Department of Nuclear Science and Engineering

The Department of Nuclear Science and Engineering (NSE) remains the strongest overall in the nation. Nuclear power is experiencing a transformation in the public's perception, as the reality of global climate change is becoming undeniable. Students are sensing the importance of energy and other nuclear technologies. The diverse research of the department is of outstanding quality and generally well funded.

The launching of the MIT Energy Initiative this year has been strongly supported by the department. We are key participants in regular course offerings in energy across the Institute, and we organized an entire session of the Energy Minicourse for alumni and faculty. Through NSE, MIT is strategically poised to provide national leadership in nuclear energy research and development both for the immediate future (in fission) and for the longer term (in fusion).

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. 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. Another strategic area, and one in which NSE has seen major recent research growth, is in nuclear and radiation applications for homeland security. Both the detection of nuclear materials and the use of nuclear techniques for detection of nonnuclear threats provide excellent research opportunities. Research in the physical science applications of nuclear interactions is strong in areas such as neutron interferometry, materials science, and quantum information. However, despite some outstanding new results at MIT, nuclear biological applications funding is difficult at present because of changes in national funding agency policies.

Yet another all-time record level of undergraduate enrollment was reached this year. Graduate applications have increased substantially and the number and quality of entering students are high.

Mohamed Elbaradei was the Rose lecturer. He was awarded the Nobel Peace Prize subsequent to his invitation. Nevertheless, he came and spoke to an overflow audience on "Nuclear Technology in a Changing World."

MIT's Department of Nuclear Science and Engineering continues to lead the National University Consortium of the Idaho National Laboratory (INL). INL has been designated as the lead national laboratory for the development of advanced nuclear energy systems. Each of the universities in the consortium has established academic centers of excellence (ACE) to carry on research in their chosen fields. MIT's ACE is focused on advanced reactor technologies, fuel cycle, and materials to support the nation's new nuclear directions. Our department's involvement should provide additional opportunities for research, shaping the nation's nuclear energy agenda and enhancing education in nuclear science and engineering.

Undergraduate Program

NSE undergraduate enrollment has risen sharply during the past few years. This increasing interest in nuclear science and engineering is part of a national trend. It also reflects an effort aimed at providing freshmen an opportunity to appreciate the broad field of nuclear science and engineering: fission energy, fusion and plasma science, medical applications, materials, and research. Some 22 members of the Class of 2008 elected NSE for the fall 2005 sophomore class. There were 25 last year. In all, 55 students were enrolled in the undergraduate program during the past year. This included 22 sophomores, 17 juniors, and 16 seniors. Sixteen students completed requirements for the bachelor's degree in nuclear science and engineering.

Graduate Program

The graduate program totaled 103 students during the fall term. Of this number, 34 were enrolled for their first term. Some 37 percent are working in fission and energy studies, with 35 percent specializing in nuclear science and technology, and 29 percent in fusion. The department awarded 20 master of science degrees and 20 doctoral degrees during the academic year.

Professor Jacopo Buongiorno contributed to MIT's expanding Energy Initiative by reshaping course 22.313J Thermal Hydraulics in Power Technology and joint-offering it in the Department of Mechancial Engineering (MechE) and the Department of Chemical Engineering (ChemE) as 2.59J and 10.536J, respectively. This course offers graduate students fromMechE, ChemE, and NSE who are interested in energy the opportunity to cover advanced topics in two-phase flow and heat transfer, which is essential to the design and operation of conventional and nuclear power plants.

Faculty Awards, Honors, and Activities

Professor Buongiorno received the Outstanding Teaching and Advising Award, presented by the Student Section of the Alumni Network Services (ANS). He also received the Ruth and Joel Spira Award for Distinguished Teaching, MIT School of Engineering. Professor Buongirono created the Center for Nanofluids Technology at MIT, an interdisciplinary center with ChemE, MechE, the Department of Electrical Engineering and Computer Science (EECS), and the Department of Aeronautics and Astronautics (http://mit.edu/nse/nanofluids).

Professor Sow-Hsin Chen received the Distinguished Alumnus Award from National Tsinghua University in Taiwan in May 2006 in recognition of his achievements in scientific research.

Professor Jeffrey Coderre received a Pilot Project Award from the MIT Center for Environmental Health Sciences. His award title was "The Role of Vascular Endothelial Cell Damage in Tissue Response to Low-Dose Radiation." He presented an invited minisymposium talk, "Selective Irradiation of the Vascular Endothelium," at the Annual Meeting of the Radiation Research Society, Denver, CO, October 2005.

Professor Jeffrey Freidberg has completed a textbook entitled *Plasma Physics and Fusion Energy* to be published by Cambridge University Press in 2007.

Dr. Pavel Hejzlar was elected a member of the Executive Committee of the Reactor Physics Division of the American Nuclear Society. He also organized the track on Long Term Reactor Program and Strategies for the 2006 International Congress on Advances in Nuclear Power Plants.

Professor Ian Hutchinson was elected vice chairman of the Division of Plasma Physics of the American Physical Society. He presented an invited lecture entitled "The Nuclear Renaissance" at the International Conference of the American Society of Mechanical Engineers.

Professor Alan Jasanoff received a 2006 Technological Innovations in Neuroscience Award from the McKnight Foundation. Earlier in the year, Professor Jasanoff took up a secondary appointment in MIT's Biological Engineering Division (BE), establishing a formal link between BE and NSE.

Professor of the Practice Andrew Kadak was elected as chair of the International Nuclear Societies Council (INSC) in June 2005. INSC acts as a global forum for nuclear societies, representing 80,000 nuclear professionals, to discuss and establish common aims and goals. In addition to continuing to serve on the US Nuclear Waste Technology 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 joined the Scientific Advisory Committee on Reactor Thermal Hydraulics and Safety for the Paul Sherer Institute in Switzerland. He gave invited lectures at the Department of Energy (DOE) Office of Naval Reactors, at the Sweden National Academy of Science Symposium on Nuclear Energy, and the 4th International Congress on Advanced Nuclear Power Plants in Reno, Nevada. In July 2005 he testified to the House Committee on Government Reform on issues of hydrogen energy.

Dr. Richard Lanza continues his work for the International Atomic Energy Agency in the area of development of nuclear techniques for humanitarian demining, use of small accelerators as neutron sources, and exploration of neutrons as applied to problems of contraband detection and security. Dr. Lanza was an invited speaker at the International Conference on Accelerators (Dubrovnik). He is the chair of the Institute of Electrical and Electronics Engineers Radiation Instrumentation Technical Committee.

Professor Neil Todreas was appointed vice chairman of the Scientific Council of the French Atomic Energy Commission's Nuclear Energy Department. He gave invited lectures at the American Nuclear Society Symposium on Economics in the Nuclear Industry in Troy, NY in March, and at the International Congress on Advances in Nuclear Power Plants in Reno, NV in June. He also presented testimony on the DOE's new Global Nuclear Energy Partnership before the House Subcommittee on Energy of the Committee on Science in April.

Professor Sidney Yip received the Hsun Lee Lecture Award of the Chinese Academy of Sciences. He delivered the Nuclear Engineering Distinguished Technical Lecture at North Carolina State University. He was a member of a National Science Foundation blue ribbon panel that produced a report identifying the new field of simulation-based engineering science. He was appointed an advisory board member of the newly established Center for Advanced Modeling and Simulation at the Idaho Nuclear Laboratory. He continues to serve on two advisory boards at the Lawrence Livermore National Laboratory, Physics and Advanced Technology Directorate, and Chemistry and Materials Science Directorate.

Research

Research Funding

NSE's primary research volume for FY2006 increased about 7.5 percent over the prior year, from $6.2 million to $6.7 million, based on preliminary data. This represents a healthy increase in overall research spending. The single largest fraction of new volume (about a half million dollars) is in the area of imaging for the Department of Homeland Security (DHS), a project awarded last year to Dr. Richard Lanza that is being carried out in large part at the Bates Linear Accelerator Facility. Fission researchers collectively have seen a significant net increase in volume, from industry sources (including Tokyo Electric Power Company, with whom our faculty have a long-standing relationship) and from the partnership with Battelle Energy Alliance, which now operates the Idaho National Energy Laboratory.

Overall volume directly from the Department of Energy, historically our largest sponsor, has decreased about 10 percent to $1.56 million. This means that the percent of overall volume has dropped from 28 to 23 percent and has actually been overtaken by industry as a group (which increased to 33 percent). This is somewhat deceptive, though, since the industry volume includes the previously mentioned contract from DHS via L3 Communications as a subcontract and so is actually government-sponsored work. In addition, some volume increase has been seen in National Laboratories, which are funded through the Department of Energy. Taken together, these facts put the DOE back at the top of our sponsor list, with about 34 percent of our overall volume in FY06. Industry without the DHS funds is at about 22 percent of overall volume.

New awards were received from the Department of Energy, Knolls Atomic Power Laboratory, Westinghouse Electric, the Space and Naval Warfare Systems Center (Department of Defense), and others. Existing collaborations continued with Tokyo Electric Power, Toshiba, Areva-Framatone, Sandia National Lab, the Nuclear Regulatory Commission, and others. Three awards (two direct and one as a collaborative subaward) were made to MIT professors under the Nuclear Energy Research Initiative (NERI) and represent three-year projects beginning in FY2006. A grant from the Cambridge–MIT Institute that was temporarily being managed by Timothy Havel, an NSE principal research scientist, was "handed back" to Professor Seth Lloyd in Mechanical Engineering, decreasing our apparent volume by $300,000, although the project continues at MIT and still involves Dr. Havel. Our students in the radiation science and technology (RST) field continue to benefit from collaborations with Harvard and area hospitals; we have received over $250,000 in support for graduate research assistants (RAs) this year for their off-campus work—about five students, consistent with FY2005. Typically, this work involves medical imaging or image processing such as nuclear magnetic resonance and is part of a joint program with the Harvard–MIT Division of Health Sciences and Technology. The prime sponsor for these students is generally the National Institutes of Health (NIH).

The primary volume of NSE represents only a fraction of the efforts of our faculty, of course, but it does include the majority of the support for fission faculty and for RST faculty outside the Francis Bitter Magnet Laboratory (Professors David Cory and Jasanoff). Funding for fusion faculty is entirely through the Plasma Science and Fusion Center. There is a continued dependence primarily on one government agency—the Department of Energy—for funding in fission, whether directly or via subawards, and the fortunes of that single entity can have a profound effect on our ability to support research and the RAs who carry it out. In the latest solicitation, the NERI program has, for the first time, a cost-sharing requirement. This is a troubling sign of weakening research funding, and our efforts continue to diversify the funding sources for research in this field, turning more and more to industry. This has the disadvantage of a narrower focus on applied solutions and leaves less room for basic science research.

In the RST field, Dr. Richard Lanza continues to attract ever more research funding for his explosives scanning technology, and well-established professors such as Sidney Yip and Sowhsin Chen have been successful in maintaining their volume. However, Professors Jacquelyn Yanch and Jeffrey Coderre have struggled to attract funding, especially from the most likely agencies like NIH and NSF, where competition is fierce and funding nationally has leveled. The department must find ways of aiding faculty in these areas to find steady funding sources to support their students and develop their research programs.

Fission: The Center for Advanced Nuclear Energy Systems

Research in fission energy is predominantly conducted through the Center for Advanced Nuclear Energy Systems (CANES). 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
- Nuclear Power for Space Applications

Detailed reports are given below.

The research program covers near-term as well as long-term technology options, with support from DOE, the Nuclear Regulatory Commission, and national and international companies.

Among the notable accomplishments this year is the initiation of a program to pursue improved reliability of materials and fuels of future reactor plants through integration of scientific simulation with engineering evaluations and industrial considerations. The Center will benefit from unique capabilities at MIT as a whole. Professors Ron Ballinger and Mujid Kazimi, working with the MIT reactor staff, demonstrated a high-temperature facility that can test materials up to 1,400° C in the MIT research reactor. This capability is very rare at any laboratory and is unique among universities. In addition, Professor Sidney Yip has over the years developed many models for atomistic and molecular simulation of materials, which his group applied to such materials as silicon carbide (SiC) and borosilicate glass. Professor Hobbs is an expert on effects of radiation on ceramics. We added a new research scientist, Dr. Thomas McKrell, with considerable experience in metal failure analysis. Combining such expertise will enable CANES to become a leading center for materials and fuels research for future nuclear systems. Another important development was the initiation of a collaboration with Knolls Atomic Propulsion Laboratory, in which three exploratory projects were undertaken for using gas-cooled reactors or the supercritical water-cooled reactor in future naval applications. The size of such reactors would be smaller than modern commercial power reactors, and their optimization considers attributes besides cost. The exploratory projects were guided by Professors Jacopo Buongiorno and Andrew Kadak and Dr. Pavel Hejzlar. A new project supported by the Tokyo Electric Power Company was started under Professor Kazimi to examine the possibility of raising the power density in boiling-water reactors using advanced fuel and fuel assembly designs. Finally, three MIT projects were initiated with funding under the nationally competitive DOE NERI program: (1) Professor Ballinger is the principal investigator on a collaborative project with Los Alamos National Laboratory that will seek to develop a corrosion-resistant material to use as fuel cladding and structural materials in lead-cooled reactor systems. The project will receive about $1 million in funding over three years. (2) Professor Neil Todreas and Dr. Hejzlar are coprincipal investigators on a project to develop nuclear reactor designs with a flexible conversion ratio for lead alloy and liquid salt coolants. This is a $500,000 grant over two years. (3) Professor Paul Barton of ChemE and Professor Kazimi will develop a model for the simulation and optimization of a system to produce hydrogen from water using the heat and/or electricity generated by a nuclear plant. The grant is for $500,000 over three years.

Two symposia were organized by CANES during the academic year. In November 2005, a two-day symposium on "Innovative Nuclear Technologies" was held at MIT under joint sponsorship with the Center on Nuclear Systems Innovation at the Tokyo Institute of Technology. In March 2006, a workshop to chart collaborations with INL was conducted on "R and D Priorities for Advanced Reactors." The symposium was attended by 60 people. In addition, in January 2006, a series of eight lectures by prominent experts was organized on the issues of Nuclear Energy and National Security. The series was video-telecast to INL and desiring universities. The series was made available on demand on the web for six months after its conclusion.

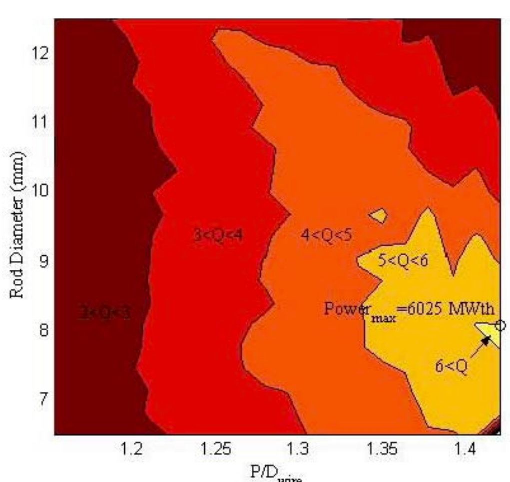
In June 2005, Professors Michael Golay and Jacopo Buongiorno organized the 14th session of the four-week Reactor Technology Course for utility executives, offered jointly with the Institute of Nuclear Power Operations. Also in June, Professors Kazimi and Todreas offered in a reformatted form the 40th session of the summer course on Nuclear Plant Safety, Professor George Apostolakis directed the 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 and the Nuclear Energy Institute.

Highlights of some of the NSE research projects follow.

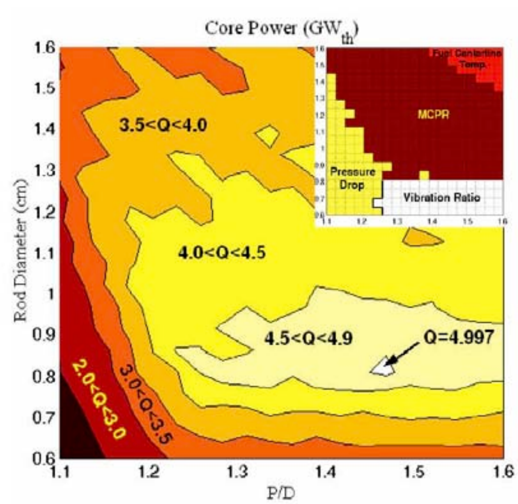
Advanced Reactor Technology

Advanced Light Water Reactors

High-efficiency fuel for light water reactors (LWRs). The use of annular fuel instead of conventional solid cylindrical fuel in LWRs has been under investigation by Professor Kazimi and Dr. Hejzlar. The internally and externally cooled fuel increases the fuel heat transfer 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. Their investigation indicates that traditional manufacturing using powder sintering techniques will provide excellent results. Samples of vibrationally packed fuel have been irradiated up to 7 MW d/kg in the MIT Research Reactor. Nondestructive postirradiation examination showed low fission gas release, which is also predicted through modeling to persist to high burnup. Use of uranium nitride instead of the oxide as fuel proved capable of providing the needed uranium loading, with U235 enrichment limited to 5 percent. In another project, TEPCO supported a scoping analysis of the use of several advanced fuel designs to raise the power density in a boiling water reactor (BWR). The project will cover smaller pins of solid geometry, annular fuel, cross-shaped fuel, and the use of uranium hydride instead of uranium oxide as fuel. Under a third project supported by the Nuclear Regulatory Commission (NRC), effects of high burnup on fuel performance during reactivity-initiated events is being modeled and compared to experiments in France, Russia, and Japan.



[Figure 1] *Achievable hydride wire-wrapped PWR core power before neutronic constraints*



[Figure 2] *Achievable hydride BWR core power (Δplimit = 0.248 MPa) before neutronic constraints*

Integrated and hydride-fueled reactors. Professor Todreas continued as the principal investigator for two advanced nuclear reactor conceptual design projects. The first is a medium power rating integral light water reactor being developed by an international consortium of industry, laboratory, utility, and universities led by Westinghouse. The second is the exploitation of a novel fuel, zirconium hydride, in light water reactors in cooperation with University of California–Berkeley and Westinghouse sponsored by the DOE's NERI program. Since 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. Wire-wrapped PWR hydride fueled cores were found to have substantially higher maximum powers than standard grid–spaced oxide fueled cores, achieving a power uprate of approximately 54 percent due to improved pressure drop, critical heat flux, and fuel rod vibration performance. BWR hydride-fueled cores achieve a power gain of 17 to 50 percent compared to oxide-fueled cores, depending on the achievable increase in core pumping power. A parallel project by UC Berkeley investigators is evaluating neutronic constraints that will reduce these power level gains, possibly significantly for PWRs. Based upon this work, a new NERI program has been started on burning plutonium in such hydride-fueled water-cooled reactors.

Nanofluids for nuclear applications. Professor Buongiorno's research program on engineered colloidal suspensions of nanoparticles in water (known as nanofluids) has broadened in the past 12 months. Fundamental transport phenomena in nanofluids are being investigated with the ultimate goal of exploring their feasibility for applications in nuclear systems such as fission reactors, accelerator targets, and fusion reactors. The emphasis is on elucidating the mechanisms of mass, momentum, and heat transfer enhancement that have been observed experimentally. This entails (1) measurements of the self- and binary-diffusion coefficients of nanoparticles in nanofluids with and without temperature gradients, which is being pursued in collaboration with Professor Cory's nuclear magnetic resonance group; (2) measurements of the thermal conductivity and single-phase convective heat transfer coefficient; (3) a robust computational fluid dynamics effort accompanying the experimental investigation, particularly in the pursuit of an explanation for the single-phase convective heat transfer enhancement; and (4) measurements of the critical heat flux (CHF) in both pool and flow boiling. This last area seems particularly promising, as the initial experiments indicate that significant CHF enhancement (up to 100 percent) is possible with nanofluids at modest concentrations (<0.1 percent vol.). Since the power of all water-cooled nuclear systems is CHF limited, the use of nanofluids could afford considerable improvements. The work is sponsored by AREVA, the INL, and the NRC. The creation of the interdepartmental Center for Nanofluids Technology at MIT provides a wealth of multidisciplinary expertise and talent to tackle the scientific challenges in this area.

Professor Buongiorno directs this center and organized a workshop on "Nanofluid Technology" at MIT this year.

Stability of boiling and supercritical water reactors. Professor Kazimi concluded studies of the stability of the supercritical water-cooled reactors (SCWR). While such reactors can achieve high power cycle efficiency, since they operate at pressures of 25 MPa and temperatures of up to 550° C, the coolant density change across the core potentially gives rise to density wave oscillations. The stability of the coupled nuclear and thermal behavior of the whole SCWR core, in symmetric and asymmetric forms, was analyzed. It was concluded that it is possible to design the SCWR to be stable by appropriate selection of inlet orificing devices, but the reactor is more sensitive to changes in power and flow conditions than is typical of current boiling-water reactors. The stability of the ESBWR—an advanced BWR with only natural circulation of in-vessel coolant for all operating conditions—is now being addressed. Such a reactor operates at a lower pressure of 10 MPa. The preliminary investigation revealed that the stability margin in this reactor is not as robust as in forced-circulation reactors when the operating conditions change.

Advanced Gas-Cooled Modular Pebble Bed Reactors

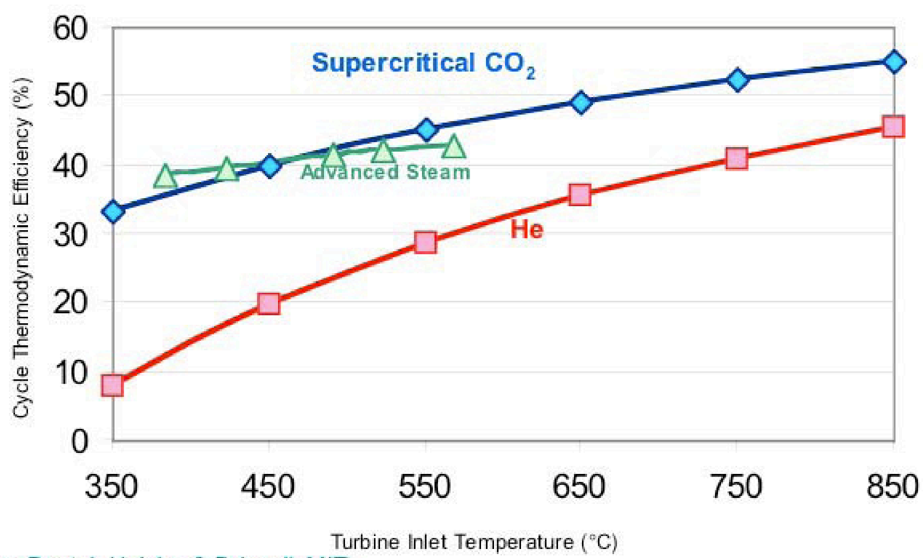
The modular pebble bed reactor is one of the two reactor concepts that is being considered for the next-generation nuclear plant to be built at the Idaho National Laboratory, which was authorized for construction by the Energy Policy Act of 2005. CANES is addressing several key areas regarding technical and economic viability of these concepts. Work continues by Professor Ballinger on the development of an understanding of the performance of the coated microsphere fuel used in both the pebble and block reactors. Professor Ballinger and his students have continued development of a model for fuel behavior and included a new chemistry model to assess the affects of high-temperature fission products on the pyrolytic carbon and silicon carbide. This year Professor Ballinger participated in an international benchmarking of fuel performance code sponsored by the International Atomic Energy Agency. The results of TIMCOAT's (MIT's fuel performance code) comparisons have yet to be published relative to other international benchmarks.

In addition, the new high-temperature irradiation facility has completed its first campaign in which advanced composite materials and nonfueled coated particle fuel have been irradiated at temperatures as high as 1,400° C to a dose of approximately 1.5 dpa. The irradiated materials will be analyzed to explore the effect of radiation damage on the SiC layer that serves as the primary barrier to fission product release from gas reactor coated particle fuel. Professor Kadak is continuing to work on developing the modularity concept that should allow smaller reactors such as the 120 MWe pebble bed to compete with much larger reactors 10 times its size. The second major area deals with safety. While high-temperature gas reactors are regarded as safe since they physically cannot melt down, there is a need to understand the impact of air ingress events on this largely graphite reactor core. In the past, Professor Kadak and his associates had developed a benchmarked capability to analyze the complicated chemical processes involved using a computational fluid dynamics code. This year, work is nearly complete on a blind benchmark of recent air ingress tests completed in Germany's Jeulich Research Center at the NACOK facility. This work is supported by Westinghouse as part of their interest in the Pebble Bed Modular Reactor being built in South Africa. CANES continues to be active in collaborations on the Chinese pebble bed project sponsored by the Institute of Nuclear Engineering Technology of Tsinghua University. Professor Kadak met with senior designers of the Chinese demonstration pebble bed reactor in Beijing in December to discuss several research opportunities to include MIT. Their full-scale demonstration plant is to be operational by 2011.

Advanced Gas-Cooled Fast Reactor

The gas-cooled fast reactor (GFR) is one of the concepts being pursued by DOE under its Generation IV Program. The MIT CANES group under the direction of Professors Michael Driscoll and George Apostolakis and Dr. Hejzlar, has completed the first year (of three) of a NERI project to develop a multipurpose GFR design (for breeding or burning transuranics and/or minor actinides for electricity and/or hydrogen production). Incorporation of probabilistic risk assessment (PRA) plays a key role in the design process and also forms the basis for a collaborative International Nuclear Energy Research Initiative effort with the French Commissariat à l'Énergie Atomique (CEA). A key achievement to date has been the development of a core design using BeO diluent, which has a very low power peaking factor throughout its burnup lifetime and is thus capable of battery-type fueling, with more than 15 years between refuelings.

Advanced Power Cycle Development



Source: Dostal, Hejzlar & Driscoll, MIT

[Figure 3] Advanced power cycle efficiency

An MIT CANES group led by Dr. Hejzlar and Professor Driscoll, with collaboration by Dr. Yifang Gong from the MIT Gas Turbine Laboratory, has worked since 2000 on development of a supercritical CO_2 Brayton power conversion system for advanced reactors, which includes most GEN-IV concepts. This cycle has the considerable advantage of high efficiency (approximately 45 percent) at moderate core outlet/turbine inlet temperatures (roughly 550° C), thus allowing use of proven materials technology. This approach has now attracted considerable interest both within the United States and abroad. A formal collaborative agreement with the Tokyo Institute of Technology is in effect, and a new research project has been initiated with the Knolls Atomic Power Laboratory on maritime applications. DOE support via Sandia National Laboratories also continues and is now focused on modeling cycle dynamics and control.

Fundamental Thermal Hydraulics for Next Generation Gas Reactors

Next-generation reactors rely to a large extent on passive means for decay heat removal to simplify the design and reduce cost while enhancing safety. Because of smaller buoyancy driving forces than in case of pumped flows, heat transfer modes often fall into transition regimes where there is a lack of reliable experimental data. The team headed by Dr. Hejzlar is investigating heat transfer regimes 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 6m-tall test facility for natural circulation gas flow in a heated vertical round tube at pressures up to 1.0 MPa has been built and experimental data are being collected using three different gases (helium, nitrogen and carbon dioxide). Data show a substantial reduction of heat transfer, by up to 70 percent, in certain mixed convection regimes. The project is supported by Idaho National Laboratory.

Advanced Materials Development for Pb-Bi Cooled Systems

One of the potential advanced reactor designs makes use of liquid lead (Pb) or lead-bismuth (Pb-Bi) eutectic as the coolant. The advantages of this type of coolant include high thermal capacity, very high boiling point, and low neutron cross section. However, current metallic materials—nickel-base alloys in particular—are susceptible to accelerated corrosion, which places a temperature limit of approximately 500° C on operation. At this temperature, the system is not economical. Professor Ballinger has been working to develop new materials that can extend the upper temperature limit for these systems to the 650–700° C range. Past success has led to the award of a NERI project to take the initial results to the point where proof of principal has been established for the use of new materials, developed in Professor Ballinger's laboratory, in the fabrication of piping and fuel cladding. Successful completion of this project will pave the way for higher, more economical operation of Pb and Pb-Bi cooled systems.

Advanced Fuel Cycle Technology and Economics

System Analysis of Actinide Transmutation Options

Professors Kazimi and Todreas and Dr. Hejzlar are investigating thermal and fast spectrum closed fuel cycles in comparison to the open fuel cycle regarding spent fuel management economics and proliferation resistance. Their work has shown that thermal reactors can be applied for reduction of the 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. Operating and safety characteristics of the combined nonfertile and uranium fuel assemblies (called CONFU) can be designed as comparable to traditional all–UO_2 fuel assemblies. In a separate collaboration with Professor Ernie Moniz of the Physics Department, the systems simulation code CAFCA has been upgraded with a more user-friendly acceptance of alternative advanced reactor options and also equipped with a capability for handling fuel transactions in three regions with distinct nuclear fuel cycle technologies. Preliminary application of CAFCA II showed that the fuel recycling capacity will be a major factor in the accumulation of spent fuel in the various regions. It was shown that the economic impact of recycling would be more limited if the cost is recovered from the electricity that produces the TRU material rather than the electricity produced by the recycled TRU.

Flexible Conversion Ratio Fast Reactors

Professor Todreas and Dr. Hejzlar have initiated a DOE–sponsored project to develop a feasible design for 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 will be designed and cross-compared to select the most promising reactor plant design. The coolants to be evaluated are lead and liquid salt (as distinguished from molten salt containing molten fuel). Gas coolant core results from an already ongoing MIT project and sodium results from Argonne National Laboratory work will be evaluated in comparison to the lead and liquid salt coolant core results.

Use of Low-Enrichment Fuel in Research Reactors

The use of highly enriched uranium (HEU) in research reactors has facilitated high neutron fluxes for use in many scientific disciplines. However, such fuel is also a strategic material, and its replacement by more proliferation-resistant, low-enriched uranium (LEU) fuel has been a goal of US DOE. Doctoral student Tom Newton, working with Professor Mujid Kaximi 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. The optimum reactor design consisted of the use of half-sized fuel elements made up of nine U-7Mo LEU fuel plates. Because the new core design contains twice the amount of uranium-235 as does the existing HEU core and produces significantly more plutonium, its fuel cycle length is twice as long at the same power level. Preliminary thermal-hydraulic and neutronic safety evaluations indicate superior performance to the current HEU fuel.

Enhanced Performance of Nuclear Power Plants

Lessons from the US Application of Risk Methods in Plant Operations

Professors Kadak and Hansen and their students completed their analysis of the impact of risk-informed regulation in the United States for the Tokyo Electric Power Company. Professor Kadak presented the results of their findings at a special meeting of Japan's Nuclear Safety Commission, to members of their regulatory staff, and to top management at TEPCO. The study was well received, supporting the use of more risk-informed treatment of regulatory requirements. Recently the Japanese regulatory authorities supported such a shift in their regulatory policy.

The Effect of Thermal Aging Properties on Stainless Steel Weld Metals

The program supervised by Professor Ballinger to evaluate the effect of long-term aging on environmentally assisted crack growth behavior of type 316L and 308L weld metals with varying ferrite content has continued. Low temperature aging, in the temperature range 300–400° C, can result in a spinodal decomposition reaction that is known to reduce weld toughness. However, there is little known about the effect of this reaction on the growth of stress corrosion cracks in high-temperature aqueous environments. This project will explore the aging and subsequent crack growth behavior in detail.

Proper sections of nuclear grade welds have been prepared by the Electric Power Research Institute and shipped to MIT. The weld samples are undergoing testing. This program is funded by TEPCO.

Assessment of the US Nuclear Fleet Outage Performance

Professor Todreas has analyzed nuclear plant outage data to identify outage duration trends and ways plants can improve their outage duration performance. While it was recognized that successful outage performance includes many factors, outage duration is judged significant enough to warrant this focused study. Performance achievement—particularly performance consistency from cycle to cycle—was analyzed by assessing the trajectory in planned and unplanned capacity loss space of each operating cycle of every plant in the United States. While the US nuclear fleet has made significant improvements in outage duration performance since 1990 overall, the best overall performance was achieved between 2001 and 2002. It is suggested that managers initially focus on enhancing equipment reliability and human performance and then try to reduce planned outage time through disciplined scheduling and efficient shutdown work. The outage data demonstrates the success of this strategy, as plants that were able to achieve high and consistent performance in recent years usually first reduced their unplanned outage rate before reducing the planned outage rate.

Nuclear Energy and Sustainability

Nuclear Energy for Hydrogen and Synthetic Fuel Production

Hydrogen production and manufactured transportation fuel development have become a national priority. The department is uniquely positioned to participate in this exciting new area due to the experience it has in gas-cooled reactor design and analysis. Professor Kazimi and a postdoctoral associate evaluated the nuclear capacity needed to generate synthetic ethanol and methanol from captured CO_2 gases from coal plants. They used the energy efficiency for hydrogen production based on applying a modified medium temperature gas cooled reactor and the electrolysis of high temperature steam. One of the main conclusions is that it is possible to cover the needs of the United States with capturing about 40 to 45 percent of CO_2 from coal power plants. However, this will require some 800 to 1,200 gigawatts thermal (GWth) of nuclear power. Total US CO_2 emissions would be reduced by nearly 20 percent if this energy scheme is used.

Self-Catalytic Materials for Thermochemical Hydrogen Production

Professor Ballinger is working on the development of structural materials that are also catalytic for the decomposition of sulphur trioxide (SO_3) to sulphur dioxide (SO_2). This reaction is key to the production of hydrogen using the high-temperature sulfur-iodine process. These new materials will be capable of very high temperature operation and of being chemical catalysts at the same time. Success in the development effort would allow combining the heat exchange and decomposition process into a single chemical reactor unit. Initial results with platinum content of a few percent indicate that the program will be successful.

Nuclear Technology and Canadian Oil Sands

As part of NSE's 22.033 Nuclear Systems Design Project, Professor Kadak's class chose to study the use of nuclear energy for electricity production and process heat to replace the use of CO_2–emitting fossil fuels to extract oil from Canadian tar sands. The extraction of oil from tar sands is expanding and ultimately could represent a significant resource of oil second only to Saudi Arabia. Unfortunately, the extraction process is heavily dependent on burning of fossil fuels. The challenge was to develop nuclear alternatives to supply the energy needs. Several nuclear plant designs and applications were reviewed, from simple steam production to electricity and hydrogen. Simplified economic analyses were performed that suggested nuclear energy was not only feasible and cleaner but also much more economical than the use of natural gas for heat and power. A report summarizing the results of the analysis was prepared, and two students presented a paper at the annual American Nuclear Society meeting in June 2006. This project has led to many inquiries to the department about future opportunities in heavy oil industry and oil sands development.

Nuclear Reactors for Space Application

While NASA is restructuring its future space missions to replace the aging shuttle fleet, work in the department continues to look to deep manned space missions. Driven largely by undergraduate interest, several undergraduate research opportunity projects have started with Professor Kadak to explore nuclear thermal rockets: specifically, the impact of exhaust plumes on astronaut radiation dose, the use of radioisotope thermoelectric generators or heat sources to regenerate fuel cells for rovers on the moon, and a continued study of thermionic systems proposed by MIT's previous design of a lunar nuclear power station. Some undergraduates have been invited to participate in a review of INL's space studies program this August.

Nuclear Science and Technology

Quantum Information Processing

Professor Cory and his students continue to explore magnetic resonance approaches to quantum information processing (QIP) through collaborations with NSE faculty members Dr. Timothy F. Havel and Dr. Chandrasekhar Ramanathan, along with Department of Mechanical Engineering's Professor Seth Lloyd and Dr. Raymond Laflamme and Dr. J. Emerson of the University of Waterloo. Our recent accomplishments focus on developments leading to fault-tolerant computation. In particular, we have developed efficient means of bounding errors based on the return of quantum states under brief periods of time-reversed dynamics. By averaging the quantum paths during these brief intervals over random states in the Hilbert space, we force the probability of return to be an accurate and efficiently measurable estimate of the error strength. We have shown that we can tailor such measurements to report on the strengths of different types of errors. Knowledge of the error types and strengths permit the design of logical encodings that may eventually reach the fault-tolerant threshold necessary for quantum computation. In related work, we have explored the resources necessary to control logically encoded quantum information, and we have experimentally demonstrated high-fidelity control over multilogical qubits.

We have just initiated a new set of experiments on coherent spintronics where the electron spin plays an essential role in control of the nuclear spin–based qubits. These are solid-state experiments with eventual implementations imagined in Si or in quantum dots. The nuclear/electron spin system is quantized such that the electron Zeeman interaction dominates, with the second leading term being the electron/nuclear hyperfine coupling. When we orient the sample such that the asymmetric part of the hyperfine interaction is stronger than the nuclear Zeeman term, then we can achieve universal control over the full Hilbert space while only applying microwave radiation at any one electron spin transition. This permits quantum information processing where the nuclear spins are the qubits and the electron spin is a quantum channel used to control the qubits. The benefits are increase in the clock speed and long decoherence times for the qubits.

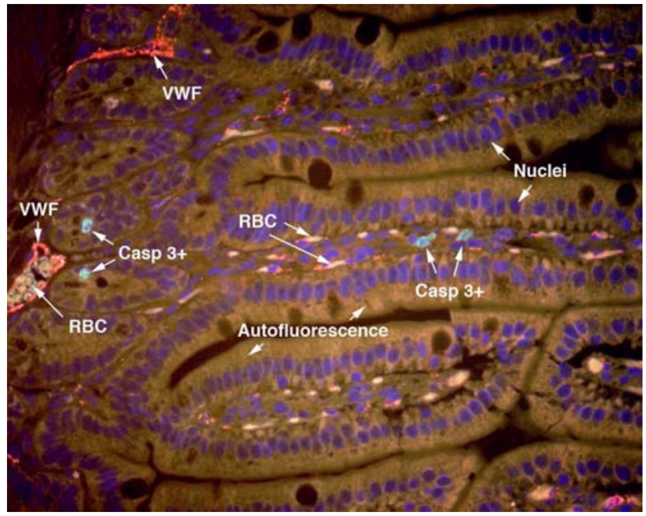
Coherent Imaging via Neutron Interferometry

In collaboration with the National Institute of Standards and Technology (NIST), we have demonstrated a reciprocal space approach to coherent imaging via a three-blade neutron interferometer. The new approach promises improved contrast and a resolution that is independent of the spatial resolution of the detector. This work has been extended to using a three-blade interferometer to create a neutron beam that is a coherent superposition of two beams separated by a controllable distance limited by the coherence length of the interferometer (about 500 angstroms in this case). This spatially separated coherent beam will enable a new class of coherent scattering and holds great promise for future neutron scattering studies in condensed matter. We are working to transition this into the first demonstration of coherent neutron scattering via neutron interferometry.

Neutron Capture Therapy

Neutron capture therapy for cancer research, directed by Professor Otto K. Harling, continued for the 20th year with support from DOE. The DOE's 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 Nuclear Reactor Laboratory (NRL) to researchers both within and outside MIT, has continued with increased activity. Thirteen 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 are principally focused 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 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 understand 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. 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. A new clinical protocol is being developed in collaboration with medical researchers at the Brigham and Women's Hospital for central nervous system metastases of melanoma. No good conventional treatment for this cancer is currently available. A suitable FDA–approved capture compound, boronated phenylalanine, which is known to concentrate in melanomas, would be used in this new clinical study of BNCT. 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.



[Figure 4] Fluorescence imaging of the mouse intestine

Mechanistic Radiation Biology

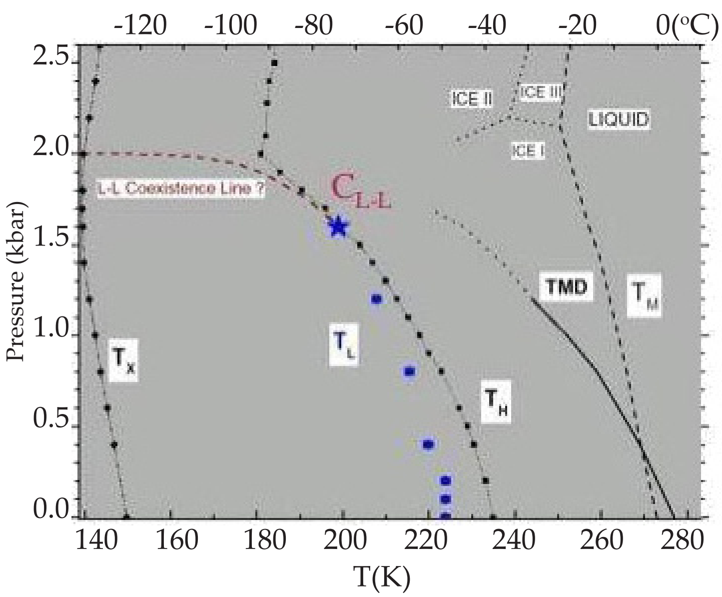
A new research initiative is under way, led by Professor Coderre. One of the major unresolved questions in radiation biology is, "What role does radiation damage to blood vessels play in the subsequent development of early or late side effects in normal tissues?" Professor Coderre has developed a novel method 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. In collaboration with Dr. Arlin Rogers of the MIT Division of Comparative Medicine, this group has shown that when using fluorescence microscopy to label specific cell types, the bright yellow autofluorescence from red blood cells (due to the combined emission of red and green wavelengths) could be misinterpreted as apoptosis (a specific type of cell death) if viewed through a standard green filter. By using a wide-pass filter to see all wavelengths, the autofluorescence is apparent and distinct from true apoptosis. Professor Coderre believes that misidentification of autofluorescing red blood cells as apoptotic blood vessel cell nuclei is the reason for some of the controversial reports in the literature. These studies could have significant implications for the development of agents to protect normal tissues during radiation therapy or to treat normal tissues after accidental radiation exposure.

Magnetic Resonance Imaging

Professor Jasanoff's research included two studies demonstrating properties of and refinements to a new family of magnetic resonance imaging calcium sensors, as well as completion of a study characterizing the evolution of brain responses to sensory stimulation in rodents during the first weeks of postnatal development.

Neutron Scattering

Pressure vs. Temperature Phase Diagram of H_20



[Figure 5] Phase diagram of water showing the location of the newly identified liquid-liquid critical point (star, C_{L-L})

Professor Chen and his group continue to use neutron and X-ray scattering techniques to investigate the structure-phase behavior relationship of soft condensed matter. Recently, quasielastic neutron scattering techniques have been used to study the dynamics and structure of water in the super-cooled state. By confining water inside nanopores so that it cannot freeze, Professor Chen and his colleagues have discovered a transition between two dynamic behaviors known as fragile and strong. In collaboration with Professor H. E. Stanley of Boston University, Professor Chen has, for the first time, experimentally verified the existence of a second liquid-liquid critical point of water. The neutron scattering work uses facilities located at various national laboratories, including the NIST Center for Neutron Research and the Intense Pulse Neutron Source at Argonne National Laboratory.

Atomistic Simulation of Materials

Professor Yip continues research in the theory and simulation of fundamental properties and behavior of materials. Contributions this year include extensions of the soliton theory of conducting polymers, mechanisms of thermal conduction in nanofluids, and defect cluster interactions in iron-based alloys. An emerging theme is predictive modeling and simulation of materials in extreme environments. Together with his former student and alumnus in the department, Ju Li, he organized a US Air Force Office of Scientific Research workshop highlighting the problem of oxidation resistance of ultrahigh-temperature ceramics.

Contraband Detection

The events of 9/11 have led to an increased interest in Dr. Richard C. Lanza's work on explosive and contraband detection. This has resulted in a significant expansion in funding for our work in neutron resonance radiography. In addition to support from the Technical Support Working Group, an interagency co-coordinating organization, we have continued a collaborative effort with L3 Communications to develop a system for the Transportation Security Agency for examination of air cargo. We continue as well our effort with the Lawrence Livermore National Laboratory in detection of potential radiological or nuclear weapons.

Dr. Richard Lanza was awarded a Deshpande Center Ignition Grant for the development of an innovative approach to low-cost medical imaging for developing countries.

Given today's costs, two-thirds of the world population will never be able to have an X-ray to diagnose life-threatening illnesses such as tuberculosis and prenatal internal hemorrhaging. This project will develop low-cost x-ray imaging systems, primarily for use in developing countries. In these countries, simple X-ray systems based on traditional film methods are not practical for two main reasons: the absence of a minimal support structure for processing film and the cost of film and storage facilities. A practical solution is an X-ray imaging system using off-the-shelf consumer digital imaging equipment, such as scanners and small personal computers. Among the next generation of inexpensive scanners are those capable of operating both horizontally and vertically, making them suitable for this application. Such scanners should be capable of resolution comparable to film and would enable digital storage and enhancement.

Neutron Resonance Radiography

[Figure 6] 3 MeV RFQ accelerator installed at Bates with members of the team from NSE, Bates, and L-3 Communication. Left to right: R. Lanza (NSE), R. Milner (Bates), G. Chen (L-3), W. Franklin (Bates), D. Perticone (L-3), G. Kohse (NSE), B. Blackburn (NSE)

We have 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, and 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 to identify potential threats in an unambiguous manner. We have established a new dedicated facility 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.

Passive 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. 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 due to 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 deployment of passive detectors to permit remote detection of possible threats at sea. We have shown that we can make use of the long transit time of ships between ports to detect materials that would not be easily detected in the limited time characteristic of inspection at ports. A preliminary patent application has been filed for this. In collaboration with Lawrence Livermore National Laboratory, we are constructing a prototype system capable of detecting such materials. Berthold Horn of the Computer Science and Artificial Intelligence Laboratory and EECS is another collaborator.

Active Detection of Fissile Materials with Low-Energy Neutrons

We have been funded by the Homeland Security Advanced Research Project Agency to develop a new approach for the detection of fissile materials using low-energy (< 100 kilo-electron-volt) 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—the materials that are the constituents of nuclear weapons—will result in such high-energy neutrons, and thus the system has an unambiguous signature for fissile materials. As part of this we have developed an all-digital signal processing technique for liquid scintillators that enables us to reliably separate neutrons from gammas.

Neutron Phase Contrast Imaging

Phase contrast imaging is an imaging technique that uses the wave properties of neutrons to greatly increase spatial resolution and contrast in materials imaging. We have installed a beamline and detector system for implementing this technique at the MIT Nuclear Reactor Lab. Recently we have examined a new approach that can lead to phase tomographic imaging, which enables us to produce three-dimensional images of materials that cannot be distinguished by their density and absorption.

Medical Imaging

We have continued our work in coded aperture nuclear medicine imaging, a technique that provides simultaneously enhanced resolution and sensitivity as compared to conventional nuclear medicine imaging methods. We have extended this concept to a mathematically related approach, coded *source* imaging. This opens up the possibility of producing three-dimensional X-ray imaging with no moving parts. The range of applicability of this technique has not yet been established, but we believe it should prove important in diagnostic screening.

Fusion and Plasma Physics

Departmental research in fusion and plasma physics is carried out almost entirely through the Plasma Science and Fusion Center (PSFC), whose report to the president should be consulted for details of the research accomplishments. NSE graduate students make up 30 of a total of 68 at the PSFC. Professor Hutchinson is coprincipal investigator of the Alcator C-Mod Tokamak Project, one of three major national facilities for fusion research in the United States. It was funded at the level of $19,237 in FY2006. Professor Ron Parker leads the lower hybrid experiment team on Alcator. Professor Freidberg is associate director of the PSFC.

Here we give just a few illustrative examples of research involving NSE students and faculty.

Current Drive Experiments in Alcator C-Mod

The classical tokamak operates by transformer action: the toroidal plasma current is induced by a transformer located in the central hole of the plasma torus. The plasma forms the one-turn secondary of the transformer and the pulse length is then limited by the time during which the primary can sustain a continuously increasing flux. An outstanding problem in extrapolating the tokamak configuration to a fusion reactor is developing steady-state operating scenarios that do not rely on this inductive mechanism to sustain the toroidal current. This problem is being addressed in Alcator C-Mod by coupling radio-frequency (RF) waves into C-Mod plasmas. The waves are caused to propagate preferentially in one direction, much in the same way that phased array radars steer their beam, and interaction with the plasma electrons generates a toroidal current. In combination with the so-called bootstrap current—a current self-generated in the plasma due to its pressure gradient—fully noninductive sustainment of plasmas produced in Alcator C-Mod becomes possible. In the past year, the first indications of RF current drive in Alcator C-Mod were achieved, as about 200 kA (out of a total of 700 kA) of plasma current was driven by roughly 0.5 MW of RF power radiated into C-Mod plasmas at a frequency of 4.6 GHz. The waves are launched by four waveguide arrays, each composed of 24 rectangular waveguides stacked in the direction of C-Mod's toroidal magnetic field and current. By varying the phase of the waves in the individual waveguides, the deposition of RF energy in the plasma as well as the energy of the electrons forming the current can be controlled. Information concerning the energetic electron population is gathered with an X-ray spectrometer that images photons emitted by the energetic electrons in the range 30–200 keV. This instrument was designed and built by student John Liptac, and the results formed the basis for his PhD thesis completed during the past year. The group responsible for carrying out RF current drive research in Alcator C-Mod is led by Professor Parker and currently includes students Greg Wallace and Andrea Schmidt (Department of Physics).

Energetic Particle Measurements and Interpretation

Alcator C-Mod plasmas are heated by the injection of several MW of RF power at the ion gyrofrequency, 80 MHz for protons at a magnetic field of 5.4 T. The protons are typically a small minority (approximately 5 percent) in a predominantly deuterium plasma and they are accelerated to energies of several hundred keV, well in excess of the bulk ion temperature, which is a few keV. Knowledge of the distribution of the protons in energy, as well as spatial localization in the plasma, is important to the understanding of the heating process and as a test of the validity of numerical models. For this purpose, a new diagnostic has been developed. The principle is based on the detection of hydrogen atoms that escape from the plasma after they are neutralized during collision events with hydrogen-like ions or atoms. The diagnostic consists of an imaging array of surface barrier diodes. When struck by a hydrogen atom, the diode produces a pulse of charge proportional to the atom's energy; the distribution in energy of the incident flux of atoms can then be mapped to the distribution in energy of the confined protons. Using this technique, graduate student Vincent Tang and Professor Ron Parker have investigated the energy spectrum and spatial distribution of the energetic protons produced by the heating by RF waves at their gyrofrequency. Two surprising results emerged, one having to do with the importance of light impurities such as boron in the exchange reactions and the other the localization of the heating power away from the magnetic axis. The latter feature has been confirmed by an elaborate numerical model of the wave physics coupled with a self-consistent Fokker-Planck calculation of the proton distribution function in the presence of RF fields. The results will form the basis of Tang's PhD thesis now in preparation.

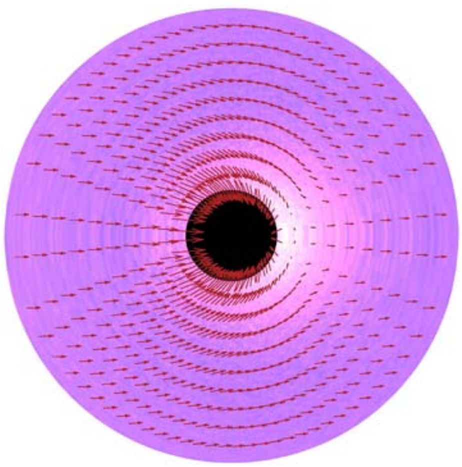
Measuring Radiation Losses from Tokamak Alcator C-Mod

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. Steve 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. But 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



[Figure 7] Computational model of the full ion distribution as a plasma flows past a collecting sphere

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 these 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

Chris Handwerk received the Manson Benedict Fellowship for excellence in academic performance and professional promise in nuclear engineering.

Tyler Ellis and Katherine Hohnhold received Outstanding Student Service awards for exceptional service to the department.

Michael Stawicki (for 22.101 Applied Nuclear Physics and 22.06 Engineering of Nuclear Systems) and Mark Visosky (for assisting fission faculty in teaching) received Outstanding TA awards for exceptional contributions as teaching assistants in the department.

Ashly Finan received the Roy Axford Award for academic achievement by a senior in NSE.

Jennifer Choy received the Irving Kaplan Award for academic achievement by a junior in NSE.

Whitney Lyke Raas was recipient of 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.

Tyler Shawn Ellis was recipient of an ANS John R. Lamarsh Memorial Scholarship Award for a student of nuclear science and engineering recognized for outstanding efforts and academic achievements in pursuit of a college education.

Graduate student Vered Anzenberg was awarded a Nuclear Engineering and Health Physics Fellowship by the US Department of Energy.

Ian H. Hutchinson
Department Head
Professor of Nuclear Engineering

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