. W. Tang, professor Jonathan Baugh, and Dr. J. Emerson (all at the University of Waterloo). A few highlights from last year are briefly described below.

Ms. Cecilia Lopez has completed an experimental study of 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 Waterloo parameterize reasonable physically relevant models from a polynomial number of measurements.

Mr. Troy Borneman has demonstrated that the optimal control methods that are used for high-fidelity control in quantum information processing (and that were developed using the NMR test bed) can be applied to improve the performance of traditional applications of magnetic resonance. In particular, he has demonstrated the improvement possible for well logging. NMR-based well logging is performed with highly inhomogeneous magnetic fields, where optimal control theory enables uniform control of the spin dynamics even when the control fields are spatially varying.

Dr. Sergio Valenzuela recently succeeded in demonstrating spin injection into Si through a metallic tunnel junction. This has been a long-standing goal of the field, and it opens up the possibility of using spin injection as a polarization source for quantum devices. The key to the success in this program was to use electron magnetic resonance readout as a monitor of the injected polarization.

Dr. Chandrasekhar Ramanathan has reported on a series of experiments that use NMR to simulate 1-D multibody dynamics. This is a system in which classic simulations fail to reveal the full complexity of the system dynamics and in which it is challenging to set up a clean measurement. One aspect of the study is investigation of the transition from classic to quantum dynamics in 1-D spin chains. Applications include using spin chains as channels for quantum information and creating highly polarized spin systems as potential transducers.

Mr. Chonlagarn Iamsumang has mapped out the changes to the resonance of superconducting striplines as a function of the backing field. He has found that, with the stripline in the plane of the magnet, the resonance does not vary with field. When place perpendicularly, the Q first increases and then decreases as expected. This observation opened up the potential for using these very high Q systems as efficient spin detectors.

Dr. Dimitri Pushin has reported on a new neutron interferometer geometry that uses quantum error correction to suppress noise from vibrations (which is the greatest experimental challenge to employing neutron interferometry). A new single crystal interferometer has been machined and is being installed at the National Institute of Standards and Technology to test these predictions.

Fusion and Plasma Physics Overview

Departmental research in fusion and plasma physics is primarily carried out through the MIT Plasma Science and Fusion Center (PSFC). NSE graduate students make up nearly half the approximately 60 PSFC students. The experimental centerpiece of the research is the Alcator C-Mod tokamak, which is one of three major national facilities for fusion research in the United States, although there are also vibrant fusion/plasma experiments at the PSFC such as the levitated dipole experiment (LDX). Alcator C-Mod was funded at a level of $22.6 million in FY2008, and NSE faculty are strongly involved. Professor Ian Hutchinson is co-principal investigator of the Alcator C-Mod tokamak project. Professor Ron Parker leads the lower hybrid radio-frequency heating experimental team on Alcator. Professor Jeffrey Freidberg is associate director of the PSFC. Associate professor Dennis Whyte leads the fusion materials analysis accelerator laboratory and is heavily involved in boundary, materials, and disruption research on Alcator C-Mod. In addition to C-Mod, the faculty has strongly participated in the design review, ongoing modifications, and research planning of the upcoming ITER burning plasma experiment that has started construction in southern France.

Alcator is operated through a five-year cooperative agreement with DOE, of which the present agreement extends through October 2008. Alcator put forward an extensive and exciting research proposal for the next five-year contract period in March 2008. The draft proposal was first commented on by an external advisory committee in February 2008 and later peer-reviewed by a panel of outside experts chosen by DOE in May 2008 during an on-site visit. The results of the review will soon be released.

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.

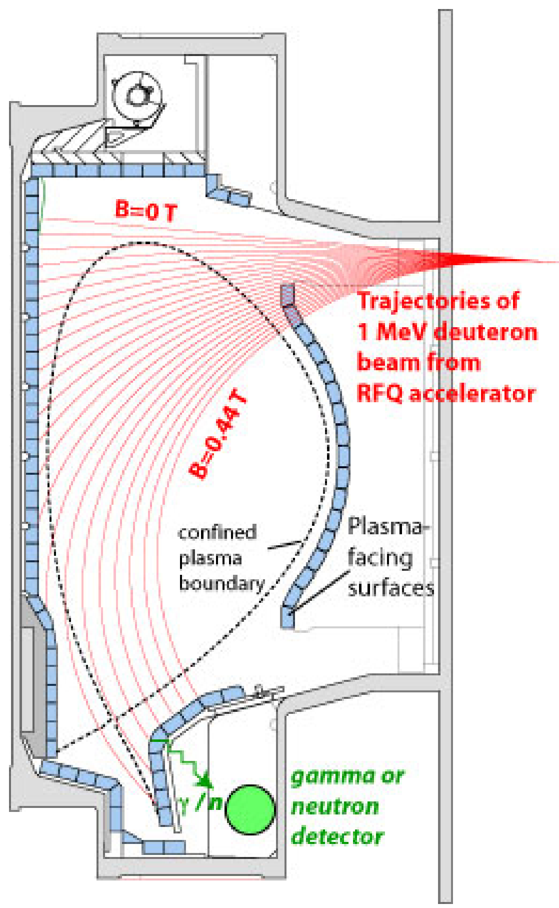
The Vanishing of Magneto Hydrodynamics Compressibility Stabilization in Closed-Line Systems

It has been know since the early days of fusion research that plasma compressibility effects can stabilize ideal MHD (magneto hydro-dynamics) interchange modes in closed-line configurations. The work by PhD student Antoine Cerfon and professor Jeffrey Freidberg focuses on this stabilizing mechanism using a more realistic plasma model than ideal MHD. One application of interest is the LDX, which can be reasonably well modeled by a cylindrical hard-core Z-pinch. The hard core stabilizes $m \geq 1$ modes. Only the $m = 0$ sausage instability can be unstable. Ideal MHD predicts that for low β this mode can be stabilized by a sufficiently weak pressure gradient near the edge of the plasma. Specifically, stability follows if $rp' / p + 2\gamma > 0$ where $\gamma = 5/3$ is the ratio of specific heat representing the stabilizing effect of compressibility.

The present work reexamines the compressibility stabilization effect using a fluid model for electrons but with a full Vlasov treatment for the ions. There are two main results to report. (1) First, an exact quadratic energy integral is derived that is valid for arbitrary 3-D static MHD equilibria, including both ergodic and closed field line configurations. This relationship shows that at marginal stability the compressibility stabilization term vanishes identically—there is no compressibility stabilization! This result is in contrast to other recent generalized theories, which predict a modified form of compressibility stabilization but do not contain all the physics in the present model. (2) The second result is a derivation of the actual dispersion relation for a linear hard-core Z-pinch. The new model shows that instability persists for all negative values of rp' / p without any possibility of compressibility stabilization. It is demonstrated that the existence of resonant particles satisfying $w = k_{\wedge}(V_{-B} + V_k + V_{E¥B})$ is responsible for the persistence of instability, thereby explaining the absence or inclusion of compressibility stabilization in the Vlasov ion or ideal MHD model, respectively.

New Accelerator-Based Technique to Probe Material Surfaces in Fusion Devices

Understanding and controlling the complex interactions between fusion-grade thermonuclear plasmas and the surrounding material surfaces, is one of the most daunting scientific and technical challenges for magnetic fusion energy. Progress on this subject has been greatly hindered by the lack of a practical method to interrogate and probe material surfaces during the operation of fusion facilities, like Alcator C-Mod. Associate professor Dennis Whyte, in collaboration with senior scientist Richard Lanza, has developed an exciting new method of diagnosing surfaces in magnetic fusion devices that has the potential to revolutionize our understanding of plasma–surface interactions in fusion. The technique has several innovations that exploit the tokamak and material expertise. A high-energy (MeV) deuteron ion beam is produced by a radio-frequency quadropole accelerator and injected in the tokamak vacuum vessel in the 15- to 20-minute period between plasma pulses. The strong and variable magnetic fields available in the tokamak can be used to steer the beam to nearly all wall locations inside the tokamak. The resulting interaction of the beam and materials produce gamma rays



Schematic of new accelerator-based technique for surface diagnosis in magnetic fusion devices. An MeV deuteron beam is injected into the tokamak and steered by intrinsic magnetic fields to various locations of the plasma-facing wall. Detection of neutrons and gammas then allows quantitative assessment of how exposure to thermonuclear plasma has affected materials.

and neutrons that are detected by protected instruments around the tokamak. Using a variety of nuclear-probing methods, the measured products provide detailed information about the material makeup of the near surface of the tokamak materials, such as the distribution of impurities and retention of hydrogen fuel, which occur due to the plasma exposure. Thus, the technique has the possibility of providing full mapping of the evolution of the material properties for the first time in a tokamak environment. This proposal won a DOE Office of Fusion Energy award for "Development of Diagnostic Systems for Magnetic Fusion Energy Sciences Experiments," which will begin in December 2008 to install a prototype on Alcator C-Mod. NSE graduate student Zachary Hartwig has begun Monte Carlo simulations of the beam steering and particle diagnosis.

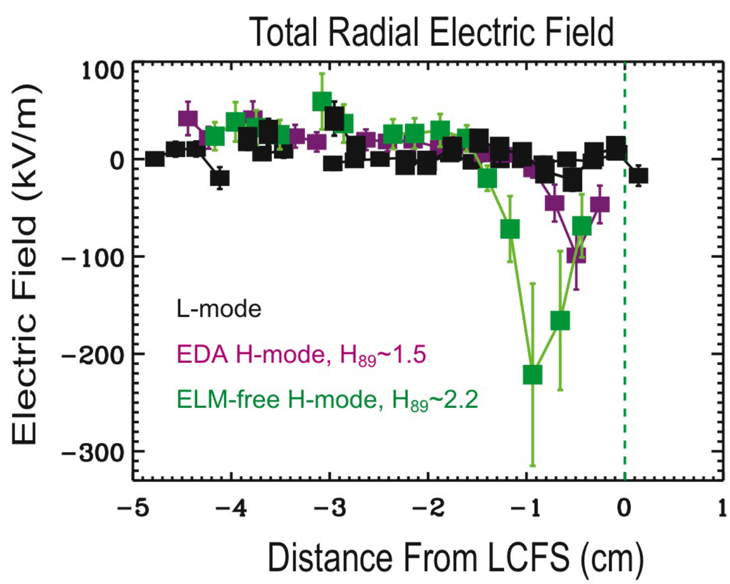
Advances Toward Steady-State Tokamak Operations

One key challenge to turning the tokamak into a true steady-state device, important for both research and ultimately reactor applications, is efficient noninductive sustainment of the plasma current. In this noninductive case, an external drive sustains the current in the plasma rather than an inductive drive from a transformer action, which is inherently pulsed. Just as important, control of the profile of magnetic field produced by the current internal to the plasma strongly influences both stability and confinement of the plasma configuration. Recent upgrades to the C-Mod facility have included implementation of a high-power microwave system to drive plasma current and control the current profile. In particular, C-Mod uses a lower hybrid (LH) radio-frequency heating system that operates at 4.6 GHz. The LH group is led by professor Ron Parker and involves NSE graduate students Greg Wallace and Orso Meneghini, and Department of Physics graduate student Andrea Schmidt. Understanding the detailed physics of wave propagation and damping, and the effects on plasma dynamics, are critical for extrapolating these techniques to ITER and reactors. In experiments so far on C-Mod, up to 1.2 MW of microwave power has been coupled. A particularly exciting result in the past year was the measurement of driven current profiles, based on a principle known as the motional stark effect (MSE), by NSE graduate student Jinseok Ko working with Princeton collaborator Steve Scott. Up to 80–90% of the current is sustained by the microwave drive in plasma with 1 million amp total current. The LH group in collaboration with PSFC senior scientist Paul Bonoli and other PSFC scientists has simulated the current drive in these discharges using state-of-the-art numerical codes, which combine ray tracing for wave propagation and Fokker Planck calculations of damping on the plasma electrons. The results of the simulations are in excellent agreement with those from the experiments, including details of the current density profile measured using the MSE method. Measurements of nonthermal X-ray emission confirm the presence of a significant fast electron population, and the electron distribution function from the modeling has been used in a synthetic diagnostic code to successfully simulate the measured hard X-ray data. New measurements of the coupling of the launched waves and the boundary plasma are yielding surprising results, including the presence of substantial current densities outside the region of core confined plasma. All these advances are critical toward the upcoming decision on implementation of LH technology and heating on the ITER international burning plasma experiment, which is starting construction in southern France. Key results from this work have been the subject of invited papers presented at the last two APS Division of Plasma Physics Meetings and a publication in *Physics of Plasmas*.

First Direct Measurements of Electric Field Wells in Alcator C-Mod

High confinement mode, or H-mode, is a plasma regime accessible to most magnetic confinement fusion devices, which boasts a factor of two improvement in plasma energy confinement over the more easily obtained low confinement mode, or L-mode. The onset of an H-mode is characterized by a sharp decrease in edge fluctuations, followed immediately by the formation of edge transport barriers (pedestals) in both the ion and electron temperature and density profiles. These barriers lead to significant increases in core temperature, density, and plasma confinement time. To reach their operational goals future fusion reactors, like ITER, must operate in H-mode regimes. However, despite intensive study by the theoretical and experimental fusion communities, over the last 25 years, the actual mechanism by which the transition takes place remains unclear, although it is known that the structure of the local electric field is critical toward suppressing turbulence by shearing eddies.

NSE graduate student Rachael McDermott, as part of her thesis work, has provided the first direct measurements of radial electric (E_r) field profiles in the edge region of Alcator C-Mod. This was a particular challenge in C-Mod since ~mm spatial resolution was required from the spectroscopic technique used for the measurement due to the compact design of C-Mod. Qualitatively, the electric field structure observed on C-Mod is very similar to that observed on other devices. Namely, in H-mode it forms a large negative well approximately half a centimeter wide located within 1 cm inside the boundary. However, the width of the well is smaller than has been seen on other devices, and the depth of the E_r well on C-Mod, up to 300,000 V/m, is unprecedented: more than twice as deep as the wells measured on other devices. A comparison of these results with those from other devices indicates the existence of a scaling of E_r well width and possibly depth with machine size. The dominant contribution in calculating E_r on C-Mod is the impurity poloidal velocity. Poloidal velocity E_r contributions of 200kV/m have been observed transiently after LH transitions and values of up to 80 kV/m are observed to persist steady state in H-modes. This is contrary to measurements made on machines, in which the diamagnetic term is the dominant contribution to E_r, hinting that the C-Mod results could be critical in establishing the proper experimental tests of H-mode transition theories due to its unique parameters.

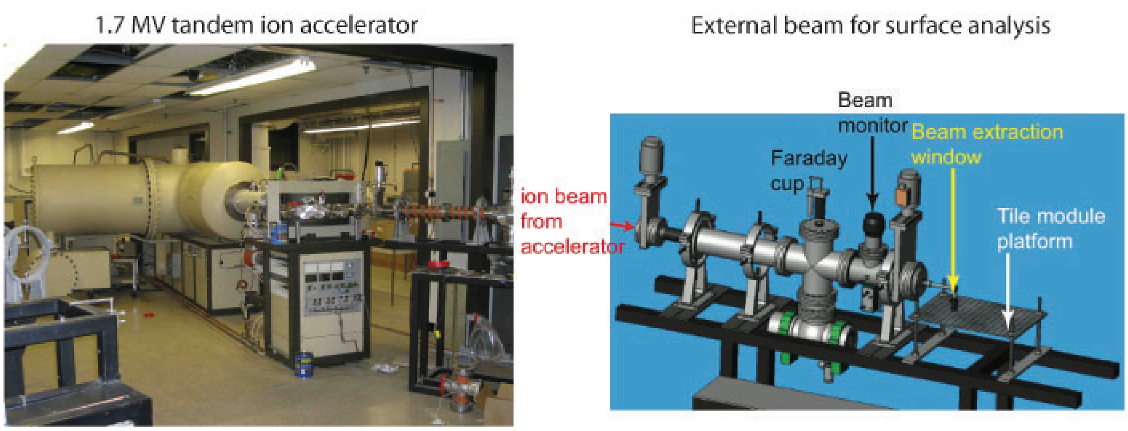


Example of new radial electric field measurements in the boundary plasma on Alcator C-mod. The plot shows electric field magnitude versus position from the Last Closed Flux Surface, which defines the boundary of the confined plasma. Profiles during various energy confinement modes are shown. The deepest radial electric field well (the dip in Er near -1 cm) correlate to the best confined plasmas.

McDermott will present these finding in an invited paper at the APS Division of Plasma Physics Meeting in fall 2008.

First Beam in Accelerator Facility

The 1.7-MV tandem ion accelerator achieved first ion beam. The accelerator was obtained gratis by associate professor Dennis Whyte from Harvard University at the time of his move to MIT. Working with NSE graduate student Harold Barnard and research engineer Peter Stahle, he completely refurbished and reassembled the accelerator, already obtaining several microamperes of beam current, with full voltage on terminal expected in summer 2008. The accelerator will be the centerpiece of the Cambridge Lab for Accelerator Studies of Surfaces, which will include both the fusion-oriented research of professor Whyte and basic surface diagnosis capabilities as a user center for local material scientists. For his master's thesis research Barnard has also constructed an "external-beam" that allows for proton-beam surface analysis without the requirement of placing samples under vacuum, thus greatly speeding up analysis of Alcator C-Mod materials.



(Left) Photograph of re-commissioned 1.7 MV tandem ion accelerator at Cambridge Lab for Accelerator Surface Studies. (Right) Schematic of external beam attached to accelerator for surface analysis without sample under vacuum.

Comprehensive Calculations of Plasma Interaction with Moving Objects

Understanding the interaction of plasma with solid objects has long been a vital problem in plasma physics with relevance to diagnostic probes, charging of spacecraft, and the dynamics of dust particles. Professor Ian Hutchinson's particle-in-cell code SCEPTIC was developed to perform comprehensive ab initio calculations of the plasma at kinetic-theory level and thus resolve some of the questions that bedevil approximate analytic approaches to the inherently nonlinear dynamics. NSE graduate student Leonardo Patacchini has greatly enhanced the code's capabilities to include the effects of a magnetic field and to enable calculations in fully six-dimensional phase space when geometries without intrinsic symmetry are studied. He has developed new, highly efficient, numerical algorithms that allow important physical systems to be modeled in short elapsed time even on the now relatively modest 36-node dedicated Beowulf computing cluster devoted to this work. A recent study using the code has investigated the theoretical reports of negative drag on dust particles in collisional plasmas. SCEPTIC has shown that the proposed phenomenon of accelerating (rather than decelerating) drag force occurs only in regimes where the ion dynamics is fluid-like and the other forces on the dust grain far exceed ion drag. The extravagant claims of some authors are thus disproved.

Student Awards and Activities

Jessica Alejandro Flores received the ANS Charles (Tommy) Thomas Memorial Scholarship Award for a student of nuclear science and engineering recognized for outstanding efforts and academic achievements in pursuit of a college education.

Bo Feng received an ANS Graduate Scholarship Award for a student of nuclear science and engineering recognized for outstanding efforts and academic achievements in pursuit of a college education.

Joseph Paul Yurko received an ANS Pittsburgh Local Section Undergraduate Scholarship Award for a student of nuclear science and engineering recognized for outstanding efforts and academic achievements in pursuit of a college education.

Paul Ernest Kollath-Romano received an ANS Graduate Scholarship Award for a student of nuclear science and engineering recognized for outstanding efforts and academic achievements in pursuit of a college education

Isaac Matthews received a Lemelson Minority Engineering Presidential Fellowship.

Amy Marconnet received a 2007–2008 Dean of Engineering Presidential Fellowship. This program was established to support excellence in graduate education by attracting the brightest students to the Institute.

Sung Joong Kim received the best paper award at the 1st ASME Micro/Nanoscale Heat Transfer International Conference for "Experimental Study of Flow Critical Heat Flux in Low Concentration Water-based Nanofluids."

Leonardo Patacchini received the Manson Benedict Award for excellence in academic performance and computational plasma physics research.

Yang Zhang received the Manson Benedict Award in recognition of the outstanding excellence of academic and research performance. He also received the Neutron Scattering Society of America's prize for cyber development of the North American neutron community at the 2008 ACNS Meeting in Santa Fe, NM, June 2008.

David Carpenter received an NSE Outstanding Student Service Award for leadership and outstanding service in ANS activities

Robert Holcomb received an NSE Outstanding Service Award for sustained leadership and contributions to program CASPAR.

Erik Johnson received the NSE Outstanding Teaching Assistant Award for effective teaching in 22.101 Applied Nuclear Physics, lectures, tutorials, and quiz reviews

Eric Forrest received the Roy Axford Award for outstanding academic achievements by a senior.

Dan Zaterman received the Irving Kaplan Award for outstanding academic achievements by a junior.

Anthony Tortorello won second prize for his essay "Why Supply Management Failed: How the Agricultural Adjustment Administration Squandered Billions in a Failed Attempt to Reduce Agricultural Production," by the Bruce Mazlish History Prize committee.

Leeland Ekstrom was president of the MIT Graduate Student Council for 2007–2008.

Lara Pierpoint received the Outstanding Graduate Presentation at the ANS Student Conference for the Fuel Cycle & Waste Management track, Texas A&M, March 2008. She also received a Hugh Hampton Young Memorial Fund fellowship through the MIT Office of the Dean of Graduate Education.

Jerzy Szablowski (professor Alan Jasanoff's UROP student) won an award from the undergraduate biomedical engineering society for his work on dopamine sensors.

Graduate student Ana Fiallos was awarded a Razin Fellowship from the McGovern Institute.

Recent postdoc Henryk Faas won a young investigator award for his presentation at the German Molecular Imaging meeting.

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/.