Department of Nuclear Science and Engineering

The Department of Nuclear Science and Engineering (NSE) at MIT remains the premier US department in its field according to the peer assessment published in *U.S. News and World Report.* The department is delighted to report that it is healthy; interest in nuclear power is growing nationally; students as well as faculty are sensing a dynamic future for nuclear applications; and the diverse research interests of the department are well funded and received.

This year the department's name changed from the former Department of Nuclear Engineering. The expansion to Nuclear Science and Engineering better reflects the breadth of the department's research and educational activities. It expresses the department's mission of educating "future leaders in the science and engineering of nuclear and radiation systems" as well as the foundation of its activities on the disciplines of nuclear science and engineering, not just on a single industry. The change has been well received by alumni and external constituencies, as well as by students and faculty.

Two new faculty members joined the department in summer 2004 and have made excellent contributions to teaching and research. The need to replace retiring faculty by recruiting approximately one-third of NSE's professorial headcount over the next five years remains a very pressing challenge—but also a great opportunity. A faculty search was begun this year, and some promising candidates have been identified.

Research overall remains very strong in energy applications (fusion and fission) and in quantum computing. Nuclear and radiation applications for homeland security have seen large growth in research funding. Funding is highly competitive in biological and medical applications.

Yet another substantial increase in undergraduate majors brings the NSE undergraduate population to its highest level ever, and graduate admissions are also up this year.

In November 2004, the Department of Energy announced that the Battelle Energy Alliance (BEA) had won the competition to operate the Idaho National Laboratory. The MIT Nuclear Science and Engineering Department is a member of the BEA winning team representing other universities in the nation. The Idaho National Laboratory has been designated to be the lead national laboratory for the development of advanced nuclear energy systems. NSE'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

The 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 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 25 freshmen selected NSE. There were 22 last year.

In all, 48 (fall 2004) students were enrolled in the undergraduate program during the past year. This included 20 sophomores, 16 juniors, and 12 seniors. Nine students completed requirements for the bachelor's degree in nuclear engineering.

Graduate Program

The graduate program totaled 100 students during the fall term. Of this number, 17 were enrolled for their first term. Some 33 percent are working in fission and energy studies, 39 percent are specializing in nuclear science and technology, and 28 percent in fusion. The department awarded 25 master of science, 1 engineer, and 15 doctoral degrees during the academic year.

Faculty Awards, Honors, and Activities

Professor George Apostolakis received the Arthur Holly Compton Award in Education and the Alpha Nu Sigma Award for excellence in teaching.

Professor Jacopo Buongiorno is the holder of the Norman C. Rasmussen Center development chair in nuclear science and engineering (July 2004). Professor Buongiorno received a Graduate Student Council Teaching Award for excellence in teaching.

Professor Sow-Hsin Chen was an invited speaker at the Gordon Conference on Physics and Chemistry of Water in August 2004 on "Observation of Fragile-to-Strong Dynamic Transition in Deeply Supercooled Confined Water Using Quasielastic Neutron Scattering."

Professor Jeffrey Coderre won a Curriculum Development Award for Undergraduate Education: Development of a Radiation Biology Laboratory Unit for 22.09 Principles of Nuclear Radiation Measurement and Protection.

Professor emeritus Michael Driscoll and Professor Michael Golay are coauthors of a newly published book on sustainable energy by MIT Press.

Professor Jeffrey Freidberg received the PAI Outstanding Teaching Award, presented by the student chapter of the American Nuclear Society.

Professor emeritus Elias Gyftopoulos was elected a fellow of the AAAS.

Professor Ian Hutchinson was appointed international advisor to the journal *Plasma Physics and Controlled Fusion.* His paper, "Ion Collection by a Sphere in a Flowing Plasma: 3 Floating Potential and Drag Force," won an Institute of Physics Publishing Select Award. He presented an invited plenary lecture entitled "Dust Particle Interaction with Flowing Plasma: Computational Discoveries" at the 4th International Conference on the Physics of Dusty Plasmas (Orleans, France).

Professor Alan Jasanoff received the Raymond and Beverley Sackler Scholar Award. He also started a new lab, finishing studies on early development of somatosensory responses studied by functional magnetic resonance imaging (fMRI) and on calcium-sensitive contrast agents for brain imaging.

Professor of the practice Andrew Kadak was nominated by President Bush to serve on the Nuclear Waste Technical Review Board, overseeing the technical work of the Department of Energy and the nation's national laboratories in the Yucca Mountain High-Level Nuclear Waste Repository. In addition, Professor Kadak was nominated by Rhode Island governor Carcieri to serve on the Rhode Island Atomic Energy Commission, overseeing the operation of Rhode Island's research reactor.

Professor Mujid Kazimi gave opening talks at two international conferences: the 1st Conference on Advances in Nuclear Reactors and Fuel Cycles organized by the Center for Excellence in Nuclear Energy, Tokyo Institute of Technology, held in Tokyo in November 2004; and the 3rd International Congress on Advanced Nuclear Power Plants in Seoul in May 2005.

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-elect of the Institute of Electrical and Electronics Engineers Radiation Instrumentation Steering Committee.

Professor Neil Todreas received the Henry DeWolf Smyth Nuclear Statesman Award, jointly conferred by the American Nuclear Society and the Nuclear Energy Institute. He gave invited lectures at the 6th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operations, and Safety in Nara, Japan.

Professor Yip received the 2005 Hsun Lee Lecture Award of the Chinese Academy of Sciences, in recognition of research accomplishments in the field of materials science and technology. He serves on the advisory boards of the Physics Division and the Chemistry and Materials Science Directorate at the Lawrence Livermore National Laboratory. He has been appointed to a blue ribbon panel by the National Science Foundation Engineering Directorate to establish the new field of simulation-based engineering science. He has completed editing the *Handbook of Materials Modeling,* a two-volume reference work published by Springer in June. He gave keynote talks at two international conferences: Multiscale Materials Modeling in Los Angeles in October and Nanotechnology 2005 in Beijing, China, in June.

Research

Research Funding

NSE's research volume, measured in terms of research funds expended, has shrunken about 10 percent from FY2004. While a concern, several activities in FY2004 involved high-cost items such as large reactor use fees and the use of outside personnel, so the decrease was not unexpected and still reflects a research volume 26 percent higher than in FY2003.

New research grants or contracts were received from L3 Communications (as a subaward of a grant from the Department of Homeland Security), Areva-Framatome ANP Inc., Sib-Tech, and the Department of Energy. NSE continued to receive research support from the Nuclear Regulatory Commission, the National Science Foundation, and various agencies of the Department of Defense and the Department of Homeland Security. NSE has grants from the Idaho, Argonne, Lawrence Livermore, and Sandia National Laboratories. Subawards from federally sponsored programs are ongoing from several universities, including the University of Nevada, the University of California, the University of Florida, the University of Tennessee, and Pennsylvania State University. Among industrial sponsors, Tokyo Electric Power Company (TEPCO), Toshiba, Honda, and the Electric Power Research Institute continue to award significant research contracts to NSE faculty. Area hospitals (Massachusetts General Hospital and Beth Israel Deaconess Medical Center) continue to fund about three to five of our graduate students per year as off-campus research assistants in the joint program with Health Sciences and Technology.

NSE's primary research volume (research expenditures specifically handled through the NSE offices, rather than through a related lab or center) is forecast based on expenditures through May 2005, and is expected to have decreased about $700,000 to $6.2M from $6.9M in FY2004. The Department of Energy (DOE), NSE's most important federal sponsor over the years, has decreased its support by about $180,000, about half of which is a decrease in support from the Idaho National Laboratory (INL), although it continues to constitute about 26 percent of NSE's total volume, which is quite consistent with FY2004. This does not include the volume received as subawards from other institutions or companies; taking that into account, NSE's volume from the DOE is close to 30 percent. INL is in management transition from Bechtel to Battelle, but Bechtel also managed the Nuclear Energy Research Initiative (NERI). While several grants under that grant program—typically a three-year award—have recently ended or will soon end, only one new NERI award was made to NSE in FY2005.

Fission: Center for Advanced Nuclear Energy Systems

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

- Advanced Reactor Technology
- Nuclear Fuel Cycle Technology and Economics
- Enhanced Performance of Nuclear Power Plants
- Nuclear Energy and Sustainability

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 expansion of work on innovative approaches to raising the power density in light water reactors. Such increases of power density would significantly reduce the cost of electricity, as well as lead to reduction of the spent fuel volume per unit of electricity production. Professor Buongiorno initiated a program on the effects of the addition of nanoparticles on the heat transfer properties of the water coolant for the purpose of increasing the power density in pressurized water reactors (PWR). Professor Kazimi and his associates concluded that the PWR power density can be increased by 50 percent by using internally and externally cooled annular fuel rods instead of today's externally cooled solid-fuel pins. His group also initiated an investigation of the use of a ceramic cladding instead of the metallic cladding used in today's reactors to negate concerns about excessively high temperatures during transients. Professor Todreas' group continued to explore the use of a hydride fuel instead of the traditional oxide fuel to allow significant power density increases.

Four symposia were organized by CANES during the academic year. In October 2004, a one-day symposium on the "Use of Simulation in the Nuclear Fuel Cycle" was attended by over 50 people. In January 2005, a joint symposium with the French Atomic Energy Commission was organized on the "Design of Gas-Cooled Fast Reactors." A two-day symposium on the "Next Generation Nuclear Power Plant: Goals and Challenges" was conducted in February 2005. The symposium was attended by 90 people. In May a symposium on SiC as a cladding option for PWR fuel was organized in collaboration with Westinghouse and Gamma Engineering.

In June 2005, Professors Golay and Buongiorno organized the 13th 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 39th session of the summer course on Nuclear Plant Safety, Professor Apostolakis directed the one-week course on Risk-Informed Operations of Nuclear Power Plants, and Professor Ballinger introduced a one-week course on Degradation of Materials in Nuclear Power Plants in cooperation with Dr. Robin Jones of the Electric Power Research Institute.

Highlights of some of the NSE research projects follow.

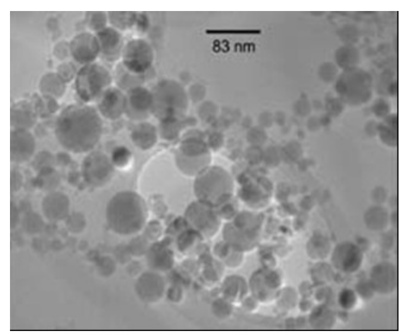
Advanced Reactor Technology

Advanced Light Water Reactors

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 (LWR)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 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 an LWR core fueled with uranium dioxide.

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 heat fluxes to the coolant and also to lower fuel temperatures. A DOE–supported project aims at investigating the ability to raise the power while maintaining or improving thermal margins in pressurized water reactors (PWR). TEPCO supported a scoping analysis of the impact of this fuel in a boiling water reactor. Fuel manufacturing techniques are being 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 prepared (VIPAC) fuel have been irradiated in the MIT Research Reactor and are awaiting examination. Modeling indicates low impact of the manufacturing technique on the fission gas release, which facilitates good VIPAC fuel performance at high burnup.

Use of nanofluids in nuclear power plants. Professor Buongiorno has initiated a research program to assess the feasibility of nanofluids for nuclear applications. Nanofluids are engineered colloids made of a base fluid, typically water, and nanoparticles—that is, 1–100 nm particles made of stable oxides or metals. Contrary to the milli- and microsize particle slurries explored in the past, nanoparticles are relatively close in size to the molecules of the base fluid and thus can realize very stable suspensions with little gravitational sedimentation over long periods of time. The presence of the nanoparticles increases thermal conductivity, single-phase convective heat transfer, and critical heat flux. Thus, in principle, the use of water-based nanofluids could improve the performance of any water-cooled nuclear system that is heat removal limited. The initial focus of Professor Buongiorno's program is on the PWR application. The program is sponsored by the Idaho National Laboratory and AREVA and comprises the following activities:

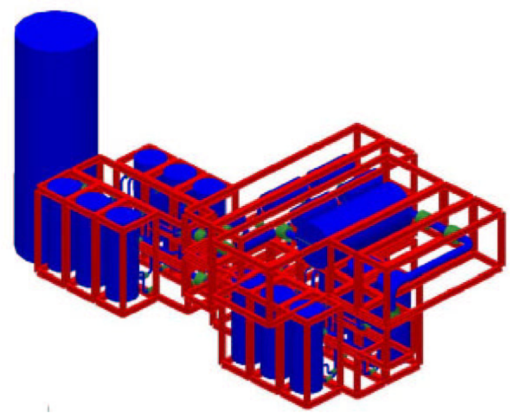


TEM picture of alumina nanoparticles.

- Procurement of water-based nanofluids with various nanoparticle materials: C, SiO_2, ZrO_2, Al_2O_3.
- Nanofluid characterization with TEM (nanoparticle size and shape, see figure), neutron activation and ICP analysis (nanoparticle loading and trace element composition).
- Property measurements: Thermal conductivity (transient hot-wire method) and viscosity (ultrasonic viscometer).
- Property modeling with Molecular Dynamics simulations.
- Single-phase heat transfer and pressure drop measurements in flow loop.
- Single-phase heat transfer modeling, both conceptual and CFD.
- Critical heat flux measurements: Experiments with heated wire and in flow loop with PWR–equivalent annulus and Zircaloy heated surface.
- Thermal-hydraulic and neutronic analyses of PWRs with nanofluid coolant.

Supercritical water reactors. Professor Kazimi and Dr. Pradip Saha continued their 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 25MPa and temperatures of up to 550°C, the density change across the core potentially gives rise to density wave oscillations. They developed a map that delineates the boundary between the stable and unstable thermal hydraulics regimes using nondimensional numbers. The stability of the coupled nuclear and thermal behavior of the whole SCWR core, in symmetric and asymmetric forms, was also analyzed. It was concluded that it is possible to design the SCWR to be stable, but the reactor is more sensitive to changes in power and flow conditions than is typical of current boiling water reactors.

Advanced Gas-Cooled Modular Pebble Bed Reactors



Modularity concept for advanced reactors.

The modular pebble bed reactor is one of the reactor concepts that is being considered for the next generation nuclear plant to be built at the Idaho National Laboratory. Emphasis continues on resolving key technical and economic questions on the viability of this and other high-temperature gas reactors. The two key technical areas that CANES is addressing are 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. His group studied silver migration through the coating of the particle and found that silver does not migrate by diffusion but most likely by a vapor transport mechanism. This reverses 40 years of assuming diffusion-based migration in coated particle fuel. Professor Kadak is working with fuel manufacturers to assess the viability of introducing advanced fuel designed particles into an integrated design and manufacturing process that will provide a mechanism for verifying the quality of the trillions of microspheres that will be needed for atypical pebble or block reactors.

The second major work area deals with the safety of high-temperature gas reactors. One of the most significant challenges for graphite-moderated high-temperature gas reactors is associated with a postulated air ingress event due to a break in piping connected to the reactor vessel. 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. At present, they are working on blind modeling of a recent air ingress test 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.

Professors Kadak and Ballinger attended a major high-temperature reactor conference in Beijing in September to further MIT/Tsinghua University collaborations.

Advanced Lead-Bismuth Cooled Reactors

Professor Ballinger continued his experimental program on the corrosion of various steels in contact with lead-bismuth. The results show that the inclusion of Si in the steel greatly reduces the corrosion in the temperature range of 450–650°C. The research resulted in the development of new alloys that have demonstrated high resistance to degradation in liquid Pb and Pb-Bi eutectic in temperatures up to 700°C. These new alloys are now the defacto standard for advanced Pb/Pb-Bi eutectic-cooled advanced reactor systems.

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 Professor Driscoll and Dr. Hejzlar continues to play a major role in the development of this concept. In April we were awarded a three-year contract to prepare an optimized version of a multipurpose GFR unit (for breeding or burning transuranics and minor actinides, for electricity and/or hydrogen production). Another key innovation is the incorporation of probabilistic risk assessment in the design process, led by Professor Apostolakis. The MIT concept also employs an advanced power conversion system (PCS)—a closed Brayton cycle using supercritical CO_2 as the working fluid. Our efforts, initiated in 2000, have now attracted widespread interest in the United States (Idaho National Laboratory, Argonne National Laboratory [ANL]) and abroad (France, Japan, Korea, UK). We currently have a contract from DOE/Sandia to develop this PCS for generic Generation IV reactor applications. During the past year we also successfully completed a three-year International Nuclear Energy Research Initiative (I-NERI) collaboration led by ANL and the Commisariat la Energie, in which MIT had prime responsibility for design of the shutdown cooling system—a key safety system. We are in the process of completing a NERI project to design a "Breed and Burn" GFR core, which would permit economic operation without requiring fuel reprocessing. This would ameliorate concerns over proliferation and permit fast reactor development well in advance of the fuel processing facilities normally required in any fast breeder reactor economy.

The GFR work identified the need for better heat transfer determination in transition regimes and spawned another project to perform fundamental studies of forced, mixed, and natural convection heat transfer. 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. The project is supported by INL and supervised by Dr. Pavel Hejzlar and Dr. Pradip Saha. A test facility has been 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), and the first data are being taken this summer.

Impact of Uncertainties on the Performance of Passive Systems

Professor Apostolakis and Dr. Hejzlar have investigated the reliability of passive safety systems. These are commonly considered to be more reliable than active systems. The lack of mechanical moving parts or other active components drastically reduces the probabilities of hardware failure. The passive cooling of a gas-cooled fast reactor was analyzed and an importance sampling Monte Carlo technique was used to propagate the epistemic uncertainties and to calculate the probabilities of passive system failures. The results show that passive system failures could be significant and therefore should be included in probabilistic risk assessments. A comparison with an alternative active design was considered also. The results showed that the active system could have, for this particular application, better reliability than the passive one.

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 open fuel cycles regarding benefits of spent fuel management and proliferation resistance. Their work has shown that thermal reactors can be applied for reduction of the actinide accumulation, provided that suitable inert fuels are developed to host the transuranic elements (TRUs) and that recycling of the TRUs is done with waiting intervals longer than 20 years to limit the spontaneous fission neutrons encountered in the fuel handling. In addition, 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.

Proliferation Measures for Nuclear Energy

Proliferation resistance has become an increasingly important aspect of nuclear energy technology development, with emphasis being placed upon developing reactors and associated fuel cycles that provide weapons-usable materials in less available forms than in the past. In work led by Professor Michael Golay, a method has been developed for comparative assessment of nuclear technologies in terms of proliferation resistance. The method uses the techniques of risk assessment to reflect the systematic interaction of the events necessary in order to divert weapons-usable materials from safeguarded facilities.

The probability of successful diversion is estimated by assessment of both the physical characteristics of the facility and performance of active systems (including humans) in preventing diversion. As inputs, both physical data and expert assessments of event probabilities are used. Thus the method is viewed most accurately as providing a statement of a state of belief concerning the integrated outcomes of the actions involved in preventing proliferation, rather than an objective quantification of the performance of a system of objects. From this assessment system, vulnerabilities and areas of most valuable improvement can be identified.

Most recently, this method was applied in a demonstration project assessing the proliferation resistance of the pebble bed, gas-cooled reactor in comparison to that of a light water (cooled) reactor.

Performance Assessments for High-Level Radioactive Waste Repositories

Performance assessments (PAs) are important sources of information for societal decisions in high-level radioactive waste (HLW) management, particularly in evaluating safety cases for proposed HLW repository development. Assessing risk from geologic repositories for HLW poses a significant challenge due to the uncertainties in modeling complex systems of such large temporal and spatial scales. Because of the extensive uncertainties, a typical safety case for a proposed HLW repository is comprised of PA results coupled with various defense-in-depth elements, such as the multibarrier requirement for repository design and insights from supplementary analyses. Professor Apostolakis' reaearch group has proposed an additional supplementary analysis—the strategic partitioning of assumption-ranges and consequences (SPARC)—that could be used (1) in a safety case to help build confidence in a repository system and (2) to provide risk information for decisions on how to allocate resources for future research. The SPARC method extracts risk information from existing PAs and supporting databases by uncovering new information—namely, what sets of model parameter values taken together could produce substantially increased doses (SIDs) from the repository—and displays the results in SPARC trees. The SPARC method has been applied to the proposed Yucca Mountain HLW repository as a demonstrative example, and the results indicate that just one or a couple of repository features working alone could "save" the repository from SIDs even in extremely challenging conditions. Such insights produced with the SPARC method could help significantly in focusing resources on future research to build confidence in the repository.

Enhanced Performance of Nuclear Power Plants

Lessons from the US Application of Risk Methods in Plant Operations

Professors Kadak and Hansen and their students analyzed the lessons learned from the application of risk information for the improvement of 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 in the nation. Continuing their work for TEPCO, Professors Kadak and Hansen are in the final stages of completing Phase II of the study of US nuclear plants and their regulation. This Phase II study was aimed at understanding how the transition to a more risk-informed regulatory process occurred in the United States. Interviews with many key people from utilities, such as regulators (including past and current chairmen of the Nuclear Regulatory Commission), were conducted to understand the process of transition and what lessons could be learned from this process. As Japan begins to look more favorably on risk information as a part of the regulatory process, this study should be quite timely in their deliberations.

Effect of Thermal Aging Properties on Stainless Steel Weld Metals

A program was begun by Professor Ballinger to evaluate the effect of long-term aging on the environmentally assisted crack growth behavior of type 316L and 308L weld metals with varying ferrite content. 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. This program is funded by TEPCO.

Including Uncertainty in Risk-Informed Decision Making

Model uncertainties can have a significant impact on decisions regarding licensing basis changes. Professor Apostolakis' group used a previously submitted licensing basis change as a case study to identify model uncertainties that may have a sufficiently significant impact on the core damage frequency (CDF) and large early release frequency that they may impact the decision. Analysis using the SAPHIRE program identified 22 basic events as important, four of which have model uncertainties that have been identified in the literature as generally important. The applicable model uncertainties are diesel generator mission time and recovery modeling, diesel generator field flashing, human reliability (errors of omission), and sump and pool strainer plugging. The decision is fairly sensitive to the uncertainties related to the diesel generator. A factor of 5 increase in the diesel generator failure rates is sufficient to move the plant's CDF enough that the change would not be approved. Of the four generally important model uncertainties that are applicable to this decision, the decision is fairly insensitive to the remaining three. In these cases, the model uncertainties would need to change the basic event probability by between two and four orders of magnitude before they would become important to the decision.

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}.

Nuclear Energy and Sustainability

Nuclear Energy for Hydrogen Production

Hydrogen energy development has become a national priority. The department is uniquely positioned to participate in this exciting new developing area due to the experience it has in gas-cooled reactor design and analysis. Professors Kazimi and two postdoctoral associates evaluated the efficiency and economic potential of various reactor and chemical technologies for hydrogen production. In particular, two approaches were considered: (1) electrolysis of high-temperature steam and (2) a hybrid approach of thermochemical decomposition of sulfuric acid followed by electrolysis of the mixture of steam and sulfur dioxide. One of the main conclusions is that it is possible to recover heat internally within the hydrogen production plant, which decouples the requirement of the reactor coolant exit temperature from the chemical reactor temperature. Thus, reactors with coolant working at a lower temperature than is needed for the hydrogen plant can be applied for this purpose. The efficiency of the overall method of the electrolysis process is less sensitive to temperature than the hybrid approach, but both can be well above that possible by water electrolysis from light water reactors.

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 SO_3 to SO_2. This reaction is key to the production of hydrogen using the high-temperature sulfur-iodine process. These new materials will be both capable of very high temperature operation and of being a catalyst at the same time. Success in the development effort would allow the combination of the heat exchange and decomposition process into a single chemical reactor unit. Initial results indicate that the program will be successful.

Infrastructure Vulnerabilities due to Terrorism

Protecting critical infrastructures from terrorism presents an enormous challenge. Recognizing that society cannot afford the costs associated with absolute protection, it is necessary to identify and prioritize the vulnerabilities in these infrastructures. Professor Apostolakis and his students have been developing models for the identification and ranking of infrastructure vulnerabilities. Infrastructures are modeled as interconnected digraphs, and graph theory is employed to identify the vulnerable scenarios. These scenarios are screened for the susceptibility of their elements to a terrorist attack, and a prioritized list of vulnerabilities is produced. The prioritization methodology is based on multiattribute utility theory. The impact of losing infrastructure services is evaluated using a value tree that reflects the perceptions and values of the decision maker and the relevant stakeholders. These results, which are conditional on a specified threat, are provided to the decision maker for use in risk management. The methodology is illustrated through the presentation of a portion of the analysis conducted on the campus of MIT.

Nuclear Reactors for Space Application

With the renewed interest in deep space applications, Professor Kadak instituted several studies on nuclear power systems for space applications using the nuclear engineering design course offered for both graduate and undergraduate students as a vehicle. The first such study considered the design of nuclear electric power for propulsion and a terrestrial power station for manned Mars missions. This project was presented to NASA senior project planners in Washington, DC, in 2003. Following that meeting and a subsequent meeting with Naval Reactor engineers, feedback was used to redesign the reactor from a highly efficient spent-fuel plutonium core to a highly enriched uranium core by a master's thesis student. This year, due to President Bush's desire to test the new concepts on the Moon, a terrestrial 100 kWe plant was redesigned for use on both Mars and the Moon in the design project in the fall of 2004. As a result of these projects, the Department of Nuclear Science and Engineering is gaining valuable experience in nuclear space applications. Three students had formal papers accepted for presentation at the June American Nuclear Society meeting in San Diego supported by the department.

Nuclear Science and Technology

Quantum Information Processing

Professor Cory and his students continue to explore nuclear magnetic resonance (NMR) approaches to quantum information processing (QIP) through a set of collaborations with Dr. Timothy F. Havel (NSE), Dr. C. Ramanathan (NSE), Professor Seth Lloyd (Mechanical Engineering), Dr. Raymond Laflamme (University of Waterloo), and Dr. J. Emerson (Perimeter Institute).

Our recent accomplishments focus on the precision of coherent control and efficient measures of this. The challenge to building a quantum computer is to find experimental means of preserving quantum information in the presence of noise. This is best achieved through logical encoding of quantum information into multiple quantum bits (qubits) with the mapping into the encoded space determined by the symmetries, correlation times, and amplitudes of the noise. We have extended our work on experimentally accessible random maps to build a metric for bounding the noise and also the characteristics of the noise. This forms the basis of the first efficient measure of scalability. In related work, we have explored the control available over logical qubits and for the first time demonstrated logical operations on multiple logical qubits. Quantum chaos and quantum simulation of physics share many features, and we have completed an experimental demonstration of localization in the perturbative area of a cat map.

We have extended a benchmark to a Hilbert space spanned by 14 spins (the computational equivalent of a PDP-11 computer in terms of storing the Hilbert space). An interesting observation is that using our classical simulators, the quantum computation as run on our NMR–based quantum information processor is more efficient.

Last year we 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 as using quantum entanglement as a resource for more sensitive metrology. We have nearly completed the construction of a simple quantum information processor based on this idea and will start experimentally exploring this approach this summer.

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. 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 300 Å 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.

Neutron Capture Therapy

Neutron capture therapy for cancer research, directed by Professor Otto K. Harling, continued for the 19th year with support from DOE. DOE's Innovations in Nuclear Infrastructure and Education supported the user facility for boron neutron capture therapy (BNCT), which opens the unique facilities and specialized expertise at the Nuclear Reactor Laboratoy (NRL) to researchers both within and outside MIT. NRL 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. The BNCT irradiation facilities were showcased during the 11th International Symposium on Neutron Capture Therapy held in Waltham in 2004.

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 us 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 amongst the different BNCT centers continues with the cooperation of European, South American, and Japanese partners.

The MIT program in neutron capture therapy continues as the leading BNCT research program in the United States and is considered to be among the top in this field worldwide.

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. New methodology was developed for analysis of the effects of radiation on the lung using a Fourier Transform analysis of the breathing rate pressure change signal. This approach has detected fine structure in the breathing rate data that is missed by the conventional peak-counting approach. The lung is not as sensitive to the radiation produced during BNCT as previously assumed. The data indicate that the fatal lung complications observed in two patients treated with BNCT for brain tumors in the MIT reactor were not due to the BNCT–related scattered radiation dose to the lung. The lung radiobiology data indicate that it is feasible to treat lung tumors with BNCT and provide a basis for the treatment planning needed for such a trial.

Basic Radiation Biology

A new research initiative is under way, led by Professor Coderre. One of the major unresolved issues in radiation biology is whether normal tissue damage is caused by damage to the microvasculature or direct damage to the clonogenic cells. 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, several recent—and controversial—reports have suggested that microvascular damage is causative in an acute effect: the loss of intestinal crypt stem cells and the subsequent development of the gastrointestinal syndrome. A novel method has been developed for selective irradiation of the microvasculature that allows direct experimental testing of the role of the vasculature in normal tissue radiation response. A boron compound has been prepared that will remain inside the blood vessels. The short path length of the radiation from the boron neutron capture reaction allows irradiation of the blood vessel walls but not the surrounding functional cells. Initial data indicate that damage to the blood vessels is not the cause of the gastrointestinal syndrome. 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.

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 coordinating organization—we have also entered into a collaborative effort with L3 Communications to develop a system for the Transportation Security Agency for examination of air cargo. We also continue our efforts 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

We have developed a new method for detecting materials, based on neutron resonance radiography (NRR). 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, 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 Room NW13 and are preparing to install a new radio frequency quadrapole accelerator at the Bates Accelerator Center operated by MIT in Middleton, MA.

Passive Detection of Fissile Materials

Coded aperture for fissile material detection.

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 to be impractical due to fluctuating levels of natural background radiation. Our recent work in coded apertures has shown that this problem can be overcome through the use of imaging gamma-ray detectors. 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 Electrical Engineering and Computer Science is another collaborator.

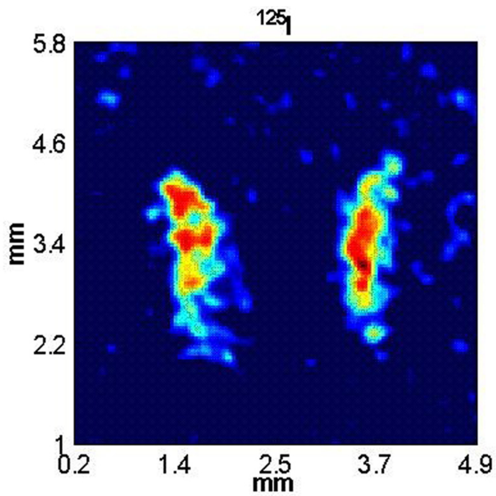
Active Detection of Fissile Materials with Low-Energy Neutrons

NSE has been funded by Homeland Security Advanced Research Project Agency to develop a new approach for the detection of fissile materials using low-energy (< 100 keV) 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 ^{239}Pu and ^{235}U—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. Interestingly, the method of producing such low-energy neutrons was first done in the Department of Nuclear Science Engineering over 10 years ago as part of an approach to boron neutron capture therapy.

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 have installed a beamline at the MIT Nuclear Reactor Lab specifically for this purpose and are installing two high-resolution electronic detectors for imaging. In addition to the phase contrast imaging, we also are installing facilities in the beam for both conventional radiography and computerized tomography. One of our first imaging tasks will be the examination of the distribution of hydrogen and water in fuel cells.

Medical Imaging



In vivo image of mouse thyroid using coded aperture nuclear medicine 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 MGH, BIDMC, 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 3-D images from a limited number of views as compared to conventional single photon emission computed tomographic imaging, thereby considerably reducing doses to patients.

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. Department of Nuclear Science and Engineering graduate students make up 27 of a total of 61 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 $19,518 in FY2005. Professor Parker leads the Lower Hybrid experiment team on Alcator. Professor Freidberg is associate director of the PSFC.

Student Awards and Activities

A number of students were recognized at the annual American Nuclear Society awards ceremony in April 2005.

The Manson Benedict Fellowship, awarded for excellence in academic performance and professional promise in nuclear engineering research, went to Jeongik Lee, Daejeon, Republic of Korea, and Xiaofeng Qian, Beijing, China.

The Outstanding Student Service Award for exceptional service to the students, the department, and the entire MIT community was presented to Whitney Raas, Somerville, MA, and Peter Yarsky, Cambridge, MA.

The Outstanding Teaching Assistant Award for exceptional service as a teaching assistant was presented to Nathan Carstens (22.06), Milwaukie, OR, and Peter Yarsky (22.033), Cambridge, MA.

The Roy Axford Award for academic achievement by a senior in NSE was awarded to Michael Stawicki, Bow, NH.

The Irving Kaplan Award for academic achievement by a junior in NSE went to Ashley Finan, Lyme, CT.

Whitney Lake Raas received the 2005–2006 ANS Graduate Scholarship Award for a graduate student pursuing nuclear science and engineering studies

Tyler Shawn Ellis received the 2004–2005 ANS John R. Lamarsh Memorial Scholarship Award for a student entering the field of nuclear science and engineering.

Paola Cappellaro also received a Graduate Student Council Teaching Award for excellence as a recitation instructor for 22.51 Quantum Theory of Radiation Interactions, and instructor for 22.920 A Hands-on Introduction to Nuclear Magnetic Resonance.

Michael Folkert was part of a group that received the William L. Stewart Jr. Award for outstanding contributions by an individual student or student organization to co-curricular activities and events during the preceding year at MIT. Michael was vice-chair of the Student Advisory Group to the Corporation Committee on the Presidency. In addition to the Stewart Award, Folkert was also awarded the Karl Taylor Compton Prize in recognition of outstanding contributions in promoting high standards of achievement and good citizenship within the MIT community.

Rong Wang, a 4th-year graduate student, received the Hugh Hampton Young Memorial Fund Fellowship for AY2004. Rong is working on the alpha particle bystander effect project.

David Carpenter is an AFCI fellow for 2005–2006.

Ian H. Hutchinson
Department Head
Professor of Nuclear Engineering

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