Department of Nuclear Science and Engineering

The Department of Nuclear Science and Engineering (NSE) continued its national academic leadership of the discipline. Nuclear power is experiencing a gradual transformation in public acceptance, as global climate change is becoming undeniable. The nation is moving steadily toward commitment to new power reactors. Students are sensing the importance of nuclear technologies. The diverse research of the department is of outstanding quality and generally well funded. The department began a development initiative leading up to its 50th anniversary next year.

President Bush's nuclear research initiative, GNEP, the Global Nuclear Energy Partnership, which proposes to rebuild US capability in fuel reprocessing and revolutionize the international approach to the nuclear fuel cycle, has dominated US fission research planning this year. Department faculty have been active in analyzing the merits of the approach, in testimony to Congress, in consultations with Department of Energy (DOE) leadership, and in public commentary. Direct support for the university nuclear education and research program was removed from the DOE Congressional submission last year. Congressional opinion does not support this termination, and universities including MIT have been active in proposing alternative approaches to sustaining the critical educational infrastructure.

By contrast, fission energy research continues to gain increasing industrial support as nuclear industries gear up for the expected new power-plant construction. Advanced reactors for diverse applications such as waste management, hydrogen production, and space propulsion are under active study for the longer term.

Fusion research remains very strong, and funding nationally has grown substantially to support the decision to proceed with the International Tokamak Experimental Reactor (ITER). MIT's national Alcator facility conducts unique research directly in support of ITER as well as more fundamental fusion plasma science. The Alcator team is highly active in the ongoing ITER international design review.

Research in nuclear and radiation applications for homeland security grew in the prior three years but has seen a significant drop this year. Homeland security, which funds it, has so far emphasized shorter-term research, which naturally has substantial volatility. The department is involved in research on detecting nuclear materials and using nuclear techniques to detect non-nuclear threats.

Research in the physical science applications of nuclear interactions is strong in areas such as neutron interferometry, materials science, and quantum information. The program in nuclear biology applications is shifting its focus away from experimental radiation therapy toward imaging, with particular relevance to neuroscience and radiation modeling.

Research funding administered directly by the department fell substantially. However, the larger department research groups, administered through laboratories such as the Plasma Science and Fusion Center, the Francis Bitter Magnet Laboratory, and the Laboratory for Energy and the Environment, fared very well.

The department continues to support educational outreach efforts. This year Professor Michael Driscoll is mentoring three minority undergraduate college students under the MIT Summer Research Program (MSRP) and five high school students selected in an international talent search under the Research Science Institute program hosted by MIT. Two of last year's MSRP participants have elected to join our department as graduate students next fall.

The MIT architecture undergraduate class 4.341 Introduction to Photography and Related Media, in the Visual Arts Program, taught by Andrea Frank, selected NSE as their focus and presented "Through the Lens: MIT Students View the Nuclear Science and Engineering Department."

Undergraduate Program

Undergraduate enrollment continues to be above historical levels for the department. Despite only seven sophomores declaring nuclear engineering in 2006, in all, 46 students were enrolled in the undergraduate program during the past year. This included seven sophomores, 20 juniors, 15 seniors, and four fifth-year students. Twenty students completed requirements for the bachelor's degree in nuclear science and engineering in 2006, perhaps our largest graduating class ever. These increases are due in part to increasing interest in nuclear science and engineering and the opportunity to appreciate the broad field of nuclear science and engineering including fission energy, fusion and plasma science, medical applications, materials, and research. Each year the department faces a continuing challenge to provide MIT freshmen opportunities to learn about nuclear science and engineering as many are not familiar with the very broad array of career options available with a nuclear science and engineering degree. It is expected that, as the nuclear industry's "renaissance" actually materializes, many more will chose to study nuclear engineering and its related disciplines.

An undergraduate course entitled "Communicating about Technology: Colossal Failures in Engineering," originally developed as a means to introduce freshmen to engineering concepts, is now a writing course that is given Humanities, Arts, and Social Sciences and Communications Intensive credits. Professor Andrew Kadak is the department's lead lecturer on the Three Mile Island accident as a learning tool for the importance of understanding basic engineering principles and management culture. Three other engineering departments participate in presenting segments about other engineering and human failures including the Columbia and Challenger accidents and the World Trade Center collapse.

Graduate Program

The graduate program totaled 107 students during the fall term. Of this number, 26 were enrolled for their first term. Some 42 percent are working in fission and energy studies, with 29 percent specializing in nuclear science and technology, and 29 percent specializing in fusion. The department awarded 25 master of science degrees and 12 doctoral degrees during the academic year.

Faculty Awards, Honors, and Activities

Professor George E. Apostolakis was elected to the National Academy of Engineering. He continues as a member of the statutory Advisory Committee on Reactor Safeguards of the US Nuclear Regulatory Commission, where he chairs the Subcommittee on Reliability and Probabilistic Risk Assessment. 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.

Professor Jacopo Buongiorno received the Outstanding Teaching and Advising Award (presented by the MIT student chapter of the American Nuclear Society), April 2007. Professor Buongiorno was track leader (long term reactor programs and strategies) at the International Congress on Advances in Nuclear Power Plants 2007 conference. He served on the organizing committee, 2007 Engineering Conferences International (ECI)—Nanofluids: Fundamentals and Applications. Professor Buongiorno delivered "Towards an Explanation of the Mechanism of Boiling Critical Heat Flux Enhancement in Nanofluids," a keynote lecture at the 5th International Conference on Nanochannels, Microchannels and Minichannels.

Professor Sow-Hsin Chen was elected as an academician in Academia Sinica of Taiwan for his outstanding contribution on soft condensed matter research. He received the 2006 Cozzarelli Prize from the editorial board of the *Proceedings of the National Academy of Sciences* for the scientific excellence and outstanding originality of the paper, "The violation of the Stokes–Einstein relation in supercooled water" (*PNAS*, 103, 12974-12978, 2006). Professor Chen organized and chaired the First US–China Joint Workshop on Neutron Science and Technology in November 2006, Beijing, China, with support from the National Science Foundation (NSF). He 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 Organization nuclear center in Sydney, Australia, in February 2007.

Professor Jeffrey Freidberg was appointed to the position of Korea Electric Power Professor of Nuclear Science and Engineering. Cambridge University Press published his book entitled *Plasma Physics and Fusion Energy* in February 2007. The book is based on lecture notes and will be used in several graduate level subjects in plasma physics.

Professor Ian Hutchinson served as vice chairman of the American Physical Society's Division of Plasma Physics and chairman of the division's Annual Meeting Program Committee.

Professor Alan Jasanoff received the McKnight Foundation Technological Innovations in Neuroscience Award. He held the Norman C. Rasmussen Career Development Chair. He continues to be a Sackler Fellow.

Professor of the Practice Andrew Kadak was elected to the Executive Committee of the Nuclear Installations Safety Division of the American Nuclear Society and serves on the American Nuclear Society Special Committee on Nuclear Non-Proliferation. In addition to continuing 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 Mujid Kazimi was elected Fellow of the American Association for the Advancement of Science. He continued as a member of the National Academy of Engineering's Committee on DOE's Nuclear Energy R&D Program, joined a blue ribbon committee on rejuvenation of scientific research in Kuwait for the Diwan of the Emir of Kuwait, and joined the advisory committee of the newly established Department of Nuclear Engineering at the Jordan University of Science and Technology. He joined the visiting committee of the Energy, Environment and National Security Directorate of Brookhaven National Laboratory.

Professor Ronald Parker received the Ruth and Joel Spira Award for Distinguished Teaching.

Professor Neil Todreas continued as vice chairman of the Scientific Council of the French Atomic Energy Commission's Nuclear Energy Division and as member of the DOE Nuclear Energy Research Advisory Committee. He gave an invited lecture at the Global Nuclear Energy Summit in Washington, DC, in March on the DOE's new GNEP.

Professor Dennis Whyte was elected a fellow of the American Physical Society. He led the Topical Group on Boundary Interactions for the US Burning Plasma Organization, is a member of the Divertor/SOL Group International Tokamak Physics Activity, and is a member of the Steering Committee on Plasma-Facing Components.

Professor Sidney Yip continued active research in the area of materials modeling and simulation. He served on advisory boards at two national laboratories: Lawrence Livermore National Laboratory–Chemistry, Materials, and Life Science Directorate, and Physics and Advanced Technology Directorate Idaho Nuclear Laboratory–Center for Advanced Modeling and Simulation.

Research

Research Funding

Volume administered directly by the department decreased substantially from FY2006 to FY2007, from about $6.7 million to $5.2 million, roughly a 23 percent decrease in funds expended. This reflects a number of multiyear research projects that ended in FY2006 or early in FY2007 and have not yet been renewed or replaced by other projects. The main sponsors whose volume dropped significantly were the Department of Defense ($400,000), L3 Communications ($280,000, prime sponsor DARPA), US Nuclear Regulatory Commission ($335,000), and Sandia National Laboratory ($215,000).

Two projects on imaging for security sponsored by the Department of Homeland Security (via L3 Communications) and the Defense Department under the direction of Dr. Richard Lanza came to an expected conclusion; other projects are being considered but at the time of this writing have not been awarded. This alone accounts for $680,000 of the volume decrease.

The Nuclear Energy Research Initiative (NERI) and smaller Nuclear Engineering Education Research programs have decreased in their national budget over the last few years, and our faculty have not been very successful in winning these grants in recent years. After dipping consistently for several years, our total volume from the DOE directly (as opposed to that received via national laboratories) has increased overall, and Professors Ronald Ballinger, Neil Todreas, and Sow-Hsin Chen have new or expanded projects. The NERI program has been reorganized and a new round of projects has been proposed, but the future of this program, which once accounted for more than half of our research volume, is not clear.

Similarly, support of the Nuclear Regulatory Commission (NRC), which was strong in FY2006, was lighter in FY2007. We expect that program to return in strength this year (FY2008), but the drop in NRC support was $325,000 between FY2006 and FY2007.

Department funds from the Idaho National Laboratory (INL) (in the form of Battelle Energy Alliance) decreased in NSE by roughly $150,000, but this was offset by funding from that organization routed through the Laboratory for Energy and the Environment, which increased $200,000 in the same period (total FY2007 volume about $930,000, split about evenly between the two departments). Our strong relationship with the INL and the Battelle Energy Alliance continues to bear fruit in the form of research support.

We established new contracts with the Shaw Group, the National Institute of Standards and Technology, and AREVA. We renewed agreements in FY2008 with the Tokyo Electric Power Company (TEPCO) and the NRC.

Fission: The Center for Advanced Nuclear Energy Systems

Research in fission energy is predominantly conducted through the Center for Advanced Nuclear Energy Systems (CANES). CANES also hosts research for non-nuclear applications using nuclear-origin methodologies. The research efforts were organized 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

Brief reports are given below.

The research program covers near-term as well as long-term technology options, with support from DOE, the NRC, INL, and national and international companies. Among the notable achievements in the last year is the demonstration by Professor Jacopo Buongiorno and Dr. Linwen Hu that nanoparticles in small fractions (less than 0.1 percent by volume) lead to significant (greater than 30 percent) enhancement in the critical heat flux in flowing water as well as in stagnant water (so-called flow and pool boiling). Additionally, irradiation of duplex SiC samples in the MIT reactor was initiated.

Modeling of this material as an advanced light water reactor fuel cladding, at steady state and under transients, showed the potential capability of extending the power density in the core by up to 20 percent, if found acceptable under irradiation.

CANES organized two symposia during the academic year. In October 2006, a two-day symposium on "Rethinking the Nuclear Fuel Cycle" was held at MIT with cooperation of the Commission on Atomic Energy (CEA) of France. The symposium was dedicated to the memory of Professor Manson Benedict, the first head of the department at MIT and a pioneer in the development of the technology of uranium enrichment and the discipline of nuclear chemical engineering. Among the non-MIT speakers were Admiral John Grosenbacher, director of INL; J. Bouchard, former director of the Reactor Engineering Division of the CEA; Admiral Frank L. "Skip" Bowman, President of the Nuclear Energy Institute; and Dr. Victor Reis, an advisor to the Deputy Secretary of Energy. In March 2007, a symposium was held on the "Supercritical CO_2 Power Cycle for Next Generation Systems" in collaboration with Knolls Atomic Power Laboratory and INL. The supercritical CO_2 (SCO_2) power cycle has drawn attention due to its ability to achieve high efficiencies (e.g., 45 percent) at moderate temperatures (e.g., 550 °C) that match the ranges of several gas-cooled and liquid-metal-cooled reactors. In addition, the SCO_2 equipment is more compact than that of the helium cycle, which is more compact than the steam cycle. The symposium, which 90 people attended, addressed the status challenges of component development, including heat transfer and materials issues in the turbomachinery and heat exchangers.

Four professional short courses were offered. In June 2006, Professors Michael Golay and Jacopo Buongiorno organized the 15th session of the four-week reactor technology course for utility executives, offered jointly with the Institute of Nuclear Power Operations. Also in June, Professors Kazimi and Todreas offered a reformatted form of the 41st session of the summer course on nuclear plant safety, Professor George Apostolakis directed a one-week course on risk-informed operations of nuclear power plants, and Professor Ballinger offered a one-week course on management of degradation of materials in nuclear power plants, in cooperation with the Electric Power Research Institute (EPRI) and the Nuclear Energy Institute.

During the Independent Activities Period, Professor Kadak, worked with the MIT Energy Club to organize a workshop entitled "Energy Myths and Realities—How are we going to deal with the challenge of global warming." The workshop speakers were advocates of solar, wind, nuclear, gas, coal, and conservation energy and provided a reality check on what is feasible and when.

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

Advanced Reactor Technology

Advanced Light Water Reactors

High-efficiency fuel for light water reactors (LWRs). The use of advanced fuel instead of conventional solid cylindrical fuel in LWRs has been under investigation by Professor Kazimi and Dr. Pavel Hejzlar. The internally and externally cooled annular fuel increases

were proposed to increase the fuel surface-to-volume ratio, thus leading to significantly lower heat fluxes to the coolant and also to lower fuel temperatures. A DOE-supported project investigated the ability to raise the power while maintaining or improving thermal margins in pressurized-water reactors (PWRs). Fuel manufacturing techniques have been investigated with industrial collaborators Gamma Engineering and Westinghouse. The various approaches for transitioning to uprated power in an existing PWR have been investigated. Given that the thermal hydraulics allow for introducing one batch of the annular fuel at a time, it was found advantageous to operate with two batches of annular fuel at 100 to 120 percent power before shutting down for adjustment of the primary and secondary coolant systems to accommodate 150 percent power.
In another project that also involved Professor Buongiorno and Dr. Thomas McKrell, 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 annular fuel proved to be less promising for uprating BWRs, as increased coolant flow limits the critical power in the hot assembly. However, the other three approaches, with some careful design choices, may be able to raise the power up to 30 percent. 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.

High burnup fuel for LWRs. Professor Kazimi, partially supported by the NRC, has been investigating effects of high burnup on fuel performance during reactivity-initiated events. A new model for fuel-clad mechanical interaction during an energy pulse has been formulated and compared with experiments in France, Russia, and Japan. The model is based on a simple criterion for failure associated with crack growth based on the J integral approach. The simplification is that, for the thin clad, failure is assumed to occur at the onset of crack tip growth. Stress strength is calculated taking into consideration the amount of hydrogen absorbed into the cladding and precipitated as hydride. The model has been implemented in our version of the FRAPTRAN code of NRC. Comparison with a wide range of fuel tests shows that, at high burnup (and therefore hydride levels in the clad), the energy required for reaching fuel rod failure is smaller than at low burnup. The pulse width is an important parameter in the burnup up to 40 MWd/kg but starts to become less important for higher burnup.

Stability of advanced BWRs. Professor Kazimi and Dr. Shih-Ping Kao examined 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 boiling water reactor (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. Thus, the stability margin in this reactor is not as robust as in forced-circulation reactors when the operating conditions are about the 100 percent nominal conditions. However, at lower powers, where even a current BWR will operate in natural convection, the ESBWR-like reactor has better stability margins.

Nanofluids for nuclear applications. In the past year, Professor Buongiorno and Dr. Linwen Hu's research program on engineered colloidal suspensions of nanoparticles in water (known as nanofluids) continued to focus on enhancement of the critical heat flux (CHF) observed in boiling nanofluids (Figure 1). Their experiments indicate that significant CHF enhancement is possible with nanofluids at modest concentrations and this enhancement was proven to occur for the first time also in a flow system. Because the performance of all water-cooled nuclear systems is CHF limited, the use of nanofluids could afford considerable economic and safety gains. The work performed has also cast considerable light on the mechanism of CHF enhancement in nanofluids. Briefly, buildup of a porous layer of nanoparticles on the heater surface was observed during nucleate boiling, and it was shown that this layer significantly improves the surface wettability, which in turn greatly increases the CHF.

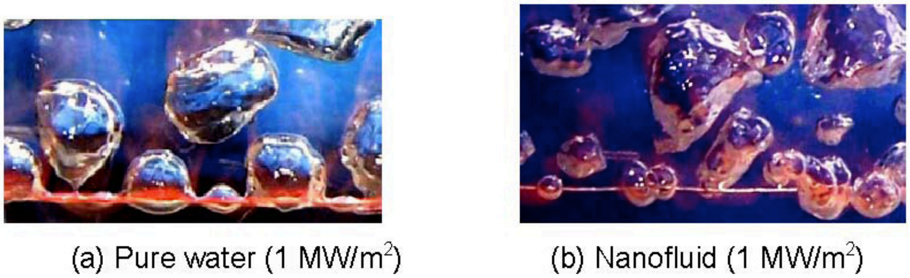
(a) Pure water (1 MW/m^2) (b) Nanofluid (1 MW/m^2)

Figure 1. Pool boiling of pure water (a) and 0.01%v alumina nanofluid (b) at the same heat flux on a stainless steel wire. While the wire has experienced critical heat flux in pure water, it is still well within the nucleate boiling regime in the nanofluid.

Among the possible nuclear applications of nanofluids being explored, one has proven particularly promising: the mitigation of postulated severe accidents when the core melts and relocates to the bottom of the reactor vessel. In such accidents, it is desirable to prevent the vessel failure by removing the decay heat through the vessel wall. This process is limited by the occurrence of CHF on the vessel outer surface. An analysis indicates that using a nanofluid instead of water as the coolant can improve the in-vessel retention capabilities of nuclear reactors by as much as 30 to 40 percent.

The nanofluid research program is in collaboration with the MIT Nuclear Reactor Laboratory (NRL) and is sponsored by AREVA, INL, DOE, and EPRI.

Hydride-Fueled Thermal and Metal-Fueled Fast Reactors

Professor Todreas continued as the principal investigator for two advanced nuclear reactor conceptual design projects. The first is the exploitation of a novel fuel, zirconium hydride, in light water reactors in cooperation with the University of California–Berkeley and Westinghouse, sponsored by the DOE's NERI program. Because the hydride fuel contains the moderating hydrogen atoms at concentrations comparable to that of liquid water, it can lead to higher total power in the same volume relative to a LWR core fueled with uranium dioxide. A novel inverted fuel assembly design has been developed for pressurized water application. Boiling water hydride-fueled cores achieve a power gain of 17 to 50 percent compared with oxide-fueled cores, depending on the achievable increase in core pumping power. A parallel project by University of California–Berkeley investigators is evaluating neutronic constraints that will reduce these power level gains, possibly significantly for PWRs. Based on this work, a new NERI program has been started on burning plutonium in such hydride-fueled water-cooled reactors. The second project in conjunction with Dr. Pavel Hejzlar is developing fast reactor concepts that can accommodate two types of cores: those that can burn up transuranics spent fuel from LWRs and those that can operate sustainably in a closed fuel cycle. Lead and salt coolant designs are being created, among them a novel chloride-salt-cooled closed cycle concept. These designs will be compared with alternative designs using gas and sodium coolants.

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 the development of the pebble bed reactor, which is one of the two high-temperature reactors being considered for the NGNP. This year, blind benchmark test predictions were completed by one of Professor Kadak's students on the German NACOK air ingress tests with very good results using computational fluid dynamics tools. This work is an important part of the safety analysis predictions of high-temperature gas reactors. This work was supported by Westinghouse as part of its interest in the Pebble Bed Modular Reactor being built in South Africa.

Professor Kadak is also continuing to work on his "lego" modularity concept by 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. CANES continues collaborations on the Chinese pebble bed project sponsored by the Institute of Nuclear Engineering Technology of Tsinghua University. Professor Kadak was invited to participate in an International Atomic Energy Agency meeting in October 2007 on high-temperature reactor safety in Beijing. He also collaborates with the South African PBMR project.

Advanced Gas-Cooled Fast Reactor

Reliability informed passive design. A MIT CANES group under Dr. Hejzlar and Professors Driscoll and Apostolakis has completed the second year (of three) on development of a multipurpose gas-cooled fast reactor under DOE NERI support. Carbon dioxide is the primary choice for coolant. Major reports were issued on design of a long-lived core having attractive safety features, on an optimized version for production of hydrogen by high-temperature electrolysis, and on passive decay heat removal reliability. The project continues as the venue for collaboration with the French CEA on probabilistic risk assessment use for guiding advanced reactor design.

Materials Studies. A facility has been designed and built to test materials corrosion in the presence of CO_2 at high temperatures. The maximum pressure it can take is 22 MPa at a temperature of 650 °C. It will be used for research by Professor Ronald Ballinger and Dr. Tom McKrell on materials limits in advanced reactors.

Fundamental thermal hydraulics. Because of smaller buoyancy driving forces than in the case of pumped flows, heat-transfer modes for decay heat removal of gas-cooled reactors often fall into transition regimes where there are few reliable experimental data. A team headed by Dr. Hejzlar investigated heat transfer in mixed convection flow and in transition flows between forced, mixed, and natural convection to develop heat-transfer correlations suitable for incorporation into integral reactor safety codes. A 6-m-tall test facility for natural circulation gas flow in a heated vertical round tube at pressures up to 1.0 MPa was built and experimental data were collected using three different gases (helium, nitrogen, and carbon dioxide). Data showed a substantial reduction of heat transfer, by up to 70 percent , in certain mixed convection regimes. The project was supported by INL.

Advanced Power Cycle Development

Significant progress has been made on developing a supercritical CO_2 Brayton power-conversion system for advanced reactors, led by a group headed by Dr. Hejzlar and Professor Driscoll, with collaboration by Dr. Kao of NSE, and with Dr. Yifang Gong from the MIT Gas Turbine Laboratory. This cycle promises high efficiency (approximately 45 percent) at moderate core outlet/turbine inlet temperatures (roughly 550 °C), thus allowing use of proven materials technology and high compactness and resulting in reduced cost. It is increasingly attracting interest both within the United States and abroad (primarily Japan, France, Great Britain, and South Korea). All these nations adopted the recompression version of this cycle proposed by an MIT group in 2001 to pursue for Generation IV reactors, and DOE officially designated it as an alternative for the intended fast reactor plant in the GNEP. During the past year, major reports were issued on plant control and on design alternatives for small- to medium-sized system versions. The layout of a 300-MWe supercritical CO2 power conversion system is shown in Figure 2, where HTR and LTR are recuperators, PRE is precooler, and IHX is intermediate heat exchanger. Support was provided by DOE via Sandia National Laboratories and by Knolls Atomic Power Laboratory.

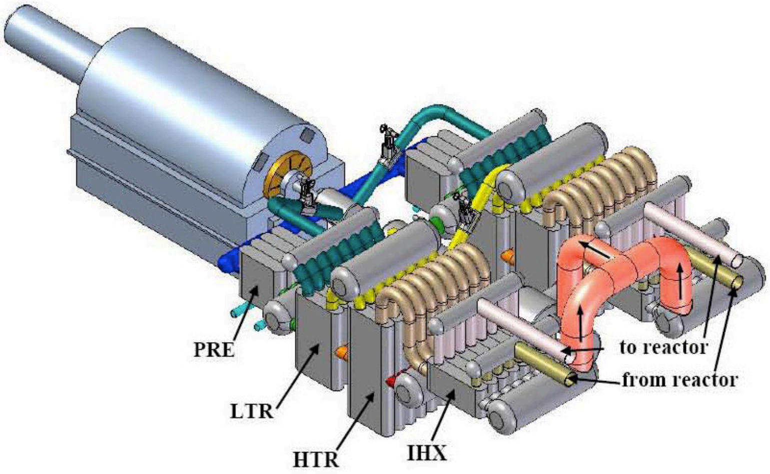

Figure 2. A 300-MWe supercritical power conversion system.

Advanced Fuel Cycle Technology and Economics

System Analysis of Actinide Transmutation Options

Professors Kazimi and Todreas 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. Their work has shown that thermal reactors can be applied to 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 percent of an LWR assembly uranium dioxide (UO_2) fuel rods, and that would lead to net destruction of transuranics. However, recycling of TRUs may need cooling intervals of about 20 years to limit the spontaneous fission neutrons during fuel manufacturing. The nuclear fuel cycle simulation code CAFCA has been upgraded with a more user-friendly acceptance of alternative advanced reactor options and also 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. Preliminary application of CAFCA system dynamics showed that only the use of a reactor with a conversion ratio near unity will have a significant impact on the uranium resource utilization. Furthermore, that availability of transuranics will ultimately drive the ratio of LWRs to fast reactors that depend on that TRU. Such an equilibrium state will not develop until about 2075, if the nuclear energy demand is growing at about 2.5 percent per year and advanced recycling technologies are introduced in about 2040.

Flexible Conversion Ratio Fast Reactors

A group led by Professor Todreas and Dr. 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.

During the fall term, students in Professor Kadak's design class undertook a project on a flexible conversion sodium-cooled fast reactor system that included the possibility not only of transmuting (or burning) high-level wastes but also breeding fuel for long-term sustainability of the nuclear energy enterprise. The student design project was presented by video conference to reviewers at both INL and Argonne National Laboratory. A paper summarizing the study was presented at the June American Nuclear Society Conference in Boston.

Use of Low-Enrichment Fuel in Research Reactors

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 and Dr. Edward Pilat, developed a design of the MIT reactor core using monolithic 20 percent enriched uranium 7 percent 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 were 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.

Enhanced Performance of Nuclear Power Plants

Reliability of Passive Safety Systems

Passive system reliability analysis has attracted increasing attention over the last decade. The expectation that overall plant reliability should increase by replacing certain active systems with passive ones is based on the fact that unreliability of active systems is primarily due to the unreliability of the energy source that is required for them to perform. Passive system functionality relies not on an external source of energy but on an intelligent use of natural phenomena, such as gravity, conduction, and radiation, which are always present. Professor Apostolakis and Dr. Hejzlar, working with graduate students, performed a time-dependent reliability evaluation of a two-loop passive decay heat removal (DHR) system as part of the iterative design process for a helium-cooled fast reactor. An important finding was the discovery that the smaller pressure loss through the DHR heat exchanger than through the core would make the flow bypass the core through one DHR loop, if two loops operated in parallel. The calculated conditional (i.e., given the LOCA) failure probability was deemed to be too high, leading to the identification of several design changes to improve system reliability.

Professor Kazimi and Dr. Kao and their students examined the impressions of 35 nuclear engineering experts about the significance of passive safety in advanced reactors. The experts spanned different sectors (vendors, utilities, regulators, academics, and representatives from nongovernmental organizations). They concluded that, although passive safety may be a way to reduce the cost of attaining reliable safety equipment, the passive systems will be subjected to longer examination periods in the licensing process, due to limited operational experience. A probabilistic study of the performance of a passive decay heat removal in an advanced BWR using an isolation condenser showed that the uncertainty of the system performance is comparable to a pumped system, when the pump failure to perform is considered.

Risk-Informed Decision Making

The use of risk information produced by probabilistic risk assessments (PRAs) in decision making involving high-hazard facilities is increasing. An issue that has been raised in the regulation of nuclear power plants is the uncertainty in the models. Professor Apostolakis and his graduate students have proposed a method to identify basic events in the PRA that have the potential to change the decision and are known to have significant model uncertainties. Because the focus is on basic event probabilities, this method is not appropriate for analyzing uncertainties that cause a structural change to the model, such as success criteria. The risk achievement worth importance measure is used with respect to both the core damage frequency and the change in core damage frequency to identify potentially important basic events. They are cross-checked with generically important model uncertainties. Then, sensitivity analysis is performed on the basic event probabilities, which are used as a proxy for the model parameters to determine how much error in these probabilities would need to be present to affect the decision.

Another area of significant model uncertainties is that of human reliability during accidents. The quantification of human error probabilities for the purpose of human reliability assessment (HRA) is very complex. Because of this complexity, the state of the art includes a variety of HRA models, each with its own objectives, scope, and quantification method. In addition to varying methods of quantification, each model is replete with its own terminology and categorizations, therefore making comparison across models exceedingly difficult. Professor Apostolakis and his students have investigated the capabilities and limitations of two prominent HRA models: the EPRI HRA calculator, used widely in industry, and a technique for human error analysis (ATHEANA) developed by the NRC.

Improved Prediction of Materials Degradation

Professor Ballinger's group has been investigating stress-corrosion crack growth in BWR weld materials. Effects of aging and environmental factors are included. The first 1,000-hour tests show that crack growth may occur under lower stress conditions. This project, already two years in progress, is supported by TEPCO for a total of four years.

Professor Sidney Yip has strengthened his research collaboration with industry on materials modeling and simulation. Besides working with Honda research and development on conducting polymers and SKF Global on bearing steel, he initiated a new project with Corning Ltd. on glass viscosity.

Nuclear Energy and Sustainability

Nuclear Energy for Hydrogen and Synthetic Fuel Production

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. Professors Kazimi and Driscoll have been studying the nuclear systems designs needed to generate synthetic ethanol and methanol from a variety of carbon sources. The first study considered captured CO_2 gases from coal plants and concluded that less than 50 percent of the carbon emissions from coal plants would be sufficient to produce all needed synthetic fuels to displace gasoline from oil. That would reduce carbon emissions from all sectors by only 20 to 25 percent. This year, carbon from municipal solid waste sources was considered. The municipal solid waste, with reasonable efficiency of processing efficiencies, was found to be able to provide carbon needed for 20 percent of the synthetic gasoline. This results in a reduction of nearly 6 to 8 percent of carbon emissions. Gasoline production will be costly, however, in the neighborhood of \$3.70 per gallon, which is only slightly less than the gasoline produced from capture CO_2 from coal power plants.

Nuclear Technology and Canadian Oil Sands

As a follow-up to last year's NSE's 22.033 Nuclear Systems Design Project on nuclear technology and Canadian oil sands production, Professor Kadak and one of his students studied the integration of nuclear energy with oil sands extraction projects in Canada. This work compared various nuclear energy alternatives in specific oil sands application from surface mining to steam-assisted gravity drainage systems. Steam, electricity, and hydrogen production options were evaluated, as were the economics, siting, and licensing challenges posed for practical applications. This project was partially supported by the University of Calgary and the Shaw Group with an advisory committee of oil sands producers.

Energy Policy

With increased concerns about global warming, the prospect of carbon taxes or other means to encourage the limitation of CO_2 releases into the environment are becoming more likely in the United States. Nuclear plants are still considered to be capital intensive and costly compared with fossil alternatives despite rising fuel costs for conventional steam power stations. Professor Kadak is working to identify what level of carbon tax would be necessary for a clear economic signal to utilities and investors that the economic choice for future electric power should be nuclear. Included in this analysis is an additional incentive premium for making the nuclear choice above simply the economic adjustments compared with coal (sequestered and not) and natural gas at varying natural gas prices.

Risk Assessment Applications in Non-nuclear Systems

Risk-Informed Decision Making in Space Exploration

The January 2004 presidential directive to NASA to adopt a goal-oriented space exploration program poses many challenges. These include sustained and affordable human and robotic space programs to explore the solar system, starting with a human return to the moon and subsequent human exploration of Mars. Meeting the exploration technical and safety goals while meeting programmatic constraints related to cost and schedule involves making complex decisions. Professor Apostolakis in collaboration with researchers at NASA headquarters has proposed a risk-informed decision-making framework to better manage uncertainties and to better balance competing priorities that decision makers face routinely during the various phases of the program execution. In this framework, stakeholder expectations related to technical performance attributes, such as safety, reliability, and mission performance, as well as for programmatic performance attributes, such as cost and schedule, can be defined in terms of a set of performance measures that need to be quantitatively assessed and monitored during the entire life cycle of the program.

Infrastructure Security

Since the events of September 11, 2001, there has been an increased awareness of the vulnerability of infrastructures to accidents and malevolent acts. Professor Apostolakis and his students have developed a scenario-based methodology for ranking the elements of a water-supply network according to their value to the network's owner. The failures of the elements due to random causes and to malevolent acts are considered. The methodology is based on multiattribute utility theory and a graph theory-based network analysis algorithm. This methodology extends approaches proposed in the literature by taking into consideration the capacity of the infrastructure's elements and their mean time to repair. The water-supply infrastructure of a midsized city serves as a case study. The infrastructure system is modeled as a network and scenarios are created to evaluate the consequences of the failure of each of its elements. The accident scenarios are ranked according to their expected disutility. The vulnerabilities to malevolent acts are ranked using a subjective combination of the disutilities and the scenario susceptibility to attack. The results are provided to the decision makers for evaluation and risk management.

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 of the 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.

Neutron and X-Ray Scattering

Among the many anomalous properties of water, the existence of the density maximum of H_2O at 4 °C (T_{max}=277 K) or, in the case of D_2O, at 11 °C, T_{max}=284 K, is most well known. The density maximum of water was discovered in 17th century by an Italian scientist, but it took another 350 years for Chen's group at MIT to discover that there is also a density minimum of water in deeply supercooled state at 210 K (See the figure below). The reason it took so long to discover the density minimum is probably because one cannot keep bulk water from freezing into hexagonal ice in such a deeply supercooled temperature. Chen's group found earlier that by confining water in nano-size silica pores of less than 20 Å diameter, the freezing process can be suppressed down to 160 K. This allows them to perform a novel small-angle neutron scattering experiment to measure absolute values of density of D_2O in this temperature range. The existence of density minimum in D_2O was published in the *Proceedings of the National Academy of Sciences* ("Observation of the density minimum in deeply supercooled confined water" by Dazhi Liu, Yang Zhang, Chia-Cheng Chen, Chung-Yuan Mou, Peter H. Poole, and

Sow-Hsin Chen (PNAS, 104, 9570–9574, 2007)), and highlighted by the editor. The significance of the existence of density minimum temperature T_{min} is two fold: the anomalous property of water disappears below the T_{min}; and the existence of T_{max} and T_{min} strongly implies the existence of the second liquid-liquid critical point of water (Figure 3). The possible existence of the second critical point was experimentally shown by an earlier paper in *Physical Review Letters*, "Pressure Dependence of Fragile-to-Strong Transition and a Possible Second Critical Point in Supercooled ConfinedWater" by Li Liu, Sow-Hsin Chen, Antonio Faraone, Chun-Wan Yen, and Chung-Yuan Mou (*PRL* 95, 117802, 2005).

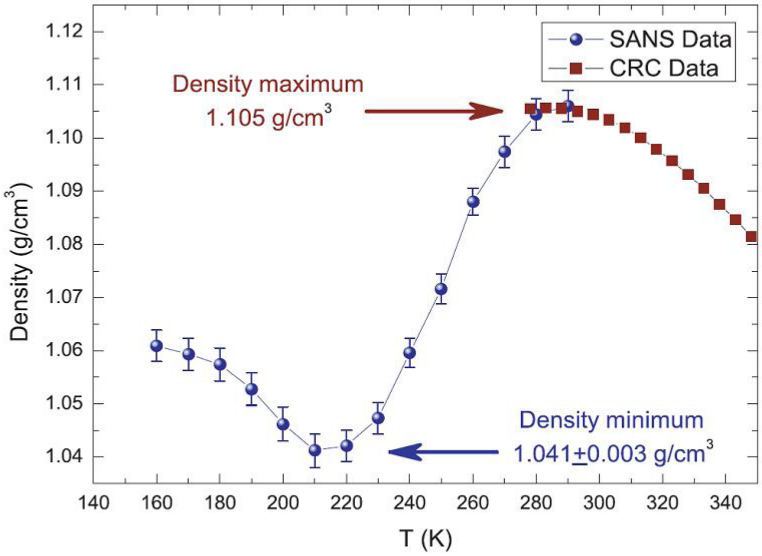

*Figure 3. Discovery of the existence of a density minimum in supercooled water made by Professor Sow-Hsin Chen's group (*PNAS*, 104, 9570–9574, 2007). Average D_2O density inside the 15 ± 1 Å pore measured by Small Angle Neutron Scattering (SANS) method as a function of temperature (the solid blue symbols). A smooth transition of D_2O density from the maximum value at 284 ± 5 K to the minimum value at 210 ± 5 K is clearly shown. The brown filled squares are the density data for bulk D_2O taken from the CRC Handbook of Chemistry and Physics.*

Chen's group is planning a series of new experiments to be carried out in a newly built spallation neutron source (SNS) to confirm the precise location of the second critical point of water. SNS, which the United States has spent 1.4 billion dollars building over the last 10 years, is the world's most powerful neutron source.

Mechanistic Radiation Biology

A major unresolved question in radiation biology is "What role does radiation damage to blood vessels play in the subsequent development of early or late side effects in normal tissues?" A novel method has been developed by Professor Jeffrey Coderre for selective irradiation of blood vessels that allows direct experimental testing of this question. It has long been assumed that early effects are due to damage to the rapidly dividing stem cell populations and that late effects are due to damage to the more slowly growing blood vessels. However, a recent, and controversial, literature report has suggested that blood vessel damage is the cause of an acute effect in the intestine: the radiation-induced gastrointestinal syndrome. Professor Coderre and his group have shown that blood vessel damage is not the cause of the gastrointestinal syndrome and that the initial report in the literature, which has been widely cited and accepted as dogma, is incorrect. The presentations and publications describing this work have attracted considerable attention. Figure 4, from one of these papers, was selected for the cover of the May issue of the *International Journal of Radiation Oncology Biology Physics* (BW Schuller, AB Rogers, KS Cormier, KJ Riley, PJ Binns, R Julius, MF Hawthorne and JA Coderre. No Significant Endothelial Apoptosis in the Radiation-Induced Gastrointestinal Syndrome. *Int J Radiat Oncol Biol Phys* 2007 68(1):205–210). These studies could have significant implications for the development of agents to protect normal tissues during radiation therapy and to treat normal tissues after accidental or intentional radiation exposure.

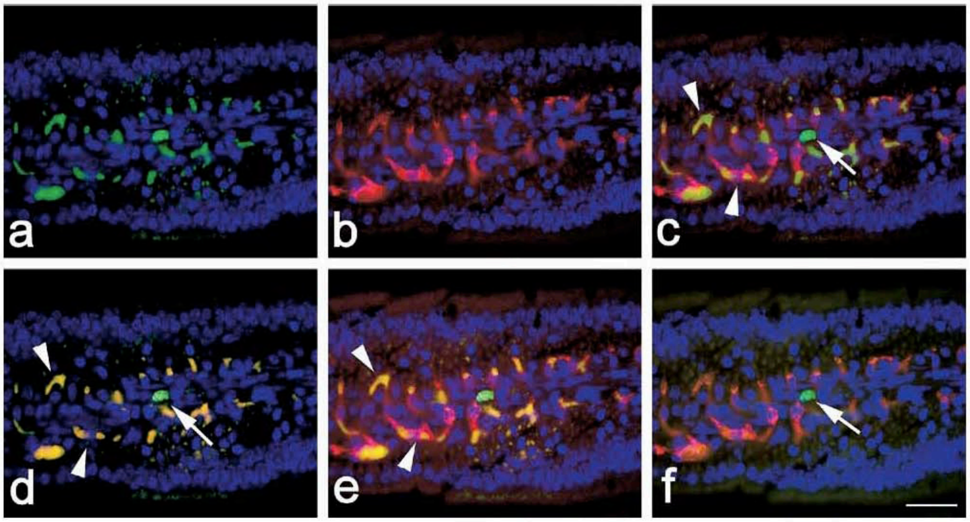

Figure 4. Illustration in the mouse intestine of how, unless properly corrected, an intense red blood cell autofluorescence can lead to misinterpretation of radiation effects on blood vessels. Double-label fluorescence immunohistochemistry in formalin-fixed, paraffin-embedded jejunum from a mouse irradiated with 12 Gy of 250 kVp X-rays, demonstrating elimination of confounding autofluorescence. (a) When excited at 450–490 Å and viewed through a narrow-pass emission filter (515–565 Å; green light only), there appear to be many cleaved-caspase 3-positive (fluorescein labeled, green) cells in the villus. (b) Vascular endothelial cells are demonstrated by Meca-32 labeling (Cy3, red, excitation 546 Å, emission >590 Å). (c) Merged image appears to show both Meca-32-positive (arrowheads) and Meca-32-negative (arrow) cleaved caspase-3-positive cells. (d) When excited at 450–490 Å and viewed through a long-pass emission filter (allowing passage of all wavelengths > 515 Å) most fluorescent figures are shown to be the result of tissue autofluorescence (yellow, arrowheads) with only a single central figure retaining green fluorescent properties (arrow). (e) Meca-32 overlay demonstrates that endothelial cell-associated figures are autofluorescent (erythrocytes). (f) Removing autofluorescence by color subtraction, only the central non-endothelial cell is confirmed to be a fluorescein-labeled cleaved caspase-3-positive cell (arrow). DAPI nuclear counterstain (blue) included in all panels (excitation 365 Å, emission >420 Å). Scale bar: 50 μm for all panels.

Quantum Information Processing (QIP)

Professor David Cory and his students continue to explore magnetic resonance approaches to quantum information processing through collaborations with Dr. Chandrasekhar Ramanathan (NSE), Dr. Sergio Valenzuela (NSE), Professor Seth Lloyd (Mechanical Engineering), Dr. Raymond Laflamme (University of Waterloo), and Dr. J. Emerson (University of Waterloo).

Over the past year we have experimentally demonstrated what were considered two grand challenges in quantum information processing: an error correction code that led to an experimentally realizable increase in the process fidelity and efficient error detection for a physical system. These findings move the theory and practice of fault tolerant quantum information processing closer together. We continue to use our nuclear magnetic resonance-based test-bed for quantum information processing to develop methods of coherent control and we have a system that can robustly operate over a 6-spin Hilbert space. In addition, we have preliminary results from a new setup that will expand the computational space to 15 spins.

We have completed the first series of experiments on coherent spintronics where the electron spin plays an essential role in control of the nuclear spin-based qubits. In particular, we have demonstrated that control of the electron spin is sufficient to have universal control over the nuclear spins in the case that the hyperfine interaction is anisotropic. We have also found a logical encoding to protect the nuclear spin's coherence from the finite electron spin lifetime.

We have installed new electron spin resonance spectrometers to enable further studies of spintronics and are rebuilding the pulses' X-band electron spin resonance to permit He-4 temperature experiments on systems involving many nuclear spins.

Dr. Ramanathan has led a series of experiments to explore and find applications for multispin dynamics in solid state systems. This includes investigating the transition from classical to quantum dynamics in one-dimensional spin chains. Applications include using spin chains as channels for quantum information and creating highly polarized spin systems as potential transducers. For example, we report spin pumping by dynamic nuclear polarization in Si where polarizations as high as five percent are achieved for the first time.

Dr. Valenzuela has carried out a series of experiments aimed at demonstrating spin transport in device structures. In particular, he is interested in showing spin injection in semiconductors.

We are starting a new program that combines spin physics and persistent current flux qubits. The project is in collaboration with Professor Terry Orlando (Department of Electrical Engineering and Computer Science) and Dr. William Oliver (Lincoln Laboratory). To enable these measurements, we are installing a set of refrigerators for low-temperature physics in the lab (two dilution refrigerators and one He-3 system). The aims of the new program are to develop new methods of coherent control for prediction-based composite fair queuing and to use high Q, nonlinear resonators as local detectors of magnetization.

Coherent Imaging via Neutron Interferometry

In collaboration with Dr. Dmitry Pushin (NSE) and Dr. Muhammad Arif (National Institute of Standards and Technology), we have demonstrated new models of measurements via a three-blade neutron interferometer. The new approaches enable us to reduce the sensitivity of interferometry to vibrations and to design new scattering experiments that extend the measurement range to lower q values. We are collaborating with the National Institute of Standards and Technology to build a new beamline at their facility and to outfit it with a next-generation neutron interferometry.

Neutron Capture Therapy

Neutron capture therapy for cancer research, directed by Professor Otto K. Harling, continued for the 21st year with support from DOE. The DOE Innovations in Nuclear Infrastructure and Education-supported user facility for boron neutron capture therapy (BNCT), which opens the unique facilities and specialized expertise at the NRL to researchers both within and outside MIT, has continued to serve a diverse user community. Several different research groups based at universities and national laboratories from around the country currently perform in vitro and in vivo experiments in collaboration with the BNCT group at the NRL. These experiments principally focus on investigating the efficacy of new, tumor-seeking capture compounds and new boron administration techniques. Preclinical research is also under way to investigate the feasibility of using BNCT for malignancies outside the brain.

A technique for imaging boron neutron capture events with subcellular resolution in stained tissue sections is being implemented in the BNCT laboratories. This technique will help elucidate how the microscopic distribution of boron capture events affects the observed biological response and is expected to complement research conducted through the user facility. The International Dosimetry Exchange for BNCT continues under the leadership of MIT. A comparison of absorbed dose measurements in three European centers and the MIT Fission Converter Beam is complete. In the last year, a dosimetry exchange with the Argentinean BNCT was completed. Progress toward the ultimate objective of pooling clinical data among the different BNCT centers continues with the cooperation of European, South American, and Japanese partners. The MIT program in neutron capture therapy continues as the leading BNCT research program in the United States and is considered to be among the best in this field worldwide. However, waning interest by the US government funding agencies puts the MIT BNCT program in jeopardy.

NMR (MRI) Imaging for Brain Science

Professor Jasanoff's lab has made significant progress in its core focus of developing molecular probes for next-generation functional imaging in animals. A new family of calcium sensors for MRI were introduced and we are now in the process of applying them in single cells and intact organisms. He also collaborated with Professor Stephen Lippard's group to develop porphyrin-based cell-permeable contrast agents that address the key problem of in vivo delivery and that could be important for future neuroimaging work. Newer projects have focused on several types of genetically controlled contrast agents. Most advanced is the work on a protein dopamine sensor that is planned for use in mapping reward-related signaling in rodents. A project to study the development of neural connectivity and hemodynamic responses in juvenile rats, in collaboration with Professor Martha Constantine-Paton's lab, was recently completed. It found that systematic changes in BOLD time courses take place from P13 to adulthood and may be related to changes in carbonic anhydrase expression that occur at this age; the changes also coincided with gross repatterning of neural activity in response to somatosensory stimuli in these animals.

Contraband Detection

The events of 9/11 have led to increased interest in Dr. Richard C. Lanza's work on explosive and contraband detection. This resulted in a significant expansion in funding for the work in neutron resonance radiography. In addition to support from the technical support working group, an interagency co-coordinating organization, a collaborative effort with L3 Communications continued to develop a system for the Transportation Security Administration for examination of air cargo. Efforts also continue with the Lawrence Livermore National Laboratory in detection of potential radiological or nuclear weapons, as have new efforts with Los Alamos National Laboratory and INL.

Dr. Lanza's group has also developed a new method for detecting materials, based on neutron resonance radiography. This technique is capable of good spatial resolution (approximately 3 mm), penetration of heavy objects, and determination of elemental composition. Element-specific resonances in total neutron attenuation cross sections that are in the range of 1 to 8 million electron volts (MeV) are exploited to enhance the contrast for imaging elements such as carbon, oxygen, nitrogen, and others, which is then used to produce elementally resolved images of objects under inspection and thus to identify the material composition of the object and potential threats in an unambiguous manner. In a collaboration with MIT and L3 Communications, a new dedicated facility has been established at the Bates Linear Accelerator facility that consists of a 3-MeV radio-frequency quadrupole accelerator and a system for inspection of large aircraft containers.

Detection of Fissile Materials

Recent events highlight the increased risk of an attack on the United States with a nuclear or radiological weapon. One of the key needs to counteract such a threat is the long-range detection of nuclear material. Though theoretically possible to distances greater than 100 m based on gamma-ray emissions from such materials, detection at 100 m has long been thought to be impractical because of fluctuating levels of natural background radiation. Recent work has shown that this problem can be overcome through the use of imaging gamma-ray detectors based on our work in coded apertures. A more recent development is a new concept in deploying large numbers of passive detectors to permit remote detection of possible threats. The potential is being examined for replacing large, fixed detection systems with large numbers of simple autonomous and mobile radiation detection systems that can self-organize ("swarm behavior") to find radiation sources over wide areas.

Development continues on a new approach for the detection of fissile materials using low-energy (<100 kiloelectronvolts) neutrons as a probe and detecting high-energy neutrons that are the result of fission. The significance of this approach is that only materials such as plutonium-239 and uranium-235—materials that are the constituents of nuclear weapons—will result in such high-energy neutrons; thus, the system has an unambiguous signature for fissile materials. As part of this, an all-digital signal processing technique has been developed for liquid scintillators that enables reliable separation of neutrons from gamma rays. Experiments have been run using the accelerator of the Laboratory for Accelerator Beam Applications located in NW13. The experimental data confirm the extensive Monte Carlo modeling done during the project.

Neutron Phase Contrast Imaging

Neutron phase contrast imaging uses the wave properties of neutrons to greatly increase spatial resolution and contrast in materials imaging. A beamline and detector system for implementing this technique has been installed at the MIT NRL. Further developments such as phase tomographic imaging are under study.

A phase contrast x-ray imaging system for mammography is being developed. The work is being done in collaboration with researchers at MIT in the Department of Electrical Engineering and Computer Science and the Computer Science and Artificial Intelligence Laboratory as well as at the Avon Foundation Comprehensive Breast Evaluation Center at Massachusetts General Hospital as part of a Deshpande Center Innovation grant.

Fusion and Plasma Physics

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 28 of a total of 58 at the PSFC. Professor Hutchinson is coprincipal investigator of the Alcator C-Mod tokamak project. Alcator C-Mod is one of three major national facilities for fusion research in the United States. It was funded at a level of $20,011,00 in FY2007. Professor Ron Parker leads the lower hybrid radio-frequency heating experimental team on Alcator. Professor Freidberg is associate director of the PSFC. Associate professor Dennis Whyte is a new member of the PSFC who is actively involved in the boundary and materials research on Alcator C-Mod and also leads the fusion materials analysis accelerator laboratory.

Here we give a few illustrative examples of fusion and plasma research involving NSE students and faculty. The PSFC report to the president can be consulted for further details of the research accomplishments.

Lower Hybrid Radio-Frequency Heating and Current Drive

The Alcator C-Mod tokamak uses only radio-frequency (RF) plasma heating for its plasma. An emerging research area in fusion is the study of the complex interaction between the radio-frequency waves in the plasma, the wave launching structures with the plasma boundary, and the simultaneous coupling of different RF heating techniques in the same device. A recent addition to C-Mod is a lower hybrid (LH) RF heating system that operates at 4.6 GHz. The LH group is led by Professor Parker and involves

NSE graduate students Greg Wallace and Nick Siefert, and Department of Physics graduate student Andrea Schmidt. A primary motivation for using LH is its effectiveness at inducing electric current in the tokamak plasma, a requirement for eventual fusion reactors. A signature C-Mod accomplishment of the summer 2006 campaign was the achievement of 800 kiloamperes of current driven (of 1,000 kiloamperes total) by the LH system injection of 1 MW of RF power. The LH also complements 5 MW of 50-MHz ion cyclotron RF heating (ICRH), which has been the standard heating system for C-Mod. New experiments examined the coupling of LH waves into plasma heated by ICRH, including plasmas operating in the high-confinement mode, which is the required confinement regime for the ITER burning plasma experiment under construction in France. The coupling efficiency is found to be consistent with expectations based on the relationship between coupling efficiency and plasma density at the LH launcher grill face previously developed for low-confinement regimes. The application of thin boron films, so-called boronization, has a marked difference in the grill density and therefore the coupling efficiency. Before the first boronization of the 2007 campaign, application of ICRH caused the density at the grill to drop to levels that resulted in poor LH coupling; after boronization, the drop in density at the grill was much reduced, and the coupling efficiency improved significantly. It is not yet understood why boronization had this effect or if it was the sole reason for this change in behavior. These experiments are attracting international interest, as lower hybrid current drive is being actively considered for installation in ITER and the C-Mod results will be important in informing a decision on whether to install LH current drive for "day 1" operation on ITER.

Development of in Situ Diagnostics for Plasma–Surface Interactions

NSE student Roman Ochoukov, with visiting students Niels Gierse (University of Cologne) and Soren Harrison (University of Wisconsin), and supervised by Dr. Bruce Lipschultz and associate professor Whyte, have designed and implemented the surface science station (SSS) diagnostic on Alcator C-Mod. The SSS allows the insertion and rotation of a large, instrumented, and replaceable probe head into the C-Mod vacuum vessel. The purpose of the SSS is to provide experimental data on the condition and modification of material surfaces in the harsh fusion environment. It is understood that the operation of future, long-pulse fusion devices such as ITER will likely be limited by the lifetime of materials that are in direct contact with the boundary plasma. The first incarnation of SSS has been used to characterize the application of thin boron films (boronization), a technique that was found to be critical in Alcator C-Mod for high-fusion performance. The SSS head is equipped with sensitive quartz microbalances that can measure monolayer changes in film thickness. The diagnostic has provided for the first time a map of the boron film deposition to the surface inside C-Mod and provided greater understanding of the experimental parameters controlling the deposition and erosion of the boron films. For example, it was found that application of a magnetic field in both the vertical and toroidal directions helped improve the localization of the B film deposition. All together, the information provided by SSS has indicated methods of improving the efficiency of boronization and better understanding its effect on fusion plasmas. Future incarnations are planned to implement even more sophisticated materials diagnostics.

Measuring Plasma Current Profiles with Motional Stark Effect

The shape of the current profile in the interior of the tokamak plasma is critical to its stability and confinement. A particular concern for extrapolating the tokamak concept to reactors is finding regimes where plasma self-generated "bootstrap" current and the applied, external current can be aligned properly so that the plasma is sustained indefinitely. While the new LH RF system on C-Mod (see above) will provide temporary access to such regimes, it is also vital to measure the evolution of the internal current profile to understand and extrapolate the experimental results. To this end, a diagnostic beam of high-energy neutral atoms is injected into the plasma. As the beam transits the plasma, its excited light is polarized due to its own velocity and the pitch of the local magnetic field due to the "motional Stark effect" or MSE. Because the pitch of the magnetic field is set by the internal and (measured) external currents, the angle of polarization can be used to accurately calculate the internal current profile. Previous attempts on C-Mod to use MSE were not successful because of poorly understood calibration difficulties. Recent work carried out by NSE graduate student Jin-Seok Ko, and supervised by Dr. Steven Scott (Princeton Plasma Physics Laboratory/C-Mod) and Professor Hutchinson, has shown that the calibration problems were primarily set by the emission of "secondary" neutrals caused by beam–plasma or beam–gas interactions, which contaminated the primary emission and therefore confused the polarization experiments. This problem has been mostly overcome by tilting the trajectory of the neutral beam six degrees as compared with the intrinsic magnetic field, a small change that was found to greatly reduce the effect of the secondary emission. As a result, for the first time the MSE diagnostic showed direct evidence that the application of LH RF waves to the plasma altered the internal current profile, a critical first step toward developing long-pulse plasma regimes in Alcator C-Mod.

Effect of Plasma Flow on Levitated-Dipole Stability

The levitated dipole is an alternative magnetic configuration for fusion to the tokamak. This concept is being explored in the levitated dipole experiment located at the PSFC. It is well known that a static closed magnetic field line configuration, such as a levitated dipole, can be stabilized by plasma compression against undesired ideal magnetohydrodynamic (MHD) interchange modes when the boundary pressure gradient is sufficiently weak. However, it is also known that many laboratory plasmas exhibit a sheared (spatially varying) plasma velocity flow, and this flow may affect the MHD marginal stability boundary. New theoretical work has addressed this issue by analyzing the effect of axially sheared flow on interchange stability in a hard-core Z-pinch, a cylindrical representation for the levitated dipole configuration. Graduate student Alexei Kuznetsov, supervised by Professor Freidberg, in collaboration with Luca Guazzotto and senior scientist Jay Kesner, carried out the research. Analytic calculations of marginal stability for several idealistic velocity profiles show that, depending on the shape of the velocity shear profile, the flow can be favorable, unfavorable, or neutral with respect to MHD stability. Numerical calculations were also carried out using more realistic experimental profiles. The research laid the theoretical underpinnings for designing optimal flow profiles in levitated dipole experiments.

Measuring Radiation Losses from Tokamak Alcator C-Mod

MIT's tokamak has molybdenum plasma-facing components. Heavy metal components of this type are under consideration for ITER and reactors because they have low erosion and uptake of hydrogen. However, heavy elements radiate strongly if they get into the plasma and can thereby limit plasma performance. Graduate student Matt Reinke is working under the direction of Professor Hutchinson in measuring the radiated losses caused by unwanted impurities in Alcator C-Mod. The results have already demonstrated that direct radiation is the limiting factor for confinement in the best confinement regimes. A more detailed measurement instrument capable of giving full two-dimensional maps of radiation losses is being constructed and will represent a major advance in this important area.

Fast Digital Tokamak Control

Graduate student Marco Ferrara, working with Professor Hutchinson and Dr. Stephen Wolfe, has implemented a fully digital control system for Alcator C-Mod with an extremely fast cycle time of about 25 microseconds. This control system, which performs real-time reconstruction of the plasma shape based on direct magnetic measurements, was designed to replace (and initially reproduce the behavior of) a hybrid analog–digital system. It has worked remarkably robustly as a drop-in replacement. Now the additional capabilities of the digital system to do more sophisticated adaptive control are being explored. This facility, together with a comprehensive simulator of the control system, will enable the establishment of control techniques that are resilient to operation near system limits and in the presence of plasma noise.

Basic Plasma Physics Studies with Particle-in-Cell Techniques

A number of important basic plasma physics problems that have resisted comprehensive solution in the past, because of their inherent nonlinearity and complexity, are now becoming soluble using large-scale computing. One such problem is the interaction of a solid sphere with a flowing plasma. Professor Hutchinson has built a computer code called SCEPTIC (specialized coordinate electrostatic particle and thermals in cell) that can obtain highly accurate solutions of the flux distribution to the sphere, the plasma distribution around it, and the resulting ion drag force, all of which are important in plasma measurements using mach probes and in dusty plasma research. The results have shown a number of surprising results, including, for example, that the flux is larger on the downstream side for some parameters. Thanks to a new NSF/DOE basic plasma physics grant, student Leonardo Patacchini has begun to work on further code development to address situations when a magnetic field is present, bringing an additional level of complexity.

Student Awards and Activities

Jonathan Hodges received the Manson Benedict Fellowship for excellence in academic performance and professional promise in research in nuclear engineering.

Chris Handwerk and Tyler Ellis received Outstanding Student Service Awards for exceptional service to the students, the department, and the entire MIT community.

David Carpenter received the NSE Outstanding Teaching Assistant Award for exceptional contributions as a teaching assistant in the department

Jennifer Choy received the Roy Axford Award for academic achievement by a senior in NSE.

Connor Galloway received the Irving Kaplan Award for academic achievement by a junior in NSE

Bo Feng received an American Nuclear Society Robert T. Liner Memorial Scholarship Award for outstanding efforts and academic achievements in pursuit of a college education.

Jessica Alejandro Flores received an American Nuclear Society Undergraduate Scholarship Award for outstanding efforts and academic achievements in pursuit of a college education.

Heisoog Kim received an American Nuclear Society John and Muriel Landis Scholarship Award for outstanding efforts and academic achievements in pursuit of a college education.

Anna Nikiforova received an American Nuclear Society Graduate Scholarship Award for a graduate student pursuing nuclear science and engineering studies.

NSE graduate students Tyler Ellis, Craig Gerardi, and Anna Nikiforova won Technical Session Awards for best paper/presentation within their technical session at the American Nuclear Society Student Conference at Oregon State.

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/.