Department of Nuclear Engineering

The MIT Nuclear Engineering Department (NED) is the premier US department in its field both by size of graduate program and by the assessment of our peers surveyed by *U.S. News and World Report.* This consistent number-one ranking over many years reflects the high quality of scholarship by the department's faculty and students.

The department has developed a new strategic plan this year. The plan, which will be available shortly at http://web.mit.edu/ned/www/strategicplan.pdf, highlights the new opportunities opening up as we see the beginnings of a renaissance in nuclear power in the United States, as fusion plasma physics moves forward in the international arena and as the broader nuclear science and technology applications are developed. The plan reaffirms the department's mission: "To educate future leaders in the science and engineering of nuclear and radiation systems; to advance and to teach the core intellectual disciplines of nuclear science and engineering; to create, develop, and apply new technologies that spring from those disciplines; and to inform public debate on the wise use of nuclear technology." The department intends to change its name to Nuclear Science and Engineering, to reflect the breadth of our field and standard usage within it, as soon as the administrative approvals can be obtained.

A major challenge identified in the plan is the need for renewal of our faculty. As the professors who have led the field for decades reach retirement, it is critical for MIT to recruit new talent that will tackle the research challenges of the coming decade and educate a new generation of nuclear engineers. Our first new fission faculty member for seven years joined the department in June 2004. We need to hire in addition at least one new professor per year for the next five years just to maintain our faculty numbers. The Visiting Committee at their meeting in December called for administration leadership and flexibility in pursuing the department faculty renewal. The present moment is a strategic turning point for the department. Institutional commitment to renewal in terms of faculty slots is essential; without them, the department will not be able to sustain its excellence.

Research has grown by a remarkable 20 percent in volume this year, and undergraduate enrollment again reached a new historic high.

The department and the Institute have entered into an agreement with Battelle Memorial Institute and others to form a team to bid for the management contract of the new Idaho National Laboratory, which is proposed to become the national center for nuclear power research and development. If we are successful, this will bring increased strength and influence to the fission research program as well as resources to strengthen nuclear teaching and to help support research at the nuclear reactor.

In April the department hosted the David J. Rose lecture by Dr. Richard Meserve, president of the Carnegie Institution. He spoke on "Nuclear Power in an Age of Terrorism." Also in April, the department held a symposium, organized by Professor Apostolakis, to honor Professor Norman C. Rasmussen, a distinguished department professor, who passed away in fall 2003. It was entitled “PRA and Decision Making: Successes and Challenges 30 years after the Rasmussen Study.”

Gifts to the department are on the rise. Our donations to principal, discounting the Tokyo Electric Power Company (TEPCO) chair payment in FY2003, increased from an annual amount of $84K to $217K. Our alumni and friends continue to increase their generosity.

Undergraduate Program

The Nuclear Engineering 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 aggressive 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. This year, 21 freshman selected NED. There were 18 last year.

Thirty-six students were enrolled in the undergraduate program during the past year. This included 17 sophomores, 12 juniors, and 7 seniors. Four students completed requirements for the bachelor’s degree in nuclear engineering.

Professor Freidberg helped organized a new freshman subject 22.001J Colossal Failures in Engineering, which received funding from the dean’s competitive curriculum development fund. The aim is to get new MIT students interested in a career in engineering. Professor Kadak taught the subject; participants from other departments included Tom Eagar (Department of Materials Science and Engineering and Engineering Systems Division), Oral Buyukozturk (Civil and Environmental Engineering) and Bill Haas (Humanities, Arts, and Social Sciences).

Professor Yip is continuing to lead the undergraduate subject on 22.00J Introduction to Modeling and Simulations, taught this year by 13 faculty members from seven departments across the Institute.

Graduate Program

The graduate program totaled 112 students during the fall term. Of this number, 28 were enrolled for their first term, 42% are working in fission and energy studies, 36% are specializing in radiation science and technology, and 22% in fusion. The department awarded 21 science masters, 2 nuclear engineering masters, and 12 doctoral degrees during the academic year.

Professor Kazimi was part of the team of faculty that offered a new course on advanced energy conversion technology in the spring term. The course was jointly offered with the departments of Mechanical, Chemical, and Materials Engineering. Over 30 students registered for the course, 20 percent of whom were seniors and the rest graduate students.

Professor Yip has introduced a new core subject in the department, 22.106 Neutron Interactions.

Faculty Awards, Honors, and Activities

Professor George Apostolakis gave the keynote speech at the OECD Workshop on Management of Uncertainty in Safety Cases in Stockholm, Sweden, on February 2, 2004. The title of his speech was "Risk in Technical and Scientific Studies: General Introduction to Uncertainty Management and the Concept of Risk." He was invited to speak at the Atoms for Peace—After 50 Years meeting in Saclay, France (July 22–24, 2003) and the Living with Risk Workshop in London, July 17–18, 2003. He gave a lecture entitled "Application of Quantitative Risk Assessment Methodology to Infrastructures and the Terrorism Threat" at the ASME Critical Assets Protection Initiatives Workshop in Washington, DC (February 12, 2004). He was invited to give a seminar at the National Center for Digital Government of Harvard University (March 1, 2004). Dr. Apostolakis was appointed chairman of the NASA Independent Peer Review Panel of the Space Shuttle Probabilistic Risk Assessment. 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 journal *Reliability Engineering and System Safety.*

Professor Sow-Hsin Chen was an invited lecturer on "attractive glass" state at the Enrico Fermi International Physics Summer School in Varenna, Italy.

Professor Jeffrey Coderre gave an invited lecture at the International Congress of Radiation Research BNCT Workshop, Brisbane, Australia, August 2003, entitled "The Radiation Biology of BNCT." He was the scientific program chairman at the 11th International Meeting of the International Society for Neutron Capture Therapy, October 2004, Boston MA. Professor Coderre was the guest editor of an issue of the journal *Applied Radiation and Isotopes* that will include peer-reviewed papers from the ISNCT-11 Congress.

Professor Jeffrey Freidberg stepped down as head of the Nuclear Engineering Department and was reappointed associate director of the MIT Plasma Science and Fusion Center. He served on the Fusion Energy Science Advisory Committee (FESAC), the Virtual Laboratory for Technology as chairman, member of the Burning Plasma Program Advisory Committee, and member of the FESAC subcommittee to evaluate the status of the US inertial fusion energy program. He was also recently appointed vice chairman of FESAC.

Professor Michael Golay serves on the US Department of Energy's Expert Group on Proliferation Resistance Evaluation Methods and contributes to development of probabilistic methods for evaluation of the relative strengths of different reactor/fuel cycle concepts to prevention of nuclear weapons.

Professor Otto Harling was made a fellow of the American Nuclear Society.

Professor Linn Hobbs was elected to the Board of Directors of the American Ceramic Society and was an American Society for Metals educational symposium invited lecturer in April 2004 at Oak Ridge National Laboratory. He organized the first Engineering Conferences International Symposium on Alternative Nuclear Waste Forms in January 2004 in Alyeska, AK. He continues to teach in the NSF–sponsored MIT Summer Institute on the materials science of material culture. Professor Hobbs served for a second year as chair of the faculty Committee on Nominations and continues to coordinate student applications to major postgraduate scholarships programs abroad as chair of the presidential Committee on Foreign Scholarships.

Professor Ian Hutchinson gave an invited presentation at the American Physical Society's annual Division of Plasma Physics meeting entitled "Ion Flux to a Sphere in a Collisionless Flowing Plasma: A Surprising Solution to a 40-Year-Old Basic Plasma Physics Challenge." He was also selected to present a talk entitled "Spin Stability of Dust in a Flowing Plasma" at the European Physical Society's Plasma Physics meeting at Imperial College, London. He presented the Templeton Lectures at Baylor University entitled "Warfare and Wedlock; Life in Science and Faith." He continues to serve as editor in chief of the journal *Plasma Physics and Controlled Fusion.*

Professor Mujid Kazimi was appointed as a joint faculty with the Department of Mechanical Engineering. In 2004, he served as an expert member of the Search Board to fill the nuclear safety chair at the Royal Institute of Technology in Stockholm, Sweden. He was a member of the panel on the hydrogen economy of the National Academy of Engineering, which released its report in January 2004. He has served as a member of the Steering Committee of the International Congress on Advanced Nuclear Power Plants (ICAPP) held in Pittsburgh in 2004 and is the US general chair for the ICAPP 2005 to be held in Seoul. Professor Kazimi gave plenary talks at two international meetings during the last year: Nuclear Engineering Thermal Hydraulics in Seoul in September 2003 and the Pacific Basin Nuclear Energy Congress in Honolulu in April 2004. He was also a speaker at the annual dinner of the Sigma Xi Chapter in Albuquerque in May and at the 5th Annual MIT Arab Alumni Meeting in Tunis in June.

Dr. Lanza and his former students have received two patents covering novel imaging and detection methods: G. Chen and R. C. Lanza, "Fast Neutron Resonance Radiography for Elemental Mapping," US Patent 6,693,281, February 17, 2004; and R. C. Lanza, R. Accorsi, and F. Gasparini, "Coded Aperture Imaging", US Patent 6,737,652, May 18, 2004.

Professor Richard Lester participated as a member of the interdisciplinary research group that produced the *MIT Report on the Future of Nuclear Power,* published in summer 2003. Professor Lester's new textbook, coauthored with Professor John M. Deutch, *Making Technology Work: Applications in Energy and the Environment,* was published last fall. Professor Lester continues to serve as director of the MIT Industrial Performance Center.

Professor Kim Molvig received the Joel and Ruth Spira Teaching Award for Distinguished Teaching. This award acknowledges the tradition of high-quality engineering education at MIT.

Professor Todreas was elected to membership in the International Nuclear Energy Academy. He gave invited lectures at the Idaho National Environment and Engineering Laboratory Seminar Series, the World Association of Nuclear Operators Biannual General Meeting in Berlin, the Bettis Atomic Power Laboratory, and the Global 2003 Nuclear Fuel Cycle Conference in New Orleans.

Professor Sidney Yip received the PAI Outstanding Teaching Award (awarded by the student chapter of the American Nuclear Society). Professor Yip continues active research in materials simulation at the chem-bio-nano interface, with invited talks overseas (Prague, Osaka, Yokohama, Munich, and Shanghai) and in the United States during the past year. He is the editor of the first volume of the *Handbook of Materials Modeling,* the first large-scale reference work in the field, to be published by Kluwer-Springer early next year.

Research

Research Funding

New research grants were received from Massachusetts General Hospital, TEPCO, Toshiba, Honda R&D, the Electric Power Research Institute (EPRI), the Cambridge–MIT Institute, and the Department of Energy (DOE) both directly and through various national laboratories. We continued to receive research support from the Nuclear Regulatory Commission and various agencies of the Department of Defense. We continued our strong relationship with TEPCO with two new research contracts awarded worth $480,000. Note that the TEPCO chair, held by Professor Kazimi, reached its fully funded status last fiscal year.

Our primary research volume (research expenditures specifically handled through the NED offices, rather than through a related lab or center) reached $6.9M, up from $4.9M in FY2003. Of this, the DOE accounts for about $2.5M directly and indirectly, which is about even with FY2003. Our most significant increase is in funds received from the Department of Defense, which went from $470K to $967K, thanks in part to Dr. Richard Lanza's research on neutron imaging for the Department of Homeland Security (contracts were awarded through the US Army previously). The Nuclear Regulatory Comission (NRC), too, doubled its investment in NED's research, going from around $300K in FY2003 to around $600K in FY2004, much of which went to Professor George Apostolakis for a new research project.

Fission: The Center for Advanced Nuclear Energy Systems

The research efforts of the Center for Advanced Nuclear Energy Systems (CANES) were organized into four programs:

1. Advanced Reactor Technology
2. Nuclear Fuel Cycle Technology and Economics
3. Enhanced Performance of Nuclear Power Plants
4. Nuclear Energy and Sustainability

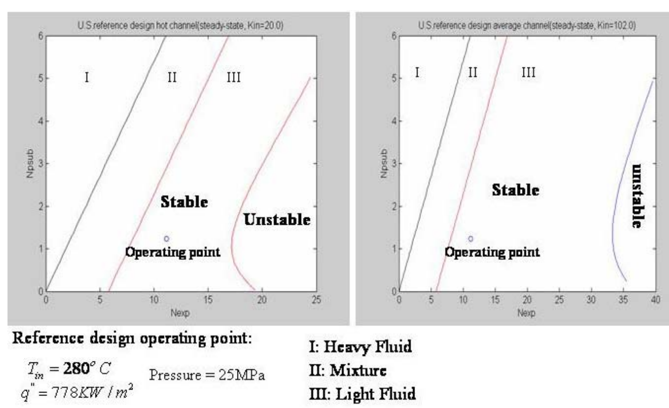
The research program continued to cover a range of advanced reactor designs and advanced fuel cycles. These will be summarized below. One of the notable accomplishments this year is the use of the MIT Research Reactor (MITR) for the first time to test nuclear fuel performance. The fuel being tested is a new design that aims at increasing the PWR power density by 50 percent. The project, supervised by Professor Mujid Kazimi, Dr. Pavel Hejzlar, and Dr. Gordon Kohse, is funded by the DOE Nuclear Energy Research Initiative (NERI) program. Another in-core test was performed under the supervision of Professor Ronald Ballinger and aimed at a better understanding of the factors affecting boiling water reactor (BWR) cladding corrosion in the presence of noble metals. This project is funded by EPRI.

A two-day symposium on Nuclear Energy and the Hydrogen Economy was conducted in September 2003 at the Tang Auditorium. The symposium was organized by Professor Kazimi and Dr. Walter Kato and was attended by 70 people. In June Professor Apostolakis directed the one-week course on Risk Informed Operations of Nuclear Power Plants. Also in June, Professor Golay organized the 12th session of the four-week Reactor Technology Course for utility executives.

Advanced Reactor Technology

Advanced Light Water Reactors

Professor Todreas was 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 the University of California–Berkeley and Westinghouse sponsored by the DOE's Nuclear Energy Research Initiative Program. Since these hydride fuels contain the moderating hydrogen atoms at concentrations comparable to that of liquid water, they can lead to higher total power in the same volume relative to a light water reactor (LWR) core fueled with uranium



Stability boundary for supercritical water-cooled reactor. Left, hot assembly; right, average assembly. Note that the hot channel requires a lower inlet restriction coefficient, kin.

dioxide. Professor Kazimi and Dr. Pradip Saha received funding from the Idaho National Engineering and Environmental Laboratory (INEEL) for their studies of the stability of supercritical water-cooled reactors. While such reactors can achieve high power-cycle efficiency since they operate at pressures of 25MPa and temperatures of up to 550°C, the density change across the core potentially gives rise to density wave oscillations. The project developed a map that delineates the boundary between the stable and unstable regimes using nondimensional numbers.

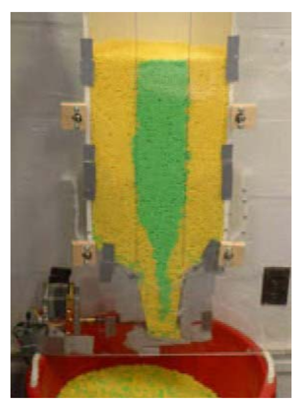
Advanced Gas-Cooled Modular Pebble Bed Reactors

Work continues on the development of the modular pebble bed reactor. Professor Ballinger continued his work on microsphere fuel performance modeling. Professor Kadak worked on two areas: safety analysis, using a state-of-the-art computational fluid dynamics code incorporating complex chemistry to study graphite corrosion; and advanced modularity techniques to revolutionize how nuclear plants are built to reduce construction time and cost and improve overall product quality. The first two projects are supported by the NRC and the third is supported by NERI.

The fuel performance modeling can be used to design and, working with a manufacturer, optimize the performance of new advanced fuel particles for use in high-temperature reactors. The air ingress accident is one of the most severe safety challenges to pebble bed reactors. Air ingress modeling has been benchmarked against tests and will ultimately be used to understand the details of the chemical reactions under accident conditions in a full-sized pebble bed or prismatic high temperature reactor.

The MIT Nuclear Engineering Department also received formal approval of a nuclear technology exchange on pebble bed reactors with Tsinghua University in Beijing, China. Professor Kadak has proposed a formal program for the first such collaboration on fuel performance using the MIT Reactor. This proposal has been accepted by the Tsinghua University. They have agreed to supply MIT with a fueled pebble for testing.

Additionally, the pebble bed project continues to experiment with pebble flow in the reactor. Professor Kadak, with the assistance of a UROP student, confirmed that the central reflector column of graphite pebbles can remain intact using his slow flow experiment. Additional collaboration with mathematics professor Martin Bazant has proposed developing a bidiverse flow using smaller graphite pebbles to reduce bypass flow in the reactor. A new NERI proposal has been submitted to support continuing research in this area.



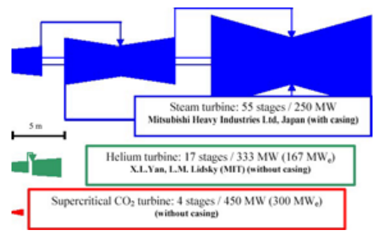
Flow experiment showing that an annular reflector maintains its configuration without internal structure; the upper shaping ring created the central column (ring not shown).

MIT is collaborating with Brayton Energy and the University of Massachusetts–Lowell in the design of the intermediate heat exchanger for high-temperature gas reactors. Using the technology of recuperators for Brayton cycles, the intermediate heat exchanger is a critical component necessary to enable thermochemical or thermally enhanced hydrogen production.

Advanced Lead-Bismuth Cooled Reactors

Professor Todreas and Dr. Hejzlar, in collaboration with INEEL, organized a special issue of *Nuclear Technology* on the design studies of a large power rating lead-bismuth eutectic cooled fast spectrum reactor aimed at both low electricity production cost and actinide destruction being. Professor Ballinger continued his experimental program on the corrosion of various steels in contact with lead-bismuth. The results show that the inclusion of silicon in the steel greatly reduces the corrosion in the temperature range of 450 to 650°C.

Gas-Cooled Fast Reactor



Comparison of turbine sizes for steam, helium, and supercritical CO2 power cycles.

Fast gas-cooled reactors provide the combined advantage of much higher fuel utilization and also higher thermal power conversion efficiency than current commercial reactors. Early work under Professor M. Driscoll and Dr. P. Hejzlar led to the successful proposal to include this concept in the DOE list of preferred future GEN IV reactors. The department currently has four separate but coordinated research projects dealing with gas-cooled fast reactor development. The principal areas of work encompass a wide scope of concept development: design of a supercritical CO_2 Brayton power cycle, which achieves high (~45 percent) thermodynamic efficiency at modest core outlet temperatures (550˚C) and has very compact turbomachinery, as shown in the figure; PRA–guided design of key reactor plant systems—the post-accident decay heat removal system in particular—for which thermal-hydraulic design is also a project focal point; and, finally, core reactor physics design. The effort includes optimization of neutronics to, among other goals, minimize coolant void reactivity and to prove-out the practicality of “breed and burn” operation in which high uranium utilization is achieved without the requirement of fuel reprocessing.

A new project, supported by INEEL, involving fundamental studies of forced, mixed, and natural convection heat transfer applicable to advanced gas-cooled reactor safety has been initiated under the supervision of Dr. Pavel Hejzlar and Dr. Pradip Saha. A test facility is being built to conduct experiments in a heated vertical round tube at pressures up to 1.0 MPa using three different gases (helium, nitrogen and carbon dioxide). The goal is to determine heat transfer regime boundaries among forced, mixed, and natural convection and develop smooth heat transfer correlations suitable for incorporation into integral reactor safety codes. Effects of buoyancy and fluid property variation on heat transfer will be studied from local velocity and temperature measurements and using computational fluid dynamics codes.

High Efficiency Annular Fuel for Light Water Reactors

The use of annular fuel instead of the conventional solid cylindrical fuel in LWRs has been under investigation by Professor Kazimi and Dr. Pavel Hejzlar. The internally and externally cooled fuel increases the fuel heat transfer surface-to-volume ratio, thus leading to significantly lower fuel temperatures. A DOE–supported project aims at investigating the ability to raise the power extracted from the core while maintaining or improving thermal margins in pressurized water reactors. TEPCO has initiated support for an examination of the use of the annular fuel in BWRs. Fuel manufacturing techniques are being investigated with industrial collaborators Gamma Engineering and Westinghouse. Several fuel samples have been manufactured by vibrational packing at Atomic Energy of Canada. Two of the samples were used for irradiation testing using the MITR. The samples will be examined in the following year to determine the impact of the manufacturing technique on the fuel performance.

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 open fuel cycles regarding benefits of spent fuel management and proliferation resistance.

Lessons from the US Improved Plant Performance

Professors Kadak and Hansen and their students analyzed the reasons for the improvement in the performance of nuclear power plants in the United States. The impact of risk-informing the regulatory requirements for maintenance and proper planning for refueling outages emerged as the major reasons for plant performance improvement. The project was supported by TEPCO and is continuing to define in depth the industry and regulatory views of the lessons learned from risk-informing the regulations for operation of existing plants.

Corrosion Control in BWRs using Noble Metals

Professor Ballinger investigated the effects of water chemistry on BWR fuel cladding corrosion in the presence of noble metals. This program was supported by EPRI and General Electric and utilized the MITR for irradiation under proper conditions of representative cladding materials.

Nuclear Safety Regulation of Severe External Events

In work concluded during 2004, alternative regulatory treatments of severe external events affecting nuclear power plants were investigated for the example of earthquakes by Professor Golay and his students, with support from TEPCO. In comparing direct and nuclear power plant–related risks, it was seen that requiring nuclear risks to be small relative to direct risks provides a practical basis for formulating regulations for nuclear power plants affected by severe external events (e.g., terrorist attacks such as those of 9/11/01). For earthquakes, it was seen that nuclear fatality risks were smaller than corresponding direct risks by factors ranging from 10^{-3} to 10^{-7}.

Reliability of Nuclear Safety-Related Software

In work concluded during 2004, a method was formulated by Professor Golay, based upon Bayesian updating of testing results, for quantification of the reliability of simple nuclear safety-related software. This work relies upon being able to test most of the software's executable modes (hence its restriction to simple software) and estimation of a value of the software's reliability that can be used in probabilistic risk assessments in a fashion similar to that of hardware reliability.

Assessment of Terrorist Aircraft Crash on a Nuclear Plant Site

Under the direction of Professor Kadak, a freshman UROP student in nuclear engineering undertook a study of the "Impact Assessment of a 747 Jet Aircraft Crash into a Nuclear Power Plant." This study focused not only on the impact of the crash vis-à-vis the containment of power reactors, it also assessed the consequential damage of debris and fire on important systems necessary to provide adequate core cooling and other safety functions.

Space Power Reactors: Mission to Mars Project

As part of the spring design project in the Nuclear Engineering Department in 2003, the challenge of developing nuclear power sources for the proposed manned mission to Mars was undertaken as a design course project under guidance of Professor Kadak. NASA has recognized that such a mission will require the use of nuclear reactors to provide the power for the electric propulsion ion or plasma engines as well as for the electricity needs of the Mars surface base. Several independent studies followed the work of the design course. The students in the course developed conceptual designs for two unique reactors for the propulsion system and the surface plant. For example, the Mars surface plant uses the carbon dioxide gas in the Martian environment as the coolant for the nuclear plant, saving the need to carry the mass to Mars. The nuclear power plant for the propulsion system uses constituents of used light water reactor fuel as the fuel source for the power plant. The work was performed in collaboration with the MIT Aeronautics and Astronautics Department.

Continuing research in this new area has focused on a new reactor design dubbed "SELENE" (for Sodium-cooled Epithermal Long-term Exploration Nuclear Engine), by Peter Yarsky, that eliminates launching a plutonium-fueled reactor and utilizes a power conversion system based on a sodium Rankine cycle. Contacts have been developed with both Naval Reactors, which is charged with the design of reactors for future space missions, and NASA.

Nuclear Energy for Hydrogen Production

High-temperature gas reactors have been selected by the Department of Energy as their high-priority technology for the next generation of nuclear plants. These plants are uniquely suited for thermochemical and thermoelectrical hydrogen production because of their high temperatures of operation. Hydrogen energy development has also 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. Professors Kazimi and postdoctoral associate Bilge Yildiz continued their study of the efficiency and economic potential of various reactor and chemical technologies for hydrogen production. They analyzed the sulfur hybrid process proposed by Westinghouse in which decomposition of sulfuric acid is followed by electrolysis of water and SO_2 mixture. Their preliminary conclusion is that the energy efficiency of this cycle is intermediate between the high-temperature steam electrolysis and the pure chemical decomposition of water using the sulfur-iodide cycle. In addition, the design project for spring 2004, with guidance from Professor Golay and Dr. Yildiz, concentrated on selection of an appropriate fast reactor and its operating conditions, as well as selection of the materials for the electrolyzer.

Nuclear Science and Technology

Neutron Scattering

Professor Sow-Hsin Chen and his graduate student Wei-Ren Chen have just discovered through neutron scattering experiments the existence of a new state of matter called the "attractive glass" state, in contrast to the commonly observed "repulsive glass" state, in a colloidal system with an extremely short range, interparticle attractive interaction. They reported in a recent issue of *Science* magazine the first determination of the glass-to-glass transition line and its end point in the phase diagram of this system.

Quantum Information Processing

Professor Cory and his students continue to explore nuclear magnetic resonance (NMR) approaches to quantum information processing through a set of collaborations with Dr. Timothy F. Havel (NED), Dr. C. Ramanathan (NED), Professor Seth Lloyd (Mechanical Engineering), Dr. Raymond Laflamme (University of Waterloo), Dr. J. Yepez (Air Force Research Laboratory). Over the last year, we have described the first potentially scalable approach to building a quantum computer based on nuclear magnetic resonance. The quantum computer is engineered in the solid state and relies on our recent advances in truncating the dipolar Hamiltonian to just nearest neighbors as well using quantum entanglement as a resource for more sensitive metrology.

In liquid-state NMR test beds of quantum computers, we have implemented the first 10+ qubit quantum processor and have shown the first quantum logic with qubits encoded against noise.

NMR of Hydrogen Storage

In collaboration with Professor Yip (NED), we have initiated NMR studies of hydrogen chemistry and dynamics in confined spaces (such as carbon nanotubes). These are prototype systems for hydrogen storage.

Coherent Imaging via Neutron Interferometry

In collaboration with the National Institute of Standards and Technology (NIST), we have implemented 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.

Neutron Capture Therapy Research

The new User Center for Neutron Capture Therapy, directed by Professor Harling, successfully completed its first year of operation. During this period, a number of users carried out small animal experiments designed to test the efficacy of new neutron capture compounds or to optimize the delivery of currently available compounds. The international dosimetry exchange has continued to progress and will soon allow dosimetry comparisons among all major clinical centers of boron neutron capture therapy (BNCT). A Li-6 filter was designed, constructed, and commissioned for use with the MIT epithermal neutron medical beam. This filter provides a small but significant additional, useful beam penetration and will be particularly important in future irradiations of brain cancer patients.

Boron Neutron Capture Therapy

The BNCT project focuses on measuring the sensitivity of the normal lung to the high-linear energy transfer radiations produced during BNCT. This project is also investigating the mechanisms by which radiation causes damage in the lung and will explore possible biochemical approaches to reduce these side effects. The methodology has been established to measure an increase in breathing rate in rats as the end point following whole lung irradiation. We have shown that the lung is not as sensitive to the radiations produced during BNCT as previously assumed. Our results indicate that the fatal lung complications observed in two patients treated with BNCT for brain tumors in the MIT reactor were most likely not due to the BNCT–related scattered radiation dose to the lung. Our lung data also indicate that it may be feasible to treat lung tumors with BNCT.

Basic Radiation Biology

A new research initiative is underway, led by Professor Coderre. The boron neutron reaction is being used as a tool to investigate the basic mechanisms of how radiation damages normal tissues. A high molecular weight boron compound has been prepared that will remain inside the blood vessels. The short path length of the radiations from the BNC reaction will irradiate the blood vessel walls but not the surrounding functional cells. This approach is unique in that it is the only way to address this major unresolved question in radiation biology of which cell type is responsible for radiation side effects in normal tissues—the blood vessel cells or the surrounding functional cells.

The effects of alpha particle radiation on DNA, on cell survival, and on the complex biological signaling pathways that exist within and between cells are under investigation. Alpha particle sources have been developed for irradiation of cells in culture and for studies on the “bystander effect,” a recently discovered phenomenon whereby nontargeted cells still experience DNA damage and death. Using a two-layer co-culture system whereby one layer of cells is exposed to the alpha particles and the second layer of cells is not irradiated but only co-cultured in the same growth medium, we have recently demonstrated significant levels of DNA damage in the *unirradiated* prostate tumor cells. This bystander effect is completely blocked by the addition of a radical scavenger into the cell culture medium. The model system will allow us to study the chemical signaling pathways involved in the bystander effect with the aim of manipulation of this pathway to increase the level of cell kill in tumor sites treated with alpha particle–labeled antibodies through synergistic effects with chemotherapy agents.

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 from the Technical Support Working Group, an interagency co-coordinating organization as well as a new effort with Lawrence Livermore 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

We have developed a new method for detecting materials, based on neutron resonance radiography. This technique is capable of good spatial resolution (~ 3 mm), penetration of heavy objects, and determination of elemental composition. Element-specific resonances in total neutron attenuation cross-sections, which are in the 1 to 8 MeV range, 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 are now taking data for this project using the 4 MeV LABA electrostatic accelerator of the department located in NW-13.

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 counteracting 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 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. 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 Electrical Engineering and Computer Science is another collaborator.

Large coded aperture for fissile material detection.

Neutron Phase Contrast Imaging

In collaboration with researchers at NIST, we are designing and constructing an imaging system that uses the wave properties of thermal neutrons to produce phase shift contrast images. This approach greatly enhances the contrast of small defects and features; initial estimates are that this technique may be as much as a factor of 1,000 times more sensitive than conventional radiography. We are presently evaluating detectors using a beamline at the MIT Nuclear Reactor Lab and are designing a special beam line specifically for this purpose.

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 expanded our group of collaborators, who now include researchers in the Center for Molecular Imaging Research at Massachusetts General Hospital, Beth Israel Deaconess Medical Center, Children's Hospital of Philadelphia, the University of Rome, and the University of Naples. Currently we are imaging small animals and a limited number of pediatric patients on an experimental basis. With National Institutes of Health funding through Children's Hospital, we are developing a Gamma Microscope that will be capable of imaging soft X-ray emitters with a spatial resolution of approximately 10 μm, which will for the first time permit the use of nuclear medicine techniques at the cellular level. With our colleagues in Naples, we have achieved spatial resolutions of below 0.1 mm using a new detector (Medipix) developed as part of a European collaborative effort. Using this with an MIT developed coded aperture, we have taken preliminary images of the thyroid of a mouse, typically about 2–3 mm long. With new three-dimensional reconstruction techniques developed in collaboration with Dr. John Idoine of Kenyon College, we have shown the ability to provide full three-dimensional images from a limited number of views as compared to conventional single photon emission computed tomography imaging, thereby considerably reducing dose to patients.

Radiation Damage, Nuclear Waste, and Isotope Batteries

Professor Hobbs continues to lead a research program on nuclear waste encapsulation in ceramic media, funded through the Cambridge–MIT Institute, that includes Professor

Yip and other investigators from NED, the Department of Materials Science & Engineering, and the Center for Materials Science & Engineering at MIT, the Department of Earth Sciences at the University of Cambridge, and British Nuclear Fuels, Ltd. The program is exploring the stability in the irradiation field of incorporated radionuclides of a variety of crystalline oxide ceramic solids (silicates; titanate perovskites; titanate, zirconate, and stannate pyrochlores) intended for alternative storage media for high-level nuclear waste and weapons-excess actinides. Two principal concerns are amorphization and phase separation into simpler suboxides. Monte Carlo and molecular dynamics modeling, using a parallel 32-processor Beowulf cluster at MIT and a similar cluster at Cambridge, are being used to simulate atom displacement cascades in these structures, while topological algorithms developed at MIT are being employed to analyze the resulting modeled disorder and to differentiate atoms that find themselves a part of point or extended defects configurations, atoms part of amorphous environments, and atoms whose local environment has not altered. Electron diffraction methods are being applied to characterize the topological changes in the structure of these ceramics experimentally amorphizing under ion or fast neutron irradiation.

Professors Hobbs and the Charles Stark Draper Laboratory are collaborating in a program to develop a miniaturized radioisotope battery providing direct conversion of radiation energy for space applications. The proposed device comprises a charge-collecting capacitor incorporating appropriate radioisotopes postactivated in the assembled device by thermal neutron irradiation. The radiation effects of activation (largely from the accompanying fast neutron flux) on the dielectric are being evaluated at MIT using the MIT Reactor as the neutron source, electrical measurements to monitor current leakage, and precision X-ray diffraction and electron microscopy to follow attendant microstructural changes.

Fusion

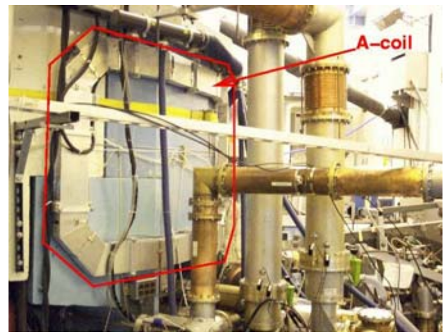
The Alcator C-Mod Experiment

The Alcator C-Mod tokamak is a major international fusion experimental facility and is recognized as one of three major US national fusion facilities. In order to assume his new position as nuclear engineering department head, Professor Ian Hutchinson stepped down in July 2003 from his 15-year direction of the C-Mod program. Professor Hutchinson led the completion of the design, construction, and the first 10 years of operation. He is succeeded by Dr. Earl Marmar, senior research scientist in the Department of Physics. Professor Hutchinson remains coprincipal investigator and very active in the research project. Professor Parker heads the Lower Hybrid upgrade part of the project. The C-Mod team has an MIT research staff of approximately 100 people total. This includes 6 faculty and senior academic staff, plus 24 graduate students, approximately half of whom are from the Nuclear Engineering Department. In addition, we have collaborators from around the world, bringing the total number of scientific users of the facility to about 165. The cooperative agreement with the Department of Energy, Office of Fusion Energy, for the C-Mod project was renewed effective November 1, 2003, for the next five-year period. Including major collaborators, total FY2004 funding for the project is $22.2M.

Research on C-Mod continued during the past year in high-performance, compact magnetic plasma confinement. Experiments this year were carried out in the science topical areas of transport, wave-plasma interactions, boundary physics and magneto-hydrodynamic stability, and in the integrated thrust areas of advanced-tokamak and burning plasma science. Facility operation for research during FY2004 was 18.5 weeks, up from 13 weeks in FY2002. The operations are largely constrained by funding. Current guidance funding for the project in FY2005 would allow for 14 weeks of planned research operation.

Highlights of recent research achievements include the following.

Alcator C-Mod this year obtained plasma currents up to 2MA for the first time. This extension was made possible, in part, by the operation of our new asymmetric control coils, which allow for nulling of the most important component of nonaxisymmetric fields.



One of the set of eight asymmetric correction coils (A-coils) installed on the Alcator C-Mod tokamak.

These coils also opened up an important research topic led by the designers, Professor Hutchinson and Dr. Stephen Wolfe. Error fields and associated locked modes can lead to confinement degradation and even major disruption. Particularly important for the International Thermonuclear Experimental Reactor (ITER) are the questions of field and size scaling of the locking threshold (in B_{error}/B_T). To investigate these issues, we have been carrying out coordinated experiments with DIII-D and JET. Initial results show that previous pessimistic scalings, developed from Compass/DIII-D/JET experiments, are not confirmed by the C-Mod. To the contrary, the sensitivity to error fields appears to be almost independent of size and shows a weak scaling with toroidal field. A unique capability of C-Mod is to extend these studies to the actual ITER fields and beyond.

Internal Transport Barrier (ITB) investigations were extended with use of high-power ion cyclotron resonant frequency (ICRF) operating at 2 frequencies, to give simultaneous on- and off-axis minority heating. The ITB is formed with off-axis heating, and then the particle peaking is arrested with the subsequent application of on-axis heating. Modeling with the GS2 gyrokinetic code indicates that it may be the growth of trapped electron modes that is responsible for the clamping of density buildup, leading to the possibility of steady-state. The on-axis heating also results in strong core temperature increases, leading to central plasma pressure approaching 4 atmospheres (400 kPa).

Studies on C-Mod to investigate the role of rotation and relation to the H-Mode threshold for various magnetic configurations (upper and lower single-null, double-null, and limited) have revealed the importance of scrape-off-layer flows. H-Mode thresholds were systematically explored for double-null discharges, upper- and lower-single-null discharges, and inner-wall limited discharges. In addition, a new 5th configuration, with the plasma limited near the bottom of the vessel on the inner-wall nose, has also been investigated. Inner-wall limited discharges have substantially higher H-Mode threshold than even the unfavorable upper-single-null configuration. The lower nose limited configuration has a threshold that is similar to the favorable lower single-null. Another important result of these studies is the extreme sensitivity of the double-null threshold to the proximity to exact double-null, as quantified by the difference in primary and secondary separatrix locations, mapped to the outboard midplane. Just a 1 or 2 mm change in this parameter can dramatically change the threshold. This sensitivity may explain previous reports of inconsistent double-null thresholds from other tokamaks. We are currently investigating the role of flows in the scrape-off layer that provide the boundary condition for core flows, which are driven by pressure gradients. The combination of drives and boundary conditions may provide a unifying picture for the sensitivities of the H-Mode threshold to magnetic configuration.

Mode conversion current drive experiments using off-axis ICRF show the ability to strongly influence the amplitude and frequency of the sawtooth relaxation oscillation. In C-Mod experiments done to date, application of about 1.5 MW of RF power, phased to drive current in the direction opposite to that of the main plasma current, increases the sawtooth period by a factor of almost 4. With increased power available in future experiments, it might be possible to stabilize the instability completely, which could be important for profile control and suppressing one of the main triggers for neoclassical tearing modes, which can limit pressure in both current experiments and in ITER.

Plasma Theory

Professor Freidberg's research involved working with students on the completion of a theoretical model for the plasma arc in the Plasmatron and understanding the MHD–driven anomalous transport in the Levitated Dipole Experiment.

Professor Molvig continued his research on the foundations of turbulent plasma transport.

Student Awards and Activities

A number of students were recognized at the annual international dinner/awards ceremony in May 2004.

The PAI Outstanding Teaching Award (presented by the student chapter of the American Nuclear Society) went to Professor Sidney Yip.

The Manson Benedict Fellowship, awarded to a graduate student for excellence in academic performance and professional promise in nuclear engineering, went to Paola Cappellaro, Milan, Italy; Lorenzo Pagani, Milan, Italy; and Peter Yarsky, Munhall, PA.

The Roy Axford Award for academic achievement by a senior in nuclear engineering was awarded to Alexandra Awai from Clovis, CA.

The Irving Kaplan Award for academic achievement by a junior in nuclear engineering went to Michael Stawicki from Bow, NH.

The Outstanding Student Service Award in recognition of exceptional services to the students, the department, and the entire MIT community was presented to Nuclear Engineering graduate student Ben Parks from Harbeson, DE.

The outstanding Teaching Assistant Award in recognition of exceptional services to education by a teaching assistant was presented to graduate students Jiyun Zhao from Shandong Province, China, and Brad Schuller from Sylvania, OH.

Other awards received during AY2004 include the following:

- Blandine Florence Laurenty received the 2004-2005 Dean of Engineering Fellowship in recognition of outstanding undergraduate record, exceptional background, and promising future.
- Mark Haig Khachturian received the 2004-2005 ANS Graduate Scholarship Award for a student entering the field of nuclear science and engineering.
- Juliet Leigh Outten and Mark Haig Khachaturian received the American Nuclear Society Graduate scholarship award. This award is for a student of nuclear science and engineering recognized for outstanding efforts and academic achievements in pursuit of a college education.
- Rong Wang, a 4th-year graduate student, received the Hugh Hampton Young Memorial Fund Fellowship. Rong is working on the alpha particle bystander effect project.

Ian H. Hutchinson
Department Head
Professor of Nuclear Engineering

More information about the Department of Nuclear Engineering can be found on the web at http://web.mit.edu/ned/www/.