MITNE-291

ACTIVITIES IN NUCLEAR ENGINEERING AT MIT

Massachusetts Institute of Technology
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Prepared by the Staff of the
Nuclear Engineering Department
Massachusetts Institute of Technology

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The ROTC programs located on the MIT campus do not fulfill all of the elements in the above statement. This discrepancy is currently under review by MIT.

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1. INTRODUCTION

This report has been prepared by the personnel of the Nuclear Engineering Department (NED) at MIT to provide a summary and guide to the Department's educational, research, and other activities. Information is presented on the Department's facilities, faculty, personnel, and students. This information has been prepared for the use of the Departmental Visiting Committee, past and present students, prospective students interested in applying for admission to the Department, and others.

1.1 Academic

The Department of Nuclear Engineering provides undergraduate and graduate education in science and engineering relevant to the peaceful applications of nuclear processes. Our research aims to advance the forefront of knowledge and to incorporate this knowledge into educational programs that include considerations of safety, environmental, economic, and societal concerns.

Departmental teaching and research activities are centered around the following four areas: 1) fission; 2) plasmas and controlled fusion; 3) radiation science and technology; and 4) energy economics and policy. Within each research area, students specialize in a particular field of interest. In the fission area, interest would include reactor engineering, reactor physics and fuel management, nuclear materials, and reliability analysis and risk assessment. Fusion students would consider topics in fusion system technology, experimental plasma physics, and applied plasma physics. Technical specialties within the area of radiation science and technology include radiological sciences, radiation health physics, applied radiation physics and molecular simulation, and the physical metallurgy portion of nuclear materials. In the area of energy economics and policy, students address problems such as the environmental impacts of nuclear and alternative energy systems, management and disposal of radioactive wastes from the nuclear power fuel cycle and other nuclear applications, and the evaluation of alternative strategies for the regulation of geologic repositories for high level wastes.

During the fiscal year ending June 30, 1990, departmental faculty supervised a research volume of more than $15 million. This figure includes research funded through the Department, the Biotechnology Process Engineering Center, the Energy Laboratory, the Harvard/MIT Division of Health Sciences and Technology, the Materials Processing Center, the Center for Materials Science and Engineering, the Department of Materials Science and Engineering, the Nuclear Reactor Laboratory, the Plasma Fusion Center, the Research Laboratory of Electronics, and the Whitaker College of Health Sciences, Technology and Management.

The Department's graduate program enrolled 149 domestic and international students during the fall semester of the academic year 1990-91. Of this number, approximately 42% expressed interest in the fission area, 27% were involved in plasma and controlled fusion, 25% registered in the radiation science and technology program, and 6% in energy economics and policy. In September 1990, our undergraduate enrollment totaled 14 students.

The Department awarded 48 advanced degrees during the academic year 1990-91. This included 21 doctoral, 1 nuclear engineer's, and 24 master's degrees. Four bachelor's degrees were awarded, two of which were joint SM/SB degrees.

1.2 Graduate Student Financial Aid

During the academic year 1990-1991, approximately two-thirds of our graduate student body were appointed to the graduate student staff, receiving financial aid in the form of full- and part-time research and teaching assistantships. The Department awards three departmentally administered graduate fellowships annually--the Sherman R. Knapp, sponsored by Northeast Utilities, the Theos J. Thompson Memorial, and the Manson Benedict. Other sources of financial aid were graduate fellowship awards sponsored by the Institute of Nuclear Power Operations, Stone & Webster, Exxon, Schlumberger, SURDNA, the Wolfe Fellowship, and the Space Grant Program. In addition, the Department receives an annual allocation from the MIT Graduate School College Work Study Program. Scholarship support was also provided by the National Aeronautics and Space Administration, and the United States Departments of the Army, Navy, and Energy.

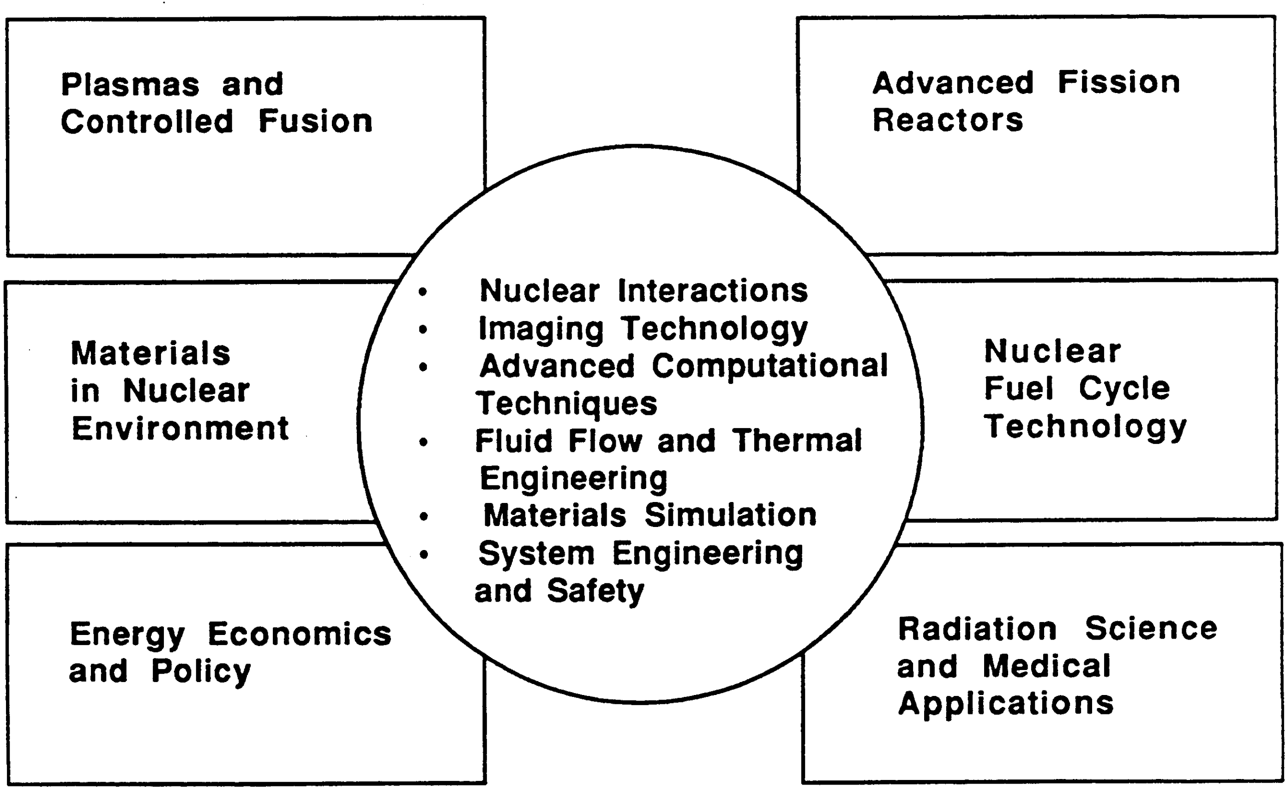
The governments of Chile, Japan, the Republic of China, and Turkey have provided support for the education of their citizens.

In May of 1986 the Department established an Endowed Emergency Financial Aid fund for Nuclear Engineering students. This fund, which was created with a generous bequest from the estate of the late Professor David J. Rose and a gift contribution from Professor Irving Kaplan, has enabled the financial aid officer of the Nuclear Engineering Department to resolve many of the financial difficulties that Nuclear Engineering Department students have encountered.

1.3 Organization of Activities Report

Section 2 of this report contains a summary of developments within the Department since September 1989. Research and educational activities are presented in Section 3. Section 4 discusses our curriculum, including the undergraduate program. Departmental facilities are listed under Section 5. In Section 6 there is a summary of Departmental personnel. Sections 7 and 8 provide statistical information about the Department and its students. The final section, 9, contains a listing of graduate theses submitted to the Department during the period September 1989 through June 1991.

MAJOR RESEARCH AREAS



2. SUMMARY OF DEVELOPMENTS SINCE AUGUST 1989

Section 2 highlights developments that have occurred in the Department of Nuclear Engineering since our last Activities Report. Changes in the academic program, accomplishments by our student organizations, and faculty activities and honors are summarized below.

2.1 Academic Program

An extensive review of the department's undergraduate program has been completed. As a result, a new program has been adopted that will become effective with the students entering the department in the fall term 1991. The three tracks or options in the former program ("fission," "fusion," and "radiological sciences") have been replaced by two tracks in the revised program ("nuclear energy" and "radiation for medicine and industry"). Students in both tracks now take an introductory subject in reactor design, an introductory subject in radiation effects, and a design project subject in common. The new program has more unity, more breadth in nuclear engineering, and more design content.

Since our last report, curriculum changes have been introduced in two areas of graduate study--radiological sciences and radiation health physics. The NED faculty and the Committee on Graduate School Policy (CGSP) approved a proposal submitted by the Nuclear Engineering Department and the MIT-Harvard Division of Health Science and Technology to offer jointly the doctoral degree in the field of radiological sciences. This program, which became effective in September 1990, enhances the accessibility of the Harvard medical community for students involved in doctoral research. The second change occurred in the field of radiation health physics. The health physics program was approved as an NED field of study at the doctoral level.

In the area of curriculum development, subjects have been introduced, as well as renumbered, revised, and/or eliminated during the past two years. An undergraduate version of graduate subject 22.812 was introduced as subject 22.082. A Seminar in Radiation Health Physics, 22.58, was organized by Professor Jacquelyn Yanch, assisted by Dr. Frank Masse and Professor Otto Harling. Topics pertinent to research and concern in the field of radiation health physics are presented as a weekly seminar series. Professor McFarland coordinated the administration of subject 22.562 Advanced Biomedical Magnetic Resonance Seminar. This seminar was designed for students interested in advanced biomedical applications of magnetic resonance and who have already mastered the basic principles. 22.563J Advanced Topics in Image Analysis for Medical Applications, will be offered jointly with the Division of Health Sciences and Technology (HST) during the coming academic year. In the materials area, 22.72J Corrosion - The Environmental Degradation of Materials will be offered next year with the Department of Materials Science and Engineering. New IAP credit offerings include 22.921, 22.922, and 22.923. Professor Lanning organized 22.921 Nuclear Power Plant Dynamics and Control; Professor Chen presented 22.922 Computer Modelling and Visualization in Engineering Science; and 22.923 Environmental Risks and Benefits of Nuclear Power will be sponsored by Professors Golay, Lester, and Yanch. Two energy-related subjects were renumbered and are now listed as subjects 22.811 Energy, Electricity, and the Environment (formerly 22.37 Environmental Impacts of Electricity), and 22.812 Nuclear Energy Economics and Policy Analysis (formerly 22.341). The descriptions for these two courses (and all energy-related subjects) can be found in the MIT Bulletin under a new NED subject subsection titled Systems, Policy, and

Economics. 22.35 Nuclear Fuel Management was revised and will be offered as a reading course. As a result of an extensive review of the plasma physics and fusion technology curriculum, material from subjects 22.66, 22.615J, and 22.616 will be combined and offered as revised subjects 22.615J Theory of Plasma Confinement I and 22.616 Theory of Plasma Confinement II.

As mentioned above, 22.66 will no longer be offered by the Department. Other subjects that have been eliminated include: 22.003 The Nuclear Age, 22.088J Human Factors in Design, 22.43 Advanced Numerical Methods in Engineering Analysis, 22.73J Radiation Effects in Crystalline Solids, 22.913 and 22.914 Graduate Seminars in Energy Assessment.

2.2 Student Organizations

The MIT American Nuclear Society Student Branch (ANS) serves as the focal point for social, athletic, professional, community service, and academic activities conducted by NED undergraduate and graduate students. For its efforts during the year, the MIT ANS Student Branch was awarded the prestigious 1991 Samuel Glasstone Award as the Most Outstanding Student Branch (among a total of 54 in North America) by the ANS national organization. Some of their accomplishments for the past year are mentioned below.

The ANS continued to bring academic and professional speakers in from all over the world to speak at MIT on issues of nuclear science and engineering. This seminar series hosted 19 seminars on issues ranging from medicine to radioactive waste, with speakers from California to the Soviet Union. To celebrate its 30th Anniversary, the Student Branch designed, produced, and sold over 150 T-shirts commemorating the event. Proceeds from the T-shirt sales were used to fund some of its activities, including social and athletic programs. They hosted 21 different social events this year. Among the most notable were the Thanksgiving Dinner, Holiday Party, and the International Dinner, all family-oriented events which each drew over 50 students, faculty, and family members. They also developed and ran a food drive to benefit the homeless. Over 100 boxed and canned food items were collected and donated to a local shelter. The program was so successful and well received that it will be continued every semester.

This was the most successful year in the history of the ANS High School Speakers Program (HSSP), a program run entirely by ANS students, which sends volunteer speakers out to high schools across New England to give talks on issues related to nuclear science, energy, and the environment. This past year 28 high schools were visited, and over 100 talks were presented to over 4000 students. Two successful Alumni Telethons to raise money for NED were planned, staffed and run by the ANS. The ANS Student Branch was the only organization to hold two telethons during the past year, one in the fall semester and one in the spring semester.

The Alpha Nu Sigma Society (ANSS), the national honor society for nuclear science and engineering, recognizes outstanding academic achievement by students in nuclear engineering by membership in the Society. In conjunction with the Society's Annual Banquet, the MIT Chapter of ANSS inducted ten new members into the Society this year. In October 1989, the Society co-sponsored the second David J. Rose Lecture in Nuclear Technology. Dr. Hans Blix, Director General of the International Atomic Energy Agency, spoke to a capacity-filled audience on the subject "World's Energy Needs and the Nuclear Power Option." The MIT Chapter designed, produced and distributed a 41-page

"Student Guide to the Department of Nuclear Engineering at the Massachusetts Institute of Technology." They are currently preparing a "Thesis Survival Manual" for distribution in the fall of 1991, and are in the process of writing a "Guide to Giving a Technical Presentation."

2.3 Faculty Activities and Honors

This section of the Activities Report highlights some of the faculty activities and honors over the past two years.

Professor Gordon Brownell was one of the founders of a new society, Medical Imaging, jointly sponsored by the IEEE. He also participated in international conferences in Amsterdam and Paris on NMR imaging and nuclear medicine.

Professor Sow-Hsin Chen was an invited speaker at the Gordon Conference on Water and Aqueous Solutions and the Annual European Colloid and Interface Science Conference. He directed a NATO Advanced Study Institute on "Structure and Dynamics of Supramolecular Aggregates and Strongly Interacting Colloids," that was held in Maratea, Italy, in June 1991.

Professor Jeffrey Freidberg received the American Nuclear Society Student Branch Outstanding Professor Award for the academic year 1990-91. Professor Freidberg and graduate students Tom Hsu and John Urbahn were active participants in the PFC high school outreach program. They gave lectures, demonstrations, and tours to a group of about 80 high school students and teachers from the Boston area.

Professor Golay organized the First MIT Conference on the Next Generation of Nuclear Reactors. He also directs the Advanced Power Reactor Studies Program.

Professor Elias Gyftopoulos' textbook, *Thermodynamics: Foundations and Applications*, was published by Macmillan. It represents an entirely new approach to thermodynamics.

Professor Kent Hansen developed an International Program on Enhanced Nuclear Safety. Eleven domestic organizations and thirteen international organizations are sponsoring this project. He was the coordinator of a special summer course on "Principles of Nuclear Technology" offered to DOE interns in the summer of 1990.

Professor Allan Henry continued as a member of the Editorial Review Board of *Nuclear Science and Engineering* and is a member of the Program Committee of the Mathematics and Computation Division of the ANS.

Professor Otto Harling presented invited papers at the Fourth International Symposium on Neutron Capture Therapy which was held in Sydney, Australia; and at the Water Chemistry Conference on Nuclear Reactors that was held in Japan. He completed the publication of a volume on the results of an international workshop on neutron sources and neutron beams for neutron capture therapy, which he organized and which was held at MIT. He and the staff from the NRL continued the successful program of offering seminars in nuclear technology to high school science teachers.

Professor Ian Hutchinson heads the Alcator C-MOD research project at the Plasma Fusion Center. He was appointed associate editor of *Physics of Fluids B, Plasma Physics*.

Professor Mujid Kazimi was appointed chairman of the High Level Waste Tank Advisory Panel to review the safety of nuclear waste storage tanks of the DOE. He continues as a member of the University of Chicago Special Committee to review the safety of the Integral Fast Reactor.

Professor David Lanning serves as co-chairman of the NSF-sponsored panel to assess European nuclear controls and instrumentation. He continues to serve on the Safety Audit Committee of the Monticello Nuclear Generating Plant which is operated by Northern States Power Company.

Professor Richard Lester was Executive Director of the MIT Commission on Industrial Productivity. The Commission was awarded the Special Prize of the Ohira Memorial Foundation of Japan for its book, *Made in America: Regaining the Productive Edge*. He is a member of the MIT Program on Industrial Performance, a new research program created to continue the work of the MIT Commission on Industrial Productivity.

Professor Lawrence Lidsky was awarded the Metcalfe Professorship (Metcalfe Professor of Engineering and the Liberal Arts). He and Professor M. R. Smith of the School of Humanities will share the chair, the title of Professor of Engineering and the Liberal Arts, and the task of guiding the Institute's Context Program. They have instituted the Context Support Office and a number of continuing Context-related activities.

Professor John Meyer participated as a member of the Technical Program Group for the Savannah River Site Limits and Uncertainty Program. He continues to chair the NED Undergraduate Committee.

Dr. Marvin Miller received the Graduate Student Council Teaching Award in the School of Engineering for 1990. He has made presentations at a Conference on Latin American Nuclear Cooperation, and to the National Research Council's Committee on Future Nuclear Power Development.

Professor Kim Molvig appeared before the Subcommittee on Investigation and Oversight of the US House of Representatives Committee on Science, Space, and Technology to present his views of "Fusion Program Strategy." He has also appeared before the Fusion Policy Advisory Committee.

Professor Norman Rasmussen received the American Nuclear Society Student Branch Outstanding Professor Award for the academic year 1989-90. He also received the "Distinguished Contribution Award" from the Society of Risk Analysis. He is a member of the Oak Ridge National Laboratory Committee to Review the Cleanup of Radioactive Waste Storage Tanks. He is a member of the President's Commission on Catastrophic Nuclear Accidents, which issued its report in the fall of 1990. He continues to serve on a committee that is reviewing the risk assessment of the Savannah River reactors. He also continues as a member of the Board of Trustees of Northeast Utilities, and is chairman of the LNG Safety Committee, Cabot Corporation.

Professor Kenneth Russell is a member of the American Society for Metals, Awards and Honors Committee; he chairs the AIME, Ferrous Metallurgy Committee; and is a member of the ASTM, Committee E-10 on Radiation Effects. He edited "Physical Metallurgy of Controlled Expansion Invar-Type Alloys," which was recently published by TMS.

Professor Nathan Siu was promoted to Associate Professor of Nuclear Engineering. He is a member of the Technical Program Committee for the Nuclear Reactor Safety Division of the American Nuclear Society. He organized and chaired a special session at the inaugural Society for Risk Analysis meeting on Probabilistic Safety Assessment and Management.

Professor Neil Todreas was named a member of the National Academy of Sciences committee, Nuclear Power: Technical and Institutional Options for the Future. Professors Todreas and Kazimi organize the special summer session, "Nuclear Power Safety," which celebrated its 25th anniversary in summer 1991.

Professor Jacquelyn Yanch is the first recipient of the Class of 1958 Assistant Professorship Chair. She will hold this chair for three years, 1989-1992.

Professor Sidney Yip edited a volume on "Atom-level Properties of Interface Materials," which will be published by Chapman and Hall, London, at the end of 1991. He was invited to lecture on molecular simulation in materials research to Japanese corporate research laboratories. He presented a series of five lectures on Radiation Science and Technology in the 1990's at the Research Science Institute in Washington, DC, which is a summer program for gifted high-school students conducted by the Center for Excellence in Education.

Table 2.1

Recent Books by NED Faculty and Staff

S-H. Chen and R. Rajagopolan, eds.
Micellar Solutions and Microemulsions - Structure, Dynamics and Statistical Thermodynamics
Springer-Verlag (1990)

E. P. Gyftopoulos and G. P. Beretta
Thermodynamics: Foundations and Applications
Macmillan Publishing (1990)

N. E. Todreas and M. S. Kazimi
Nuclear Systems: *Volume I* *Thermal Hydraulic Fundamentals*
Volume II *Elements of Thermal Hydraulic Design*
Hemisphere (1990)

M. J. Driscoll, T. Downar and E. E. Pilat
The Linear Reactivity Model for Nuclear Fuel Management
American Nuclear Society (1990)

M. L. Dertouzos, R. K. Lester, R. M. Solow and the MIT Commission on Industrial Productivity
Made in America: Regaining the Productive Edge
MIT Press (1989)

Ian Hutchinson
Principles of Plasma Physics
Cambridge University Press (1987)

Jeffrey P. Freidberg
Ideal Magnetic Hydrodynamics
Plenum Press (1987)

Table 2.2

Administrative Responsibilities in NED
For the Academic Year 1990-1991

Department Head	Mujid S. Kazimi
Chairman, Committee on Graduate Students	Allan F. Henry
Graduate Financial Aid Officer	David D. Lanning
Graduate Admissions Officer/Chairman, Admissions Committee	Richard K. Lester
Chairman, Committee on Undergraduate Students	John E. Meyer
Undergraduate Recruiting/Financial Aid Officer and UROP Coordinator	Ronald G. Ballinger
Faculty Coordinators, Department Areas:	
Fission	David D. Lanning
Plasma Physics and Fusion Technology	Jeffrey P. Freidberg
Radiation Science and Technology	Sidney Yip
Energy Systems and Policy	Richard K. Lester
Radiological Science Program Director	Eric W. McFarland
Advanced Reactors Program Director	Michael W. Golay
Health Physics Coordinator/Advisor	Jacquelyn C. Yanch
ANS Student Chapter Faculty Advisor	Nathan O. Siu
Alpha Nu Sigma Faculty Advisor	Elias P. Gyftopoulos
Coordinator, Independent Activities Period	Sow-Hsin Chen
Chairman, Safety Committee	Mujid S. Kazimi
Chairman, Computer Committee	Nathan O. Siu
Chairmen, Faculty Search Committees:	
Nuclear Chemical Engineering	Neil E. Todreas
Reactor Physics and Control	Allan F. Henry
Radiological Science	Gordon Brownell

Table 2.3

NED Faculty Service to the Institute, Academic Year 1990-1991

Committees of the Institute

Committee on Academic Performance	Sow-Hsin Chen
Committee on Corporate Relations	Kent F. Hansen, Chairman
Committee on Graduate School Policy	Allan F. Henry
Committee on Nominations	Elias P. Gyftopoulos, Chairman
Athletic Board	Sidney Yip
Committee on the Center for Materials Science and Engineering	Mujid S. Kazimi
Institute Council on Environmental Health and Safety	Norman C. Rasmussen
Faculty Club Advisory Board	Kim Molvig
Committee on Radiation Exposure to Human Subjects	Sidney Yip, Chairman Gordon L. Brownell
Committee on Radiation Protection	Jacquelyn C. Yanch
Committee on Reactor Safeguard	Norman C. Rasmussen, Chairman Otto K. Harling Mujid S. Kazimi David D. Lanning Kenneth C. Russell
Advisory Committee on Shareholder Responsibility	Allan F. Henry

Committees of the Provost and Dean of Engineering

Committee on Large Scale Systems	Michael W. Golay Richard K. Lester
Review Committee of the Laboratory on Electromagnetic and Electronic Systems	Kent F. Hansen
Committee on MIT's International Context	Richard K. Lester
Committee on K-12 Education	Lawrence M. Lidsky
Advisory Committee on a New Dean of Engineering	Neil E. Todreas

3. RESEARCH AND EDUCATIONAL ACTIVITIES

3.1 Fission

3.1.1 The Program for Advanced Nuclear Power Studies

During October 1990 the Massachusetts Institute of Technology established the Program for Advanced Nuclear Power Studies. The purpose of the Program is to assist in the creation and deployment of a successful next generation of nuclear power technology. Establishment of the Program reflects the strong commitment of the Institute to ensuring the successful future of nuclear power. The Program is located in the Department of Nuclear Engineering, reflecting the strong commitment of that faculty to the future success of nuclear power. However, the Program draws upon the broad capabilities of the entire Institute.

Activities of the Program

The work of the Program fills a void in current efforts to develop advanced nuclear power technology. Its major activities (summarized in Table 1) are the following:

- Consensus building for the attribution of desirable nuclear reactors,
- Research and technological strategic studies,
- Student education.

The purpose of these activities is to attract and educate the next generation of leaders for the nuclear power enterprise, to provide technological research contributions, to assist formation of consensus regarding acceptable forms of nuclear power technology, and to identify important strategies for nuclear power technology development.

Consensus Building and Public Education

The future success of nuclear power in any democracy will require a broad industrial and public consensus that the technology being used is acceptable--as defined by the people involved. To this point public discussions of advanced reactor technologies have not been effective in forming such a consensus. Rather, they have typically consisted of commercial presentations by technologists of reactor concepts, with an uncritical emphasis upon their potentially attractive features. Comparative assessment of competing technological claims and oversight usually has not been pursued vigorously. It often appears that the promises of such reactor concepts have been accepted among laymen as the reality rather than the potential. Widespread belief of the concept of inherent safety as an attainable goal exemplifies such an acceptance. Also, among technologists an understanding of the realistic requirements of the public, based upon data derived from them, has remained largely undeveloped. Possibilities abound for disappointment and misunderstanding when the next generation of technology is deployed.

TABLE 1

OVERVIEW OF AREAS OF ACTIVITY OF THE MIT PROGRAM FOR ADVANCED NUCLEAR POWER STUDIES

CONSENSUS BUILDING

- International MIT Advanced Nuclear Power Conference Series as a mechanism for consensus formation
- Writings for the educated public
- Participation in advanced reactor panels, conferences, symposia
- Advice to governmental agencies
- Interviews

STUDENT EDUCATION (more than 150 students at all degree levels graduated, or involved in projects)

- Student research projects and theses
- Advanced reactor symposia and short courses
- Student research and internships at industrial sites

RESEARCH PROJECTS (typical project areas are listed)

- Nuclear Power Plant Technologies
    - Specialized technical conferences (e.g., 1991 International Workshop on the Closed Cycle Gas Turbine MHTGR)
    - Reactor concept development, evaluation and strategies
    - Design methods (design evaluation system, models, methods, design strategies)
    - New technologies (e.g., instrumentation and control, seismic isolation, Brayton cycle systems)
    - Crucial topics (e.g., severe accident performance, human reliability improvement, modularization)
- Nuclear Fuel Cycle
    - Waste disposal implications of different nuclear power plant technologies (e.g., actinide burning)
    - Nuclear weapons proliferation
- Institutional and Public Policy Topics
    - Factors affecting public acceptance of nuclear power
    - Alternative methods of safety regulation
    - Technology transfer to less developed countries
    - Global warming implications for nuclear power technologies

TABLE 2

RECENT PUBLIC COMMUNICATIONS ACTIVITIES WITHIN THE PROGRAM FOR ADVANCED NUCLEAR POWER STUDIES (A Partial Listing)

CONFERENCES

- The First MIT International Conference on Future Advanced Nuclear Power Technology, October 1990, M. W. Golay, Chairman.
- The June 1991 Conference on the MHTGR Brayton Cycle Nuclear Power Plant System, L. M. Lidsky, Chairman.
- Participation in preparation of the IAEA's 1991 International Conference on the Safety of Nuclear Power: Strategy for the Future, by M. W. Golay.

WRITINGS

- L. Lidsky, "Safe Nuclear Power," *The New Republic* (December 1989).
- K. Hansen, et al., "Making Nuclear Power Work: Lessons from Around the World," *Technology Review* (17 August 1989).
- M. W. Golay and N. E. Todreas, "Advanced Light-Water Reactors," *Scientific American* (April 1990).
- M. W. Golay, "Longer Life for Nuclear Plants," *Technology Review* (May-June 1990).

INVITED PANELS

M. W. Golay and L. M. Lidsky

- US House of Representatives, May 1990.
- Symposium on (R)Evolutionary Reactor Types, Ultra-Centrifuge, Alemlo NL, May 1991.

M. W. Golay

- Congressional Staff Briefing on Union of Concerned Scientists' Report on Advanced Reactor Concepts, July 1990.
- The Future of Nuclear Power: Responding to the Challenges of Public Concerns, MITRE Corp. Conference, September 1990.

N. E. Todreas

- A televised educational panel: Nuclear Power: Reemerging in the 1990s? Man, Energy and the Environment Series, Jefferson Energy Foundation, October 1990.

A role which the Program has begun to play is that of an informed broker of ideas to assist the process of consensus formation. It is doing this through increased efforts in public communication--principally through writings and talks by the faculty on the prospects and limitations for future nuclear power technology (a summary of related work is presented in Table 2), and through initiation of a dialogue among those who will likely have a voice concerning the acceptability of future nuclear power technologies. The latter initiative is being pursued through a series of International Conferences on the Future of Nuclear Power. The first of this series was held at the Institute on October 4-5, 1990. The range of participants extended from reactor manufacturers to anti-nuclear organizations. These Conferences are seen as vehicles for assisting consensus formation, by providing a means for the different constituencies—including industrial organizations, environmental protection and anti-nuclear groups and governmental agencies—to be involved in future nuclear power decision-making to learn the needs and realities of the other interested parties.

This process provides nuclear technologists with a clearer understanding of the performance requirements which their products must satisfy. It provides consumers of advanced technologies with a better understanding of what they may realistically demand. Because many of those involved in this process are approaching it from very diverse perspectives, often with little appreciation of the viewpoints of others, this process of consensus building is time-consuming. The First MIT International Conference on the Next Generation of Nuclear Power Technology provided its participants with a means of hearing the views of a broader range of thoughtful persons than they would have otherwise encountered. However, concerns over nuclear safety, waste disposal, global warming, the environmental effects of coal burning and for economic efficiency provided those involved with the motivation to participate seriously in this process of defining realistically acceptable technologies.

The Program is undertaking this role because consensus formation is essential to the future success of the nuclear power enterprise, and because the expertise and objectivity of those who work in the Program contribute unique validity to its efforts as a broker of ideas among contending parties.

Important areas of consensus found in The First MIT International Conference on the Next Generation of Nuclear Power Technology include the following:

- No single reactor concept emerges as being so superior that it alone should be the object of future development resources.

- Regardless of the reactor concept, significant future performance improvements can be expected providing that care is taken in engineering and operations.

- Persistent social opposition to nuclear power appears to be based substantially upon distrust of the organizations using the technology; consequently, efforts seeking public acceptance through education campaigns (based upon the belief that "If you knew what I know you would think as I think") may continue to be ineffective.

- Successful terrestrial disposal of high level nuclear wastes appears feasible, if pursued carefully; however, sectors of the public affected by such a project must be provided much greater benefits and involvement than has been typical in the past.

- Consumption in fast-spectrum reactors of HLW actinides from all nuclear power plants may be feasible, but involves serious technological problems and will require more than a decade to provide significant benefits.

The *Proceedings* of the First Conference were issued in June 1991. The Second Conference is scheduled for 13-14 October 1992.

Research and Technological Strategic Studies

The areas of research of the Reactor Innovation Project are summarized in Table 3. The research addressing power plant technologies includes work on reactor concepts cooled by water, helium and sodium as well as generic efforts concerned with advanced instrumentation and control and improved design methods.

The research efforts of the Program succeed and will enlarge upon those of the Reactor Innovation Project. In doing this the educational structure of basing all research efforts upon student thesis research will be retained. Current funding for such efforts is approximately $1.0 million annually. Current research projects include collaboration with the General Electric Co., GA Technologies, Westinghouse Electric Co., the Electric Power Research Institute, Argonne National Laboratory, Oak Ridge National Laboratory, and the US Department of Energy.

Other research areas of the Program include:

- the nuclear fuel cycle, and
- socio-institutional issues and policies.

Previous work in the fuel cycle area has concerned the fuel cycle implications of the integral fast reactor, used to consume actinides some fission products.

Work in the socio-institutional area has been concerned with rationalizing the system of nuclear safety regulation under the rubric of non-prescriptive regulation. As with our research concerned with power station technology innovation there are many areas of work into which we would like to expand if the needed financial resources were available. The overall strategic plan of research is summarized in Table 4, extracted from our 1989 proposal to the National Science Foundation to establish the Center for Advanced Nuclear Power Studies.

Education

The Institute has the largest faculty and body of nuclear engineering graduate students in the United States. During 1983, the Institute became unique among United States universities by strengthening its activities relating to nuclear fission technology. It did this through establishment of the Reactor Innovation Project. In this project research was undertaken in collaboration with the national nuclear power concept development programs. The work of the Reactor Innovation Project has all been conducted through the thesis research of students at all degree levels. By means of this structure advanced reactor research efforts contribute naturally to the education of our students with a focus upon future fission power. This project has graduated approximately a hundred students over the past eight years, and has involved approximately sixty additional students in non-thesis studies.

Recent Advanced Nuclear Power Research Activities

During the past two years research in the different areas listed in Table 3 has continued to be pursued vigorously. Important aspects of this work are discussed below.

TABLE 3

AREAS OF ACTIVITY OF THE REACTOR INNOVATION PROJECT

Modular High Temperature Gas-Cooled Reactor

- Power Plant Design
  - Core design; Studies of economies of scale and of serial production

- Safety Analyses
  - Severe accident analyses; Passive reactor cooling; Probabilistic risk analysis

- Safety Experiments
  - Fission product transport in coolant systems (DABLE); Passive containment cooling

- Brayton-Cycle Conceptual Studies

Liquid Metal-Cooled Reactor

- Passive Reactor Cooling

- Passive Containment Cooling Experiment

- Consumption of High Level Wastes Analysis

- Chemical Processing of Fuel

- Environmental Impact Assessment

Light Water Reactor

- Conceptual Design
  - Simplified boiling water reactor (SBWR): Emergency control center; Semi-passive safety system pump modeling; Semi-passive containment cooling analyses and experiments; Probabilistic risk assessment of preliminary SBWR design
  - Passively-safe pressurized water reactor

- Independent Technological Advances
  - Use of horizontal steam generators; Implementation of the leak-before-break concept

- Improved Safety LWR
  - Conceptual design; Plant design methodology; Non-prescriptive nuclear safety regulation; System simplification; Plant modularization; Design for human error reduction; Operations; Maintenance; Catalog of safety innovations

Advanced Instrumentation and Control

- Automatic Control
  - Reactor power level, (1) Small core (global neutronic, thermal feedback), (2) Large core (spatial-varying neutronic, thermal hydraulic feedback); PWR steam generator water level; BWR water level; Multi-modular power plant control

- Fault-Tolerant Sensor Diagnosis
  - Plant heat rate minimization; LMR natural convection

- Plant Diagnosis
  - Maintenance scheduling using PROLOG; System fault and remedy analysis

3.1.1.1 Condensing Heat Transfer in the Presence of Non-Condensable Gases

The severe accident performance of any reactor depends upon the ability to remove post-shutdown decay heat from the containment building. With the SBWR an important aspect of that problem concerns heat transfer from the containment atmosphere to the isolation condenser of the passive containment cooling system. The rate of heat transfer is strongly influenced by the presence of non-condensable gases (e.g., air, hydrogen), which reduces the rate of transfer by means of steam condensation.

Experimental and analytical projects have been undertaken to understand better the dependence of the condensation heat transfer rate upon the concentration and types of non-condensable gases. This work has been concerned with:

A. Condensation within an open plenum, upon the plenum inner surfaces, under natural convection conditions

B. Condensation within a vertical tube, under forced convection conditions.

Both cases are of strong interest for design of containments.

Both experiments have been performed within the 4.5 m long MIT Condensing Heat Transfer Facility (CHTF), which was constructed for this work. It consists of a right circular vertical tank, in which steam-gas mixtures can be introduced at pressures ≤ five atmospheres. The experiments differ according to the cooling system geometry. In Case A the cooling system uses a vertical water-filled tube, with condensation occurring upon the exterior of the tube. In Case B the cooling system utilizes a cooling water jacket arranged outside a vertical tube, the interior of which communicates with the steam air mixture created within the CHTF. The tube inner diameter is 2.0 inches and the effective length is 8.5 feet. This mixture flows downward through the tube to the ambient atmosphere, with condensation occurring within the tube as the mixture passes through it. In both experiments empirical correlations of the data obtained are then formulated. In complementary work, computational models to simulate the behavior of the experiments have been developed.

Case A – Condensation within an open plenum: The experimental conditions of this work include atmospheric pressures of 1.5, 3.0 and 4.5 atmosphere, and air mass fractions within the air-steam mixture which range from 0.25 to 0.90. Within the range of the data the new, more detailed, correlation is expected to replace that of Uchida, which has been used for containment thermal analysis for the past 25 years.

Case B – Condensation within a vertical tube: Our work concerned with condensation within a vertical tube followed that of Case A, and has not yet resulted in a final correlation. The range of experimental conditions is over a temperature range from 100°C to 140°C, a velocity range from 0.7 m/s to 8.0 m/s, and an air mass fraction ranging from 0.10 to 0.95. It is found generally that the rate of heat transfer observed is somewhat greater than in Case A, due to augmentation of sensible heat transfer as a consequence of the higher velocities of forced convection.

In later work within this phase of the project preliminary data have also been obtained for steam-air-helium mixtures. This work is being performed in order to obtain information regarding the effects upon condensation of a buoyant non-condensable gas. For safety reasons helium is being used rather than hydrogen. It is seen that for equivalent conditions the displacement of air by helium increases the heat transfer rate, due to the higher thermal conductivity of helium.

Future work is expected to include the natural convection behavior of steam-air-helium mixtures in the geometry of Case B, and means of augmenting condensing heat transfer rates in the presence of non-condensable gases.

Investigators: Profs. M.W. Golay and M.S. Kazimi; A.A. Dehbi, M. Siddique, F. Francis

Support: USDOE and EPRI via the General Electric Co.

Related Academic Subjects:

22.312	Engineering of Nuclear Reactors
22.313	Advanced Engineering of Nuclear Reactors
22.36J	Two-Phase Flow and Heat Transfer

Recent References:

A.A. Dehbi, M.W. Golay, M.S. Kazimi,"The Effects of Noncondensable Gases on Steam Condensation Under Turbulent Natural Convection Conditions," Report No. MIT-ANP-TR-004, MIT Program for Advanced Nuclear Power Studies (1991), based on A.A. Dehbi's Ph.D. Thesis.

A.A. Dehbi, M.W. Golay and M.S. Kazimi, "A Theoretical Modeling of the Effects of Non-Condensable Gases on Steam Condensation under Turbulent Natural Convection," National Heat Transfer Conference (1991).

M. Siddique, M.W. Golay and M.S. Kazimi, "Forced Convection Condensation of Steam in the Presence of Air," Winter American Nuclear Society Meeting (1991).

3.1.1.2 Capacity Increase for Passive LWRs

A project was undertaken to investigate the implications for containment design of increasing the power level of the 600 MWe "passive" LWRs under current development in the United States, the SBWR and the AP-600 PWR. Strong economic incentives exist for such an increase. For this purpose simple computer models were written for analysis of the containment thermal performance following a loss of coolant accident (LOCA). These models were used to investigate the long term cooling of the containment of each reactor concept when the power plant is increased in power to 900 MWe.

SBWR Results: For the SBWR it is found that the ultimate pressurization is strongly sensitive to the amount of air (rather than steam) left in the drywell following the blowdown phase of a LOCA. This amount is uncertain because air is displaced by steam into the wetwell during the blowdown transient. It is found that the containment design pressure is exceeded when the residual post-blowdown air concentration exceeds approximately 25% of the mixture mass. The possible design responses appear to be either strengthening the containment pressure capacity or devising a means of reliably removing air from the drywell atmosphere.

AP-600 Results: For the AP-600 it appears that the most important containment thermal performance sensitivity involves the time when cooling water is applied to the exterior of the containment shell. Because the reactor decay power is greatest immediately after start of a LOCA, with a rapid decay thereafter it is most important to start cooling within minutes of the end of the blowdown transient. If this is not done the containment atmosphere pressure can exceed the design value by a factor of 2.4 within approximately 20 minutes. However, if adequate evaporative cooling assistance is provided for at least three hours the containment can survive unassisted afterwards. The main means of reducing this sensitivity is to increase the heat transfer surface area of the containment building.

Investigators: Professors M.W. Golay and M.S. Kazimi; Dr. A.A. Dehbi

Related Academic Subjects:

22.312	Engineering of Nuclear Reactors
22.313	Advanced Engineering of Nuclear Reactors
22.33	Nuclear Engineering Design
22.36J	Two-Phase Flow and Heat Transfer

Recent Reference:

A.A. Dehbi, M.W. Golay and M.S. Kazimi, "Passive Containment Cooling for a 900 MWe Reactor," Report No. MIT-ANP-TR-006, MIT Program for Advanced Nuclear Power Studies (1991).

3.1.1.3 Advanced Light Water Reactor Concepts Optimized for Passive Decay Heat Removal

One of the major characteristics of the next generation nuclear power plants is passive decay heat removal. The present work concentrates primarily on this issue and investigates various design alternatives for passive decay heat removal with the goal of finding the maximum achievable power which can be removed using only natural heat transfer phenomena.

The three fundamental passive heat transfer mechanisms are identified and characterized with respect to their heat removal capabilities. Utilizing these mechanisms, the existing designs of advanced reactors have been reviewed and their achievable power limits assessed.

Next an investigation of various alternatives of passive decay heat removal from the core to the ultimate heat sink through the various physical barriers was performed. Three ultimate heat sinks — water, air, and the earth — were explored. Water appears to be the most efficient heat sink, while the heat transfer rates to earth are very limited. For LWRs, the vessel wall was found to be the most restricting thermal resistance to heat transfer.

Finally, the potential for new designs of Light Water Reactors (LWR) capable of dissipating decay heat energy under severe loss of coolant accidents was assessed. The constraint imposed was that emergency liquid makeup was not available so that decay heat removal capability was to be evaluated assuming the core was completely uncovered. The goal was to evolve a concept which maximized the full power operating level under this constraint.

Two design approaches are being pursued — a solid matrix core in a pressure vessel and a system of solid matrix pressure tubes dispersed in a low pressure calandria. Introducing a solid matrix into an LWR core considerably enhances the capability to transmit the decay heat out of a fully uncovered core by conduction. The latter pressure tube approach yields much higher potential with respect to achievable power output and also eliminates the choke point on the heat transfer path posed by a thick pressure vessel wall.

Investigators: Professors N.E. Todreas, M.J. Driscoll; Chris Owens, Pavel Hejzlar, Jan-Ru Tang

Support: Fellowships from the US Army, MIT School of Engineering and the Institute of Nuclear Energy Research (Taiwan)

Related Academic Subjects:

22.312	Engineering of Nuclear Reactors
22.32	Nuclear Power Reactors
22.36J	Two-Phase Flow and Heat Transfer

Recent References:

C. Owens, "Passive Decay Heat Removal Approaches for Light Water Reactors," MITNED M.S. Thesis, February 1990.

P. Hejzlar, N.E. Todreas and M.J. Driscoll, "Passive Decay Heat Removal in Advanced Reactor Concepts," MIT Nuclear Engineering Dept. Technical Report No. MIT-ANP-TR-003, May 1991.

3.1.1.4 Mixed Convection Flow Recirculation in LMR Rod Assemblies

This project is concerned with the development of thermal hydraulic methods for use in assuring the effectiveness of the passive decay heat removal in liquid metal cooled reactors (LMR) by natural convection. In particular, thermal hydraulic interaction occurs under the natural convection mode between hot core assemblies and the upper plenum in a pool-type LMR with an immersion-type sodium to air auxiliary heat exchanger. This interaction may lead to penetration of cold fluid from an upper plenum into blanket and fuel (with lower probability) assemblies as well as flow recirculation within these assemblies. This work investigated the basic mechanism underlying the onset and extent of flow penetration and flow recirculation in rod bundles.

Three investigation approaches, experimental, 3-D numerical, and analytical were employed in a complementary fashion. Laboratory experiments involved water flow visualization and temperature measurement in a 4x4 rod square channel. Numerical experiments using the TEMPEST code involved three-dimensional simulation of water and sodium behavior. Correlations based on a flow reversal model were developed for prediction on onset and depth of flow penetration and recirculation. The concept of channel mass defect condition was introduced to explain the occurrence of both phenomena as well as to provide a problem simplification method.

The depth of flow penetration into adiabatic channels connected to an upper plenum, for the case of water, was found experimentally to depend on the local power level where flow penetration occurs. It was affected neither by the bundle total power level nor by the power skew. A highly fluctuating temperature in the region of the hot/cold flow interface was observed. Laminar flow simulation results showed that for sodium, in contrast to water, power skew was an important parameter that causes flow penetration. A semi-empirical annular model was successfully developed to predict the onset and depth of flow penetration of the experimental data. The model requires knowledge of the temperature gradient of the flow. Flow penetration into a channel subject to wall cooling was numerically simulated for water and sodium. The results showed that wall cooling enhanced flow penetration. There was much more enhancement in sodium than in water.

Flow recirculation was experimentally explored in a channel without an upper plenum and subject to wall cooling. It was found that the power skew effect is important for both water and sodium. An increase in power skew accelerated the onset and increased the depth of flow recirculation. The decreasing influence of power skew and the linearization of axial temperature profiles as recirculation depth increased were also observed. A semi-empirical model was developed, based on the physical insight obtained from the experiments, to correlate the experimental data.

Investigators: Professor N.E. Todreas; W. Luangdilok and D.W. Jerng

Support: Power Reactor and Nuclear Fuel Development Corporation of Japan

Related Academic Subjects:

22.312	Engineering of Nuclear Reactors
22.313	Advanced Engineering of Nuclear Reactors

Recent References:

W. Luangdilok and N.E. Todreas, "Flow Reversal under Mixed Convection Conditions in Rod Bundles," MIT Nuclear Engineering Technical Report No. PNC/MIT-DHR-20TR, June 1990.

N.E. Todreas and D.W. Jerng, "Decay Heat Removal in Large Breeders -- Plenum-Channel Thermal Hydraulic Interactions," MIT Nuclear Engineering Progress Report No. PNC/MIT-DHR-22, March 1991.

N.E. Todreas and D.W. Jerng, "Decay Heat Removal in Large Breeders -- Plenum-Channel Thermal Hydraulic Interactions," MIT Nuclear Engineering Progress Report No. PNC/MIT-DHR-23, May 1991.

3.1.1.5 Modular Gas-Cooled Reactors

The modular high temperature gas-cooled reactor is a basis for an attractive next generation nuclear power plant. The reliance on demonstrable passive safety and small size (mandated by passive safety) offers substantial licensing and institutional advantages. The key to acceptance of this new technology is the development of a plant with satisfactory economics. Professors Lidsky, Lanning, and their students have been studying the combination of the modular high temperature gas-cooled pebble bed reactor (MGR) with the direct gas turbine cycle. The resulting combination (MGR-GT) is able to take full advantage of the modular reactor's capabilities. The low power rating of the reactor can be ideally matched by a small gas turbine and the high temperature capability can be fully utilized. The resulting system performance considerably exceeds that of equivalent steam cycle plants and does so with a smaller, simpler, and presumably less expensive power conversion system. It appears feasible to build a direct cycle, gas turbine power plant, based on current reactor technology, that uses existing materials within existing design codes that will yield more than 45% net efficiency at a cost substantially below that of alternative power plants, both fossil and nuclear. Professors Lidsky, Lanning, and their students have developed several design options as well as studied potential future developments based on higher power density systems.

MIT was the site of the 1991 International Workshop on the Closed Cycle Gas Turbine Modular High Temperature Gas-Cooled Reactor. This workshop was supported by the US Department of Energy and several utility research consortia. It is expected that several follow-on studies will lead to interesting international collaborations on the topic.

Investigators: Professors L.M. Lidsky and D.D. Lanning; Dr. X.L. Yan, Research Associate; M. Ames, E. Iverson, R. Klann, V. Kubali, C. Martin, J. Martin, Scott Pappano

Support: US Department of Energy, Tokyo Electric Power Company, Inc.

Recent References:

D.D. Lanning, "Modularized High-temperature Gas-cooled Reactor Systems," Nuclear Technology, Vol. 88, No. 2, November 1989, pp. 139-156.

D.D. Lanning and S.W. Pappano, "Environmental Impacts of the Modular High Temperature Gas-Cooled Reactor (MHTGR)," Energy and the Environment in the 21st Century, Conference Proceedings Sponsored by the Energy Laboratory, MIT, Cambridge, MA, March 1990.

L.M. Lidsky, "Audience, Rationales and Quantitative Measures for Demonstrations of Nuclear Safety and Licensing by Tests," presented at the First MIT International Conference on the Next Generation of Nuclear Power Technology, Cambridge, MA, October 1990.

X.L. Yan and L.M. Lidsky, "Dynamic Analysis and Control System Design for an Advanced Nuclear Gas Turbine Power Plant," MITNPI-TR-035, 1990.

X.L. Yan and L.M. Lidsky, "Design Study for an MHTGR Gas Turbine Power Plant," Proceedings of the 53rd American Power Conference, Chicago, IL, April 1991.

X.L. Yan and L.M. Lidsky, "Highly Efficient Automated Control for an MGR Gas Turbine Power Plant," ASME 91-GT-296, May 1991.

R.T. Klann, "Utilizing Radiation Heat Transfer to Increase the Power Density in a Gas-Cooled Reactor," M.S., Nuclear Engineering, MIT, June 1991.

J.L. Martin, "DABLE: a Facility for Measuring Fission Product Transport in Gas-cooled Reactors," Ph.D., Nuclear Engineering, MIT, June 1991.

L.M. Lidsky, D.D. Lanning, J.E. Staudt, X.L. Yan, H. Kaburaki, and M. Mori, "A Direct-Cycle Gas Turbine Power Plant for Near-Term Application: MGR-GT," Energy, 16, pp. 177-186, 1991.

3.1.1.6 Natural Circulation for Decay Heat Removal

Rejection of decay heat to ambient air by natural convection is now a well-established feature of virtually all advanced reactor designs. The department continues to pursue its long-standing research interest in advanced reactor design with emphasis on passive means of decay heat removal.

A semi-scale (full diameter, half height) experimental model of a riser duct has been constructed and has been used to develop experimental data for validation of correlations for Nusselt number and friction factor.

Experiments were carried out using air in a heated upflow pipe in the forced and mixed convection regimes to determine Nusselt numbers and friction factors over a wide range of conditions, which include projected Modular High Temperature Gas Cooled Reactor (MHTGR) Reactor Cavity Cooling System (RCCS) operating and off-normal conditions. Large (maximum of 50%) decreases in Nusselt number and a slight increase in friction factor compared with forced convection values were found under the most severe mixed convection conditions. Results were compared with literature data, theory and correlation, and calculations using a k-ϵ computer program described in the next paragraph. Consideration of air property changes as a function of temperature both in the analysis and in analytic simulation of the experiments was found to be important. The correlated experimental results were used in a computer code, RECENT, to calculate the overall heat transfer from the reactor vessel to the ambient air, to evaluate the impact of design parameter and other changes on RCCS performance, and to optimize the RCCS riser design. The calculated results show that: 1) no single parameter dominates the RCCS performance, nor is performance sensitive to changes in design or operating conditions; and 2) the present riser design will provide adequate cooling to the reactor vessel under even severe off-normal conditions.

The k-ϵ computer program developed in the previous report period is being used to study, and develop correlations for, heat transfer and pressure drop in the mixed convection regime. In this period it was improved to incorporate temperature-dependent properties. Verification and validation of the revised computer program CONDOR (Convection in Ducts or Risers), which utilizes a k-ϵ turbulence model was the main objective of the present work. Comparisons have been made against the available experimental data and the correlations which represent the experimental data-base, and analytical/theoretical solutions where available. Step by step examination showed that the program was coded correctly, and there was not significant error or error propagation. Accuracy is very well maintained for laminar flow regime with a less than 1% discrepancy in heat transfer coefficients, friction factors, and velocity and temperature profiles from the analytic solutions. Validation that the program represents the correct physical behavior of the system has been obtained for the turbulent flow forced and mixed convection heat transfer regimes, based on extreme comparisons against experimental data and correlations: principally those addressed by Jackson and Cotton, and Petukhov and Polyakov.

Investigators: Professors N.E. Todreas and M.J. Driscoll; Gang Fu, Jian-Chiu Han, S. Yesilyurt

Support: DOE via Bechtel and ORNL

Related Academic Subjects:

22.313	Advanced Engineering of Nuclear Reactors
22.43	Advanced Numerical Methods in Engineering Analysis (no longer offered)

Recent References:

J-C Han, M.J. Driscoll and N.E. Todreas, "The Effective Thermal Conductivity of Prismatic MHTGR Fuel," MIT Energy Lab and MIT NED, September 1989.

G. Fu, M.J. Driscoll and N.E. Todreas, "Radiation Heat Transfer from the Reactor Vessel to RCCS Risers in the MHTGR Vessel Cavity," MIT NED, April 1990.

G. Fu, M.J. Driscoll and N.E. Todreas, "Experimental and Analytic Evaluation of Gas-Cooled Reactor Cavity Cooling System Performance," MIT Nuclear Engineering Technical Report No. MITNPI-TR-038, April 1991.

S. Yesilyurt, M.J. Driscoll and N.E. Todreas, "Numerical Calculation of Mixed Convection in a Duct under MHTGR Conditions," MIT Nuclear Engineering Technical Report No. MITNPI-TR-038, May 1991.

3.1.1.7 Advanced Instrumentation and Control Studies

It has been recognized for some time that improvements can be made in reactor instrumentation and control and that the evolution toward digital systems can be an important part of the improvements. One major need identified is in the area of signal validation with fault detection and identification (FDI). Some potential improvements in this area were studied as a joint program between the Charles Stark Draper Laboratory (CSDL) and MIT. The goal of the program is to reduce human error and improve plant availability by utilizing fault detection and fault tolerant technology in reactor instrumentation, and to consider future improvements such as diagnostics and closed loop digital control.

The principal features of the FDI method involve the use of digital computers for consistency-checking of sensor signals, together with the use of models to provide analytic redundancy for independent checking. Although general techniques exist for taking these inputs and detecting faults, the real time analytic models of nuclear plant systems are only partially developed. Thus, the MIT program involves development of the real time analytic models and overall applications of the methods for signal validation and FDI. An important component of this program is the demonstration of the FDI techniques and of nonlinear closed loop digital control by utilizing the MIT Research Reactor (MITR-II). Considerations involve the potential for diagnostic information developed from the fault detection, and the investigation of closed loop controls with specific applications to large nuclear power plants or plant components and to reactors for space power or propulsion.

In addition to the members of the Nuclear Engineering Department, the MIT group has involved contributors from other MIT departments. In particular, control and control display systems have been studied with the assistance of the Mechanical Engineering Department for human factor engineering considerations at the man-machine interface. Funding from the National Science Foundation (NSF) was provided for studies of the nonlinear closed loop digital control methods. Funding has been provided by the Department of Energy (DOE) to study the applications of the concepts to control of large reactor cores, and funding has been received from Sandia National Laboratories for studies of automatic rapid maneuvering of reactor power. These studies are a combination of analytical modeling, simulation, and actual control experiments utilizing the MITR-II. Computer equipment for these studies was originally provided by CSDL and has recently been significantly upgraded with project funding. Approval from the NRC has allowed expanded studied in the closed loop control by including the shim blades. Some of the most recent advanced experiments and demonstrations in digital computer control have been initiated under these programs.

The above-mentioned project supported by DOE included the development of a real-time supernodal code with transient reactor physics and coupled thermal hydraulics. The object is to incorporate fast-running and analytical information into the closed loop nonlinear digital control (NLDC) concept that has been developed. This NLDC has been developed and demonstrated on the control of the MIT Reactor with point kinetics as the reactor physics code. The DOE project extended the concept to the large, multi-dimensional core effects that occur in large pressurized water reactors (PWRs).

The control studies supported by Sandia National Laboratories have included the development of digital control systems and algorithms for rapid maneuvering of a space nuclear power plant. Tests of the control design concept were initiated with the MIT Reactor to demonstrate the controller capability within the allowable power rates at the MITR. The experiments were then continued at Sandia in the Annular Core Research Reactor (ACRR) where demonstration of the automatic controller included raising the power by a factor of 10% to a desired power and leveling off without significant overshoot in a total time of about 6 sec (an e-folding time, or period, of 0.5 sec). Enhancement and demonstration of this controller has continued. Work on the design of space nuclear power systems is discussed further in Section 3.1.1.9.

In an earlier program, we began to study techniques to improve power plant performance monitoring. Results from this program are now available, and we hope to incorporate them in future (as yet unsponsored) programs. One major result came from an effort to specify methods to quantify uncertainties for installed power plant sensor signals. New methods were found that give good uncertainty information in practical cases for which prior approaches diverge. A second result came from a study of some examples of ways to use CSDL signal validation methods applied to a "thought experiment" installation of new sensors on an existing (Foxboro Heat Transfer Laboratory) shell and tube heat exchanger. The interrelations between sensor uncertainty and calculation input parameters were studied.

Automation improvements of many types can contribute to the PWR upgrade portion of the Advanced Nuclear Power Studies. In particular, great operational benefit (in terms of a large decrease in the number of plant trips) is expected to accompany improvements in automatic control of steam generator water level. We have, therefore, embarked on developing new methods for digital computer control of water level, concentrating on the especially crucial range below about 15% reactor power. Our evolving control method is a strongly physically based one that incorporates an analytic steam generator model developed earlier (Strohmayer, Ph.D. Thesis, 1982). A special feature of the ongoing study is its heavy reliance on actual operating data that we have obtained from an existing 1150 MWe PWR plant.

A new series of studies has been initiated on the automatic control of multi-modular nuclear power plants. Proposed passively safe advanced reactors include use of small reactor modules combined into a single power plant. Methods to automatically control such power plants are needed to provide safe and economic operation. Initial funding for these studies has been received from Oak Ridge National Laboratory, and continued funding was received from DOE.

Investigators: Professors D.D. Lanning, J.E. Meyer, and A.F. Henry; Dr. J.A. Bernard (MIT-NRL); M.G. Houts, R.P. Jacqmin, K.S. Kwok, E.S.H. Lau, P.T. Menadier, R.T. Soule, and M.L. Zerkle

Support: National Science Foundation, US Department of Energy, Sandia National Laboratory, Charles Stark Draper Laboratory (computer support), Oak Ridge National Laboratory, self-supporting students with NED computer funding

Related Academic Subjects:

22.211	Nuclear Reactor Physics I
22.32	Nuclear Power Reactors
22.36J	Two-phase Flow and Heat Transfer
22.42	Numerical Methods in Engineering Analysis

Recent References:

J.A. Bernard and T. Washio, "The Utilization of Expert Systems within the Nuclear Industry," Proceedings of the 1989 American Control Conference, Pittsburgh, Pennsylvania, Vol. 1, pp. 373-78, June 1989; also in Proceedings of the EPRI Conference on Expert Systems Applications in the Electric Power Industry, June 5-8, 1989, Orlando, Florida.

J.A. Bernard, K.S. Kwok, F.J. Wyant, and F.V. Thome, "Demonstration of the Reactivity Constraint Approach on SNL's Annual Core Research Reactor," Transactions of the American Nuclear Society, Vol. 59, Suppl. 1, Aug. 1989, pp. 28-30.

S.H. Lau, J.A. Bernard, K.S. Kwok, and D.D. Lanning, "Experimental Evaluation of Predictive Displays as an Operator Aid," Transactions of the American Nuclear Society, Vol. 59, Suppl. 1, August 1989, pp. 33-35.

S.H. Lau, T. Washio, K.S. Kwok, J.A. Bernard, D.D. Lanning, and F.J. Wyant, "A Methodology for the Control of Core Average Temperature in Spacecraft Nuclear Reactors," Transactions of the Seventh Symposium on Space Nuclear Power Systems, CONF-900109, Albuquerque, NM, January 1990, pp. 956-961.

J.A. Bernard, K.S. Kwok, P.T. Menadier, F.V. Thome, and F.J. Wyant, "Experimental Evaluation of the MIT-SNL Period-generated Minimum Time Control Laws for the Rapid Adjustment of Reactor Power," in Space Nuclear Power Systems 1988, M.S. Genk and M.D. Hoover, eds., Orbit Book Co., Malabar, FL, February 1990, pp. 495-508.

M.K. Waltrip, D.D. Lanning, and J.A. Bernard, "Supervisory Constraint Control of Advanced Multi-modular Nuclear Reactor Plants," 1990 American Control Conference, May 23-25, 1990, San Diego, California.

B.A. Aviles, D.D. Lanning, and J.A. Bernard, "Supervisory Constraints for the Control of Neutronic and Thermal Power in a Pressurized Water Reactor (PWR)," Proceedings of the ANS International Topical Meeting on Advances in Mathematics, Computations, and Reactor Physics, Vol. 5, April 1991, pp. 24.1 (2-1--2-13).

K.S. Kwok, "Automated Startup of Nuclear Reactors: Reactivity Estimation, Computer System Development, and Experimental Evaluations," MIT Department of Nuclear Engineering, Ph.D. Thesis, June 1991.

R.T. Soule, "Advanced Instrumentation Concepts and Their Application to Nuclear Power Plants," MIT Department of Nuclear Engineering, S.M. Thesis, May 1991.

3.1.1.8 Modelling and Fault Diagnosis of Complex Physical Systems

This research is aimed at analyzing abnormal behavior in complex, dynamical physical systems, with the goal of providing meaningful aid to experienced human operators involved in fault diagnosis tasks. The methodology consists of a representation language for capturing the structural and functional features of physical systems; techniques for efficiently modeling system behavior; methods for adaptively processing sensor signals; and techniques for reducing the computational complexity of localizing equipment faults. The complete methodology has been implemented in a program and has been tested for a portion of a chemical process plant; the simulations have shown the viability of the system for modelling complex physical systems and diagnosing faults in such systems. The major results to date include methods for representing, combining, and abstracting the behavior of mechanical systems that exhibit feedback; the use of hierarchical constraints and bounded resources to locate faults; and ways for dynamically abstracting and processing sensor signals via artificial neural networks. Scaling experiments indicate that these techniques are applicable to large, real-world systems.

Investigators: Professor L.M. Lidsky; A.B. Dobrzeniecki

Support: Internal

Recent References:

A.B. Dobrzeniecki and L.M. Lidsky, "Automated Reasoning Methods for Managing Power Plant Equipment Test and Maintenance Requirements," MIT-NPI-TR-020, 1987.

A.B. Dobrzeniecki and L.M. Lidsky, "Modeling and Analysis of Complex Physical Systems Using Model-Based Reasoning with Constraint Satisfaction," Proceedings of IEEE Control Systems Conference, Knoxville, TN, 1989.

L.M. Lidsky, D.D. Lanning, A.B. Dobrzeniecki, K.M. Meyers, and T.G. Reese, "The Use of PROLOG for Computerized Technical Specifications," ANS Topical Meeting on Artificial Intelligence, Snowbird, UT, 1987.

A.B. Dobrzeniecki and L.M. Lidsky, "Reasoning About Sensor Signals Using Neural Networks," Proceedings of the International Symposium on Artificial Intelligence, Robotics and Automation in Space, Kobe, Japan, 1990.

A.B. Dobrzeniecki, "Sensor Data Processing and Fault Diagnosis Using Artificial Neural Networks," Proceedings of the National Science Foundation Workshop on Applications of Artificial Neural Network Methodology in Power Systems Engineering, Clemson, NC, 1990.

3.1.1.9 Space Nuclear Power Applications

A program has been initiated on the study of applications of small nuclear power systems in space. The initial program was supported by the Air Force (Kirtland Air Force Base). The study involved a review of the "STAR-C" type high temperature reactor ex-core, utilizing thermionic conversion to electric power. Design variations have been assessed, and control methods were studied.

An active group of students are now involved in the Space Nuclear Power Program. Work on studies of the neutronic and thermal hydraulic aspects of the "particle bed" fuel for use in space nuclear power systems, initiated as part of the advanced instrumentation and control studies described in Section 3.1.1.7, has been continued. The particle bed fuelled reactors, originally designed by Powell at the Brookhaven National Laboratory, have a potential for very high power densities. The design studies on this concept are continuing in the Nuclear Engineering Department with students supported by NASA fellowships.

Investigators: Professors D.D. Lanning, M.S. Kazimi, J.E. Meyer, and A.F. Henry; Dr. J.A. Bernard; J.K. Witter, T.F. DeLorey, W.E. Casey, and M.G. Houts

Support: US Air Force

Related Academic Subjects:

22.03	Engineering Design of Nuclear Power Systems
22.32	Nuclear Power Reactors
22.033/33	Nuclear Engineering Design

References:

R.S. Tuddenham, "Thermal Hydraulic Analysis of a Packed Bed Reactor Fuel Element," MIT Department of Nuclear Engineering, Engineer's Thesis, May 1989.

W.E. Casey, "Transient Thermal Hydraulic Analysis of a Packed Particle Bed Reactor Fuel Element," MIT Department of Nuclear Engineering, Engineer's Thesis, June 1990.

M.G. Houts, "Out-of-Core Thermionic Space Nuclear Reactors: Design and Control Considerations," MIT Department of Nuclear Engineering, Ph.D. Thesis, January 1991.

3.1.1.10 Design Methods

From the initiation in 1983 of the Reactor Innovation Project it has been appreciated that many problems encountered in actual nuclear power technologies have arisen from the omission of important plant performance factors from the explicit, quantitative design optimization process. Reflecting this evaluation, a consistent component of our advanced reactor research has been a focus upon improved methods to guide design optimization. This has been done previously in the areas of simplification and modularization. In more recent work we have initiated such work in the area of increasing human reliability.

Everyone is familiar with the concept of "user friendly" technologies. However, translating this concept into practical nuclear power technologies has proved difficult. A major cause of this difficulty is the lack of a basic science to guide development of such technologies. Most of the available engineering literature is empirical and limited, as exemplified by the lore of human factors. The literature of human behavior is very large, but little of it has been sufficiently focused upon quantitative prediction of human performance in a way which is useful within the engineering design process. The purpose of our work is to lay the foundations for a scientifically based design approach to increased human reliability.

As with our prior work in the area of simplification this work has involved a component of experimentation using human subjects. The purpose of this work is to quantify the dependence upon the difficulty of a problem of the success frequency of trained subjects in solving it successfully. The reason for investigating this question is the need for designers to know the limits of the difficulty of the tasks which they could assign to human operators, and have a high likelihood of successful performance.

In experiments involving human subjects we found the following results for the dependence of performance on the information content I in a problem, where $I = \log_4 N$, and N is the number of potential solutions.

- For a given type of problem a threshold value of I exists, below which essentially perfect performance can be expected and above which the quality of performance (measured by the frequency of successful problem attacks) declines as a linear function of I

- For problems sufficiently complex that performance is not perfect the gradient of the success frequency as a function of I is approximately constant, independent of the type of problem and skill of the subject

- The effect of the skill of the subject is to increase the threshold value of I at which performance degradation begins to be observed; however, once degradation begins to occur it occurs at the same rate, independent of the skill level of the subject.

The implications of these results for improved designs are that designers of systems should:

- Determine the information content of the problems expected to be presented to system users
- Restrict the allowed problem information level to values below the threshold relevant for the type of problem involved
- Require good training for system users
- Provide in the initial system design instrumentation for automated system analytical aids to be provided for user assistance.

Investigator: Professor M.W. Golay; W.G. He

Support: EPRI

Related Academic Subjects:

22.32	Nuclear Power Reactors
22.33	Nuclear Engineering Design
22.38	Reliability Analysis Methods
22.40J	Advanced Reliability Analysis and Risk Assessment
22.82	Engineering Risk-Benefit Analysis

Recent References:

M. Golay, "Methodology for Design of Advanced Nuclear Power Reactors," submitted to *Nuclear Engineering and Design* (1991).

W.G. He, "The Dependence of Human Deductive Capabilities upon Problem Complexity," S.M. Thesis, MIT Nuclear Engineering Department (1990).

W.G. He and M.W. Golay, "The Dependence upon Complexity of Human Success Rates in Deductive Problem Solving," Intl. Conf. on Probabilistic Safety Assessment and Management, Beverly Hills, CA (1991).

3.1.1.11 Socio-Institutional Research

The main recent research of the Program for Advanced Nuclear Power Studies related to socio-institutional issues has concerned continued advancement of non-prescriptive safety regulation. This has been done in two areas:

- Stimulating the Nuclear Regulatory Commission (NRC) to initiate formulation of non-prescriptive regulations

- Initiating formulation of a non-prescriptive safety evaluation structure for use in the USDOE's New Production Reactor (NPR) project.

In prior work, sponsored by the NRC, a basic approach to non-prescriptive safety regulation was formulated, and its potential benefits for both design and safety were illustrated (Ref. 1). Following intermittent negotiations with the NRC research staff and others a briefing was arranged for the NRC commissioners to make the case that the NRC should begin to institute a non-prescriptive safety regulatory approach.

Following this briefing the agency undertook an investigation of how to formulate maintenance-oriented non-prescriptive regulations. This effort resulted in issuance of draft regulations in June 1991 requiring power reactor license holders to show, using test data, that their emergency AC power systems would satisfy explicit reliability performance goals. The NRC also issued guidance that ultimately expected plant performance criteria were to be used as the basis, by license holders, for formulating and justifying to the agency the adequacy of their individual plant maintenance plans. These actions are modest steps in the direction of creating a comprehensive non-prescriptive regulatory system, but they are the strongest actions yet taken in this area. It is important that these initiatives prove to be successful. Consequently, a major goal of the Program will be to make future contributions to that success.

A project has been initiated to formulate a non-prescriptive safety regulatory approach for use in improving the safety of the DOE's New Production Reactor. The two major areas of focus are:

- Measuring the extent to which the level of safety of the NPR is equivalent to that of civilian power reactors

- Evaluating whether the safety capabilities of the NPR remain at their initial levels during the life of the plant.

The fundamental basis of this work is use of probabilistic risk assessment, coupled with explicit evaluations of the uncertainties associated with expected risk estimates. These evaluations are used to test the degree to which a reactor plant satisfies explicit, performance-based acceptance criteria. They also reveal effective ways to improve overall performance and to reward good designs and operations.

Investigators: Professors M.W. Golay, V.P. Manno (Tufts University)

Support: USDOE

Related Academic Subjects:

22.32	Nuclear Power Reactors
22.33	Nuclear Engineering Design
22.38	Reliability Analysis Methods
22.40J	Advanced Reliability Analysis and Risk Assessment
22.811	Environmental Impacts of Electricity (new title: Energy, Electricity, and the Environment)
22.82	Engineering Risk/Benefit Analysis

Recent Reference:

M.W. Golay, V.P. Manno and C. Vlahoplus, "Nonprescriptive Nuclear Safety Regulation: The Example of the Loss of Offsite Power," *Nuclear Safety* 29, 6-20 (1988).

3.1.2 Reactor Physics

Reactor physics is concerned with the space, time and energy behavior of neutrons and neutron-induced reactions in nuclear reactors. While the numerical results differ from application to application as, say, between thermal and fast reactors, many of the experimental and calculational techniques used to study and define neutron and reaction behavior are basically similar. Furthermore, reactor physics and reactor engineering are closely interrelated. Consequently there is considerable overlap in the work described in the following sections.

3.1.2.1 Subjects of Instruction

The basic subjects of instruction in reactor physics include the undergraduate subject 22.021 Nuclear Reactor Physics and the three graduate subjects, Nuclear Reactor Physics I, II, and III, which are offered in a three-semester sequence.

22.021 Nuclear Reactor Physics, is an introduction to fission reactor physics covering reactions induced by neutrons, nuclear fission, slowing down of neutrons in infinite media, diffusion theory, the few-group approximation, and point kinetics. Emphasis is placed on the nuclear physics bases of reactor design and their relation to reactor engineering problems. Lectures are in common with 22.211; homework, exams, and recitation are separate.

22.211 Nuclear Reactor Physics I, is an introduction to problems of fission reactor physics covering nuclear reactions induced by neutrons, nuclear fission, slowing down of neutrons in infinite media, diffusion theory, the few group approximation, and point kinetics. Emphasis is placed on the nuclear physical bases of reactor design and their relation to reactor engineering problems.

22.212 Nuclear Reactor Physics II, deals with problems relating to the operation of nuclear reactors at power, including few group and multi-group theory, heterogeneous reactors, control rods, poisons, depletion phenomena, and elementary neutron kinetics. Attention is directed to the application of reactor theory to actual reactor systems.

22.213 Nuclear Reactor Physics III, considers current methods for predicting neutron behavior in complex geometrical and material configurations. Emphasis is placed on the transport equation and methods for solving it, systematic derivation of group diffusion theory and homogenization, synthesis, finite element response matrix, and nodal techniques applied to reactor analysis.

Most undergraduate students in the Department take 22.021, and most graduate students take 22.211. Those whose special interests lie in the general area of nuclear reactor physics also take 22.212 and 22.213.

22.09 Principles of Nuclear Radiation Measurement and Protection, is the undergraduate offering of graduate subject 22.59.

22.59 Principles of Nuclear Radiation Measurement and Protection, combines lectures, demonstrations, and experiments. Covers effects of radiation on persons; control of radiation exposure within applicable standards; theory and use of α, β, and n detectors and spectrometers; use of isotopes, radiation shielding, and dosimetry. Includes demonstration and experiments using the MIT research reactor, accelerators, and power reactors.

22.35 Nuclear Fuel Management, characterizes the space-time history of nuclear fuels and the effects upon fuel costs. Topics covered include physical and material constraints upon fuel and their effects on fuel management policies; methods of analysis for the optimization of fuel costs; and qualitative description of current methods of management and areas of future development.

22.42 Numerical Methods in Engineering Analysis, is a subject in numerical and mathematical methods which deals with analytic and numerical methods useful in solving problems in reactor physics. Review of specific mathematical techniques for solving engineering problems including linear algebra, finite difference equations, and numerical solution of equations. Special topics such as multigroup diffusion methods.

22.44 Modeling and Simulation, introduction to the processes of constructing models of physical and nonphysical systems and the simulation of model behavior. Topics include a general view of modelmaking and their mathematical representation, as well as procedures useful in computation. Specific examples drawn from such diverse fields as social systems, particle transport, chaos and turbulence, Markov processes, and plasma simulation. No specific numerical background is necessary but some experience with computer use is expected.

3.1.2.2 Reactor Physics Research

The long-range goal of the theoretical work on reactor physics being carried out in the Department is to increase the accuracy and/or decrease the cost of analyzing the behavior of large power reactors. Since the application is more immediate and since the calculations are both cheaper to perform and more challenging to the method, specific developments are usually carried out and tested for thermal reactors. However, many of the ideas apply equally well to fast reactor systems. The ultimate goal is to develop a practical capability to analyze space-dependent nuclear phenomena throughout lifetime under both static and dynamic conditions. Very real progress towards reaching that goal has been made.

It is becoming generally accepted by the utility industry that the most efficient procedure for predicting the detailed behavior of the neutron population in a large power reactor is to make use of a systematically derived nodal method. The basic idea of a nodal scheme is to partition the reactor into a number of subvolumes called nodes, the volume of a given node for a light water reactor being approximately 20 x 20 x 30 cm^3. Homogenized few-group cross sections are found systematically for each node along with correction factors (called "discontinuity factors") that correct for the fact that the homogenized node is actually heterogeneous. The nodal equations (for either static or transient situations) are then solved, and, if desired, local fuel pin powers are reconstructed.

Production versions of nodal codes have been created and are now being used by utilities in the United States. Many of the ideas underlying these codes have been developed and first tested at MIT. We have continued this effort during the past two years, devoting some attention to the analysis of static problems but with an increasing emphasis on predicting dynamic behavior.

1) Static Reactor Analysis

The nodal code QUANDRY was developed at MIT some twelve years ago. It has now been reprogrammed (and renamed "ARROTTA") by EPRI and is being used by some utilities. QUANDRY makes use of analytical expressions to describe the transverse integrated, two-group fluxes within a node, and updating the resultant matrix elements during a transient is quite expensive. We have now completed the static part of a new code (QUAGMIRE) in which the intranodal fluxes are described by quartic polynomials and in which the number of neutron energy groups is not restricted to two (as in QUANDRY). Updating coefficients is much faster and a new iteration scheme also improves running time.

QUANDRY and QUAGMIRE are in XYZ geometry. However, certain designs (notably those contemplated for the New Production Reactor) are in hex-Z geometry. Accordingly, an experimental two-group nodal code in two-dimensional regular hexagon geometry and employing the finite difference approximation corrected by discontinuity factors was created. Studies with that code indicated that, for reactors of the Savannah River type, discontinuity factors derived from infinite lattice calculations are not sufficiently accurate to provide acceptable results for finite, reflected reactors. Since a major part of the error which such factors had to correct was that associated with using the finite difference approximation with ~ 18 cm mesh spacings, we turned to a higher order, quadratic polynomial scheme for solving the nodal diffusion equations. Accuracy was improved substantially, and a three-dimensional (hex-Z) general energy group code has now been completed.

2) Transient Reactor Analysis

A) Basic Model Studies

There are theoretical reasons for expecting that use of so-called bilinearly weighted few-group parameters, as opposed to regular flux-spectrum-weighted parameters, should improve the accuracy of predicted transient behavior. Earlier studies based on a variational principle showed that this was often, but not always, the case. Further studies, based on a more complicated but more physically satisfying principle, resulted in bilinearly weighted parameters that consistently improve accuracy. However, the study also showed that the standard flux-weighted parameters produce acceptably accurate results. Hence -- at least for the cases examined (typical light water reactors) -- there appears to be no reason to abandon the present standard procedures for finding few-group cross sections.

B) Method Development

A long-range goal of the reactor physics effort is to provide fast and accurate procedures for predicting detailed, space-time behavior of reactor power in faster than real time. Such information can be used for on-line monitoring or even automatic digital control. Thus we seek schemes that give promise of reduced computational effort with negligible loss in accuracy. In this connection, the possibility of using coarse mesh finite difference equations corrected by discontinuity factors found from reference, full core, static calculations was examined and found to provide acceptably accurate prediction of space-dependent behavior during typical PWR transients.

In the same vein we are currently examining a nodal model that uses a quadratic representation of the intra-nodal flux in the fast group and a quartic representation in the thermal group.

A major effort has recently led to the development of a procedure for inferring space-dependent, transient, reactor power and reactivity from the output of (noisy) neutron detectors distributed either internally or in the reactor reflector. The group-fluxes are represented as a linear combination of a set of precomputed static flux shapes which bracket the reactor conditions (different power levels, different central rod positions) expected during the transient. The time-dependent coefficients of combustion for these shapes are found from a least square fit to the counter readings. No information about the transient thermal hydraulic conditions is needed to carry out the synthesis. The method is fast: a 180 second rod-withdrawal transient for a large PWR took 80 seconds of micro-VAX computer time.

Because of this success, a code applying the point synthesis method (combined with a thermal-hydraulic model) to an entirely theoretical prediction of transient behavior is now being programmed.

C) Code Development

The equations specifying the transient extension of the quartic, three-dimensional, (Cartesian geometry) nodal code QUAGMIRE and the quadratic, hex-Z code have been derived, and computer programs embodying these equations are being created. In addition, a quadratic polynomial, nodal code in RZ geometry is being created. All these codes will include thermal-hydraulic models and will make use of discontinuity factors to improve accuracy.

D) Testing of Approximate Methods

An important application of calculational methods having a high order of accuracy or capable of simulating very complex physical situations is the testing of approximate methods or experimental procedures. Along these lines, a student (under the prime direction of INEL) has used the Monte Carlo code MCNP to analyze proposed designs for the Advanced Neutron Source Reactor, thus permitting evaluation of a finite difference diffusion theory code applied to the same end. Similarly, the space-time nodal code QUANDRY has been used to evaluate the validity of the point kinetics model (used in conjunction with a control rod bank calibration curve) for predicting transient behavior during start-up from source level to full power. (The point method was found to be very inaccurate.) QUANDRY was also used to validate theoretically a standard method of calibrating rod banks in PWR's by a succession of small rod bank withdrawals compensated by the addition of soluble neutron absorbing material. Here the numerical test showed that the method should be very accurate.

Investigators: Professor A.F. Henry; J.T. Broda, M.E. Byers, J.M. Fox, J.C. Gehin, R.P. Jacqmin, K. Lee, S.A. Parra, E. Redmond, Y.A. Shatilla, C. Steele, F. Tarantino, and M.L. Zerkle

Support: MIT Energy Laboratory Utility Program; DOE; Oak Ridge National Laboratory

Related Academic Subjects:

22.211	Nuclear Reactor Physics I
22.212	Nuclear Reactor Physics II
22.213	Nuclear Reactor Physics III
22.42	Numerical Methods in Engineering Analysis

Recent References:

A.F. Henry, "The Physics of Thermal Reactors: A View of Where We Are and How We Got There." International Conference on the Physics of Reactors: Operation, Design and Computation, Supplementary Volume, p. 29, Marseille, April 1990.

Myung H. Kim and A.F. Henry, "Flux-Adjoint Weighted Few-Group Cross Sections Used for Reactor Transient Analysis," Nuclear Science and Engineering, Vol. 103, No. 3, p. 276-282 (1989).

K. Rempe, K. Smith (Studsvik), A. Henry (MIT), "Verification of the SIMULATE-3 Pin Power Distribution," Proc. 1988 Int. Reactor Physics Conf., Jackson Hole, Wyoming, Sept. 18-22, Vol. III, p. 19.

K.R. Rempe, K.S. Smith and A.F. Henry, "SIMULATE-3 Pin Power Reconstruction: Methodology and Benchmarking," Nuc. Sci. Eng. 103, 334-342 (1989).

F.A. Tarantino, R.P. Jacqmin, A.F. Henry, "The Validity of the Point Kinetics Model During Reactor Start-Up," International Nuclear Simulation Symposium, Schliersee; October 1990 - Proceedings, Edited by Moshe R. Heller, Springer-Verlag.

R.P. Jacqmin and A.F. Henry, "A Semi-Experimental Determination of Three-Dimensional Plus Flux Shapes and Reactivity," Transactions of the International Topical Meeting on Advances in Mathematics, Computations and Reactor Physics, Pittsburgh (April 1991).

3.1.2.3 Fuel Management and Fuel Cycle

With the retirement of Professor Driscoll, the level of activity in this area is now minimal. However, subject 22.35, Nuclear Fuel Management, was offered as a reading subject spring term 1991. A monograph on the linear reactivity model of reactor core behavior, based in large part on earlier research and teaching efforts at MIT, has been published by the ANS.

For closely related work in the area of nuclear waste management, see Section 3.4.6.

Investigator: Professor (emeritus) M.J. Driscoll

Support: Internal

Related Academic Subjects:

22.211	Nuclear Reactor Physics I
22.212	Nuclear Reactor Physics II
22.213	Nuclear Reactor Physics III
22.35	Nuclear Fuel Management
22.77	Nuclear Waste Management

Recent Reference:

M.J. Driscoll, T.J. Downar and E.E. Pilat, "The Linear Reactivity Model for Nuclear Fuel Management," American Nuclear Society (1990).

3.1.3 Reactor Engineering

Because of the important and the worldwide expanding role of nuclear power reactors in central station electric power generation, the Department gives major attention to teaching and research in a broad spectrum of reactor engineering fields, including reactor thermal analysis, reactor dynamics, power reactor safety, nuclear reactor and energy system design, nuclear fuel, and power system management.

3.1.3.1 Subjects of Instruction

A total of fourteen subjects of instruction are offered under the heading of reactor engineering by the Department. The following paragraphs present a description of all of the subjects in reactor engineering.

22.03 Engineering Design of Nuclear Power Systems, is an undergraduate offering which introduces nuclear engineering principles to analyze the system design of current US central station power reactors. Topics covered include: the elementary economic aspects of electric power generation; heat generation, transfer, and transport; radiation protection and safety analysis.

22.031 Engineering of Nuclear Reactors, topics covered include power plant thermodynamics, reactor heat generation and removal (single-phase as well as two-phase coolant flow and heat transfer), and structural mechanics. Engineering considerations in reactor design. Lectures are in common with 22.312, but assignments differ.

22.033 Nuclear Systems Design Project, is a group design project involving integration of reactor physics, control, heat transfer, safety, materials, power production, fuel cycle management, environmental impact, and economic optimization. The subject provides the student with the opportunity to synthesize knowledge acquired in other subjects and apply this knowledge to practical problems of interest in the reactor design field. The subject meets concurrently with 22.33, but assignments differ.

22.311 Energy Engineering Principles, is intended primarily for students who did their undergraduate work in physics or other fields which did not provide much instruction in engineering principles. Topics dealt with include fundamentals of engineering thermodynamics, fluid flow, heat transfer, and elasticity, with examples of applications to various energy sources.

22.312 Engineering of Nuclear Reactors, covers engineering principles of nuclear reactors emphasizing applications in central station power reactors: power plant thermodynamics; energy distribution and transport by conduction and convection of incompressible one- and two-phase fluid flow in reactor cores; and mechanical analysis and design.

22.313 Advanced Engineering of Nuclear Reactors, emphasizes thermo-fluid dynamic design methods and criteria for thermal limits of various reactor types. Topics treated include fundamentals of transient heat transfer and fluid flow under operational and accidental conditions. Detailed analysis of fluid flow and heat transfer in complex geometries.

22.314J Structural Mechanics in Nuclear Power Technology, deals with techniques for structural analysis of nuclear plant components. It is a joint subject with three other engineering departments (Civil, Mechanical, and Ocean) since nuclear plant components illustrate applications of these disciplines. The structural aspects of plant components are discussed in terms of functional purposes and operating conditions (mechanical, thermal, and radiation). A designer's view is adopted, emphasizing physical rationale for design criteria and methods for executing practical calculations. Application topics include fuel performance analysis, reactor vessel safety, flow induced vibrations, and seismic effects.

22.32 Nuclear Power Reactors, is a descriptive survey of engineering and physics aspects of current nuclear power reactors. Design details are discussed including requirements for safety of light and heavy water reactors, high temperature gas-cooled reactors, fast reactors (liquid-metal and gas-cooled), and fast breeder reactors. Reactor characteristics are compared both in class and by individual student projects. Development problems are discussed and potentials for future improvements are assessed.

22.33 Nuclear Engineering Design, is a group design project involving integration of reactor physics, control, heat transfer, safety, materials, power production, fuel cycle management, environmental impact, and economic optimization. The subject provides the student with the opportunity to synthesize knowledge acquired in other subjects and apply this knowledge to practical problems of interest in the reactor design field. The subject meets concurrently with 22.033, but assignments differ.

22.35 Nuclear Fuel Management, prepares students for work in the area of nuclear fuel economics and management. Characterizes the space-time history of nuclear fuels and the effects upon fuel costs. Topics covered include physical and material constraints upon fuels and their effects on fuel management policies; methods of analysis for the optimization of fuel costs; and a qualitative description of current methods of management and areas of future development. (Reading Course)

22.36J Two-phase Flow and Heat Transfer, is a specialized course in the power reactor engineering curriculum offered in conjunction with the Mechanical Engineering Department. Topics treated include phase change in bulk stagnant systems, kinematics, and dynamics of adiabatic two-phase flow, with boiling and/or evaporation, thermal and hydrodynamic stability of two-phase flows and associated topics such as condensation and atomization. Both water and liquid metal applications are considered under each topic where data exists.

22.38 Reliability Analysis Methods, covers the methods of reliability analyses including fault trees, decision trees, and reliability block diagrams; discusses the techniques for developing logic diagrams for reliability assessment, the mathematical techniques for analyzing them, and statistical analysis of required experience data. Practical examples of their application to the risk assessment of nuclear power reactors and other industrial operations are discussed.

22.39 Nuclear Reactor Operations and Safety, deals with the principles of operating nuclear reactor systems in a safe and effective manner; emphasizes light water reactor systems with transient response studies including degraded core recognition and mitigation. Other topics include: consequence analysis and risk assessment; lessons from past accident experience; NRC licensing and regulations. Demonstrations include operation of the MIT Research Reactor and the use of a PWR concept simulator. An optional lab section is available.

22.40J Advanced Reliability Analysis and Risk Assessment, deals with the extended application and use of reliability and probabilistic risk analysis methods. Methods for common mode failure analysis and treatment of dependencies are covered. Other areas discussed are Bayesian statistics applied to reactor safety problems, error sensitivity analysis, and the application of selected reliability analysis computer codes. Case studies are made of safety analyses performed in nuclear and non-nuclear areas.

Most undergraduate students in the Department take 22.03, 22.031, and 22.033, and most graduate students take 22.311 or 22.312. Those whose special interests lie in the general area of reactor engineering or related areas choose various courses in advanced engineering subjects.

3.1.3.2 Safety Characteristics of Operating Light Water Reactors of Western Design

This project presents and compares the safety characteristics of operating light water nuclear reactors of Western design. Consequently, designs of pressurized water reactors by US vendors, Siemens (Germany) and Framatome (France), and boiling water reactors by General Electric, Siemens and ABB (Sweden) are discussed.

The methodology involved identifying the standard plant designs each vendor has produced and comparatively presenting their safety characteristics in the areas of Reactivity Control, Fuel, Pressure Control, Reactor Vessel Materials, Water Level Management, Power Sources, Electric Networks, Emergency Water Makeup, Post-Accident Heat Removal, Containment and Severe Accident Features. Such a comparative presentation has not been published to date.

A second unique feature of the project is the chronological listing of all plants of a given standard design by country. This listing, which we refer to as the family trees, graphically illustrates the evolving deployment of plants of each standard design. It is interesting to note that most designers did not have this information collected in this form in their archives. Rather, with their cooperation we constructed it from available records and the recollections of key design personnel. From such a listing it is possible to identify the general characteristics of any specific plant although the reader is cautioned that many plants have significant features which are atypical of their nominal standard type designation. This is because of the lack of standardization within the nuclear industry (with the notable exception of France) in the initial design and post construction upgrade phases.

Investigators: Professors N.E. Todreas, D.D. Lanning; Mirela Gavrilas, Pavel Hejzlar, Thomas Ippolito, Youssef Shatilla

Support: US Department of Energy

Related Academic Subjects:

22.211	Nuclear Reactor Physics I
22.312	Engineering of Nuclear Reactors
22.32	Nuclear Power Reactors
22.39	Nuclear Reactor Operations and Safety

Recent Reference:

M. Gavrilas, P. Hejzlar, N.E. Todreas and Y. Shatilla, "Report on Safety Characteristics of Light Water Reactors of Western Design," Draft, MIT NED, December 1990.

3.1.3.3 An International Program For Enhanced Nuclear Power Plant Safety

This project is concerned with improving the operations of existing power plants so as to reduce the likelihood of a major accident. A serious accident at any plant will have a profound effect on every other plant in the world. It is literally true that every national nuclear program is hostage to every other nuclear program. Thus, this project is international in scope and sponsorship.

The major areas of research are

(1) The Science and Technology of Service and Maintenance.

The focus is upon improved technology to reduce the likelihood of hardware failures that could be the precursor to an accident.

(2) The Science of Management of Nuclear Power Plants.

The research is directed toward developing an understanding of how organizational structure and behavior can influence plant safety and operations.

(3) The Role of Public Policy in the Safe Operation of Nuclear Power Plants.

In this part of the project we are attempting to determine the variety of external agents that influence nuclear energy policy and, in turn, how these policies affect nuclear plant operations.

Investigators: Professors K.F. Hansen, N.C. Rasmussen, and N. Siu; plus other departments

Support: Multiple sponsors (11 US sponsors and 8 international sponsors)

Related Academic Subjects:

22.312	Engineering of Nuclear Reactors
22.38	Reliability Analysis Methods
22.39	Nuclear Reactor Operations and Safety

3.1.3.4 Thermal Phenomena in Severe LWR Accidents

Under severe accident conditions, the heat transferred from the core melt to concrete can lead to concrete decomposition accompanied by gas generation, which, along with direct heating of the atmosphere, will lead to a pressure rise in the containment. The cooling rate of the core melt and the amount of gas generated by concrete decomposition will also affect the degree of which fission products may be released from the melt.

There is some uncertainty in the possible heat transfer from the melt to concrete. Data from Sandia, ANL and Germany were reviewed and analyzed using the DECOMP code of EPRI. It was seen that the initial contact heat transfer will have a strong effect only for a short time after the interaction.

The potential for early failure of the MARK-I BWR containment following the ejection of core melt materials outside the vessel has been one of the concerns in risk analysis of nuclear reactor severe accidents. Such a potential arises as a result of the possible rapid spreading of the melt onto the drywell floor towards the steel liner which may result in its failure due to thermal attack by the high temperature melt. The conditions that may lead to failure have been evaluated using numerical values based on a semi-empirical heat transfer model that was developed at MIT.

Investigators: Professor M. Kazimi; K. Vilece

Support: Electric Power Research Institute and Fauske and Associates

Related Academic Subjects:

22.312	Engineering of Nuclear Reactors
22.313	Advanced Engineering of Nuclear Reactors
22.36J	Two-Phase Flow and Heat Transfer

Recent References:

M.S. Kazimi, "On the Liner Failure Potential in MARK-1 BWR's," Nuclear Science & Engineering, Vol. 103, 1989: 59-69.

K.D. Vilece, "Severe Accident Analysis: Core-Concrete Heat Transfer Models in the DECOMP Code," S.B. Thesis, June 1990.

3.1.3.5 Accident Scenario Analysis in Risk Assessment

This project is aimed at upgrading the currently used event tree analysis method for modeling accident scenarios. The event tree is well-suited for treating scenarios involving logical dependencies between failure events. It is less well-suited for scenarios in which the physical behavior (e.g., pressurizer level response) of the system and dynamic operator actions in response to the physical behavior are major factors in determining system success or failure, as was the case in the TMI-2 accident. To address this fault, we have developed a dynamic event tree methodology for treating complex scenarios.

The dynamic event tree approach differs from conventional event trees in that the integrated, time-dependent response of the plant/operating crew system is treated explicitly. The approach tracks changes in the operating crew's internal state (including its current state of knowledge) as well as changes in the plant hardware state and process variable values.

The dynamic event tree approach has been applied in an analysis of a pressurized water reactor steam generator tube rupture (SGTR) accident. Quantitatively, the analysis indicates that conventional event tree analyses of SGTR may actually be overly conservative. Qualitatively, the analysis identifies a number of potentially important scenarios that require a more detailed treatment than that provided by conventional analysis. The analysis results also identify a number of potential problems with current operating procedures whose rectification could improve the dynamic response of the operating crew to the accident.

Investigators: Professors N. Siu and N. Rasmussen; C. Acosta

Support: NRC

Related Academic Subjects:

22.38	Reliability Analysis Methods
22.40J	Advanced Reliability Analysis and Risk Assessment

Recent References:

N. Siu, "Dynamic Accident Sequence Analysis in PRA: A Comment on 'Human Reliability Analysis - Where Shouldst Thou Turn?'" Reliability Engineering and System Safety, 29, 1990.

N. Siu and C. Acosta, "Modeling Dynamic Interactions Between Humans and Hardware in PRA," NUREG/CP-0114, Proceedings of 18th Water Reactor Safety Information Meeting, Rockville, MD, October 22-24, 1990, pp. 149-174.

N. Siu and C. Acosta, "Dynamic Event Tree Analysis - An Application to SGTR," Society for Risk Analysis International Conference on Probabilistic Safety Assessment and Management, Beverly Hills, CA, February 4-7, 1991, pp. 413-418.

3.1.3.6 Dynamic Human Error During Accident Sequences

A central feature of the dynamic response of a nuclear power plant during an accident sequence is the behavior of the operating crew. This project involves the development and coding of a simulation model for the crew under accident conditions. With such a model, the relative importance of various group characteristics (e.g., group structure, distribution of ability, distribution of confidence) with respect to accident response can be determined.

The model treats each member of the crew as a separate, reasoning entity. Since the crew is highly trained in its response to an accident situation, and since the crew actions in such situations are highly proceduralized, most of the reasoning process is represented using scripts. However, more complex problems (e.g., fault diagnosis) are treating using a separate "control activity." Individuals in the crew interact via communication. Communication can involve non-task related as well as task-related information.

To date, the model has been applied towards the analysis of the behavior of three actual nuclear power plant crews during their response to a steam generator tube rupture training exercise. (The model parameters characterizing these crews are quantified based on the results of interviews with these crews and their training supervisors.) Results indicate an excellent agreement between the predicted results and actual observations. Sensitivity analyses to determine the relative importance of selected model parameters are ongoing.

Investigators: Professors N. Siu and D. Lanning; Y. Huang and V. Dang

Related Academic Subjects:

22.38	Reliability Analysis Methods
22.40J	Advanced Reliability Analysis and Risk Assessment

Recent References:

Y. Huang, N. Siu, D. Lanning, and J. Carroll, "Data Analysis - Operating Crew Characteristics and Interactions During Steam Generator Tube Rupture Simulation," MITNE-290, June 1990.

Y. Huang, N. Siu, D. Lanning, and J. Carroll, "Modeling Control Room Crews in Accident Sequence Analysis," to be published in Transactions of the Eleventh International Meeting on Structural Mechanics in Reactor Technology, Tokyo, Japan, August 18-23, 1991.

3.1.3.7 Simulation Methods in Risk Assessment

The purpose of this project is to develop practical simulation-based tools for use in risk assessment. These tools will be useful in treating the dynamic behavior of systems, behavior which cannot be adequately treated using current models.

Two major weaknesses in the simulation approach are: (a) the need to employ many simulation trials to treat the occurrence of rare events, and (b) the lack of structural information in the results of a simulation analysis (which are needed to determine the major contributors to risk). A survey of methods to address the first problem has been performed, and a simple importance sampling method relevant to accident scenario analysis has been developed. The method has been satisfactorily demonstrated on a test problem for a chemical process control system with continuous feedback. Work on the second problem, and on the identification of an improved simulation language (to succeed the SIMSCRIPT II.5 language currently used) is ongoing.

Investigators: Professors N. Siu and N. Rasmussen; V. Dang

Related Academic Subjects:

22.38	Reliability Analysis Methods
22.40J	Advanced Reliability Analysis and Risk Assessment

Recent Publications:

V.N. Dang, "Improved Methods for Simulation-Based Risk Assessment," S.M. Thesis, February 1991.

N. Siu, "Risk Assessment Methods for Dynamic Process Systems: A Review," to appear in Risk Assessment in the Chemical Process Industries, S. Kaplan, M. Kazarians, and R.F. Boykin, eds., CRC Press, Inc., Boca Raton, Florida, 1991.

V.N. Dang, D.L. Deoss, and N. Siu, "Event Simulation for Availability Analysis of Dynamic Systems," to be published in Transactions of the Eleventh International Meeting on Structural Mechanics in Reactor Technology, Tokyo, Japan, August 18-23, 1991.

3.1.3.8 PRA Applications to Improve Plant Service and Maintenance

Probabilistic risk assessment methods can be used in a variety of ways to assist service and maintenance activities and thereby reduce the likelihood of accidents. Two projects are currently underway that apply this concept. The first project is concerned with the modeling of accident precursors; its results can be used to direct maintenance efforts to reduce the likelihood of precursor events. An analysis of a particular precursor, loss of main feedwater, has identified areas of opportunity where improved maintenance of a relatively small number of components can lead up to a two-fold decrease in precursor frequency. The analysis also identifies a potential weakness in a current feedwater control system design. The second project models the impact of maintenance program changes on the frequency of common cause failure events and power plant risk. The results of this work can be used to identify program changes that are effective in controlling risk.

Investigators: Professors N. Siu and N. Rasmussen; V. Dang

Related Academic Subjects:

22.38	Reliability Analysis Methods
22.40J	Advanced Reliability Analysis and Risk Assessment

Recent Publications:

N. Siu and N. Rasmussen, "Using PRA to Assist Nuclear Power Plant Service and Maintenance," presented at the Conference on the MIT International Program on Enhanced Nuclear Power Plant Safety, March 8-9, 1990.

N. Siu, J. Yoshimura, M. Ouyang, K. Credit, and N.C. Rasmussen, "PRA Applications in Nuclear Power Plant Service and Maintenance," to be presented at ICONE-1, the 1st JSME-ASME Joint International Conference on Nuclear Engineering, Tokyo, Japan, November 4-7, 1991.

3.1.4 Nuclear Materials and Radiation Effects

The nuclear materials program has three major objectives: (1) to provide students in the Department with sufficient background in the principles of physical metallurgy and physical ceramics to incorporate a fuller consideration of reactor structural and fuel materials in their thesis programs; (2) to advance reactor materials technology in the areas of materials selection, component design, irradiation behavior modeling, environmental degradation of materials, safeguards analysis, quality assurance, and reliability assessment; (3) to conduct instructional and research programs into both the fundamental nature of radiation effects to crystalline solids and the interrelationships between radiation-induced structural problems on an interdepartmental and interdisciplinary manner in the general fields of energy conversion, energy transmission, environmental effects, fusion technology, and other appropriate technology as related to power production.

3.1.4.1 Subjects of Instruction

In the area of nuclear materials and radiation effects, 22.070J Materials for Nuclear Applications is available for undergraduates. Graduate students can select from other subjects described below.

22.070J Materials for Nuclear Applications, is an introductory subject for all students. Topics covered include applications and selection of materials for use in nuclear applications, radiation damage, radiation effects and their effects on performance of materials in fission and fusion environments. The subject meets concurrently with 22.70J, but assignments differ.

22.70J Materials for Nuclear Applications, is the corresponding introductory subject for graduate students. This subject meets concurrently with 22.070J, but assignments differ.

22.71J Physical Metallurgy, is the base physical metallurgy subject for graduate students who did their undergraduate work in engineering and science fields which did not provide formal instruction in metallurgy and/or materials science. Discusses structure-property relationships in metallic alloys selected to illustrate basic concepts of physical metallurgy and alloy design. Considers mostly mechanical properties. Also considers structural features: structural stability, grain size, interstitial and substitutional solutes, precipitates, second phase particles, eutectics and eutectoids, and composites. This and subsequent courses are conducted jointly between the Department of Nuclear Engineering and the Department of Materials Science and Engineering.

22.72J Corrosion: The Environmental Degradation of Materials, covers topics related to the fundamentals and applications of the interaction of the environment, including radiation, with structural materials in engineering systems. Forms of corrosion and corrosion testing. Methods of corrosion control including alloy selection, water chemistry, design rules, anodic and cathodic protection, and coatings. Course is taught with 3.54 in the Department of Materials Science and Engineering.

22.74J Mechanical Behavior of Materials, covers basic topics related to the mechanical behavior of materials, including the effects of radiation. Reviews elasticity theory. Elements of plasticity theory. Strengthening mechanisms in metals. Mechanical behavior of polymers. Application of principles of linear elastic fracture mechanics to brittle fracture and to fatigue crack propagation. Micromechanisms of fracture (cleavage, ductile fracture, fatigue, creep, stress corrosion cracking). Principles of failure analysis.

3.1.4.2 Environmentally Assisted Cracking of Ni-Cr-Fe Alloys

An investigation is being conducted to investigate the effect of environmental and microstructural factors on the cracking susceptibility of Ni-Cr-Fe alloys used in nuclear power systems. The program is designed to develop an understanding of the behavior of existing alloys and to develop more advanced materials. The program consists of a number of major thrusts:

Environmental Assisted Cracking of High Strength Materials for Nuclear Applications: The goals of this research program are: (1) to understand the fundamental mechanisms of embrittlement of nickel-base alloys in high temperature aqueous systems and (2) to develop materials that are resistant to embrittlement. The detailed electrochemical and mechanical behavior of nickel-base alloys are being studied. Environmental effects being studied include stress corrosion cracking, hydrogen embrittlement and corrosion fatigue. As a result of this program a new series of environmentally assisted cracking resistant alloys has been developed and a more fundamental understanding of the interaction between an aqueous environment and high strength materials has been developed.

Initiation and Growth of Short Cracks in High Strength Nickel Base Alloys: The initiation and growth of small cracks is being investigated using a newly developed crack detection technique that makes use of multifrequency AC potential drop. The investigation is being conducted in high temperature aqueous systems. The goal of the program is to quantify the relationship between processing variables and environmentally assisted crack initiation in nickel-base alloys.

Hydrogen Diffusion and Trapping in *Ni-Cr-Fe* Alloys: The interaction between hydrogen and microstructure in *Ni-Cr-Fe* alloys is being studied. The role of precipitate type and morphology on hydrogen trapping is being studied. Information from this program will be used to model hydrogen embrittlement phenomena. This is the first research that seeks to understand the details of the interaction between hydrogen and precipitation hardened metallic materials.

Modeling Crack Tip Chemistry in Aqueous Systems: The goal of this research program is to develop an understanding of the evolution of the environment at the tip of a sharp crack such as would exist in environmentally sensitive fracture. Effects being modeled include: (1) convection, (2) diffusion ion migration and chemical and hydrodynamic boundary layer effects. The model developed as a result of this program is the most complete and fundamentally correct model yet developed.

Effects of Radiation on the Environmental Cracking of Metals: The goal of this research program is to develop analytical techniques for modeling the transient and steady state concentration of radiolytically created chemical species in high temperature aqueous environments. In addition to model development, a comprehensive thermodynamic data base is being built. This program is conducted jointly with Professor Harling at the MIT Nuclear Reactor Laboratory.

Irradiation Assisted Stress Corrosion Cracking in Boiling Water Reactors: The irradiation assisted stress corrosion cracking (IASCC) behavior of stainless steels and structural materials is being investigated at the MIT Nuclear Reactor Laboratory. In-core stress corrosion cracking and tensile behavior of materials are being evaluated using a specially built test facility. In addition, the effect of radiation on microstructural evolution and elemental segregation is being investigated. This program is conducted jointly with Professor Harling at the MIT Nuclear Reactor Laboratory.

Modeling the Effects of Neutron and Gamma Radiation on Aqueous Chemistry: The effect of neutron and gamma radiation on aqueous chemistry and electrochemistry is being modeled. The model is both local (i.e., within a crevice) and global (i.e., outside of a crevice).

The Effect of Radiation on the Nodular Corrosion Resistance and Phase Stability in Zirconium Alloys: The nodular corrosion behavior of zirconium alloys is not well understood but is known to depend on material processing history and in-core environment. A program is underway to evaluate the effect of neutron dose on the stability of intermetallic precipitates in these materials and subsequent corrosion behavior. The program involves irradiations at the MIT Reactor followed by TEM/STEM studies and corrosion tests in 450°C steam.

Crack Initiation and Growth in Low Alloy Steels: A program is under way to understand the initiation and propagation of stress corrosion cracks in low alloy steels. The program is focused on pitting and crack initiation from pits. The environment is that of PWR steam generators as well as BWR primary systems.

Investigators: Prof. R. G. Ballinger; Dr. I. Hwang

Support: Electric Power Research Institute, US Department of Energy, General Electric Corporation

Related Academic Subjects:

22.70J	Materials for Nuclear Applications
22.71J	Physical Metallurgy
22.72J	Corrosion: The Environmental Degradation of Materials
22.74J	Mechanical Behavior of Materials

Recent References:

Hosoya, K., R.G. Ballinger, et al. "The Role of Microstructure in Environmentally Assisted Cracking of *Ni*-Base Alloys." *Corrosion*, 44; 1988: 838-853.

Prybylowski, J., R.G. Ballinger, and C. Elliott. "Quantitative Analytical Electron Microscopy of Multiphase Alloys." *J. of Electron Microscopy Technique*, 11; 1989.

Hwang, I.S., R.G. Ballinger, and K. Hosoya. "Electrochemistry of Multiphase Nickel-Base Alloys in Aqueous Systems." *J. Electrochemical Soc.*, Vol. 136, No. 7, 1989.

Prybylowski, J. and R.G. Ballinger. "Environmentally Assisted Cracking in Alloy 718." *Corrosion,* in press.

I.S. Hwang and R.G. Ballinger, "A Multi-frequency A.C. Potential Drop Technique for the Detection of Small Cracks." *J. Meas. Science and Technology*, in press.

Ballinger, R.G., C.S. Elliott, and I.S. Hwang. "Corrosion Fatigue of Alloy X-750 in Aqueous Environments." Int'l Conf. on Environment Induced Cracking of Metals, October 2-7, 1988, Kohler, WI.

A. Turnbull, R.G. Ballinger, I.S. Hwang, and R.M. Gates. "The Influence of Microstructure on Hydrogen Transport in Nickel-Base Alloys," Proceedings of the Fourth International Conference on the Effect of Hydrogen on the Behavior of Materials, Jackson Lake Lodge, Moran, Wyoming, September 12-15, 1989, pp. 121-132.

M. Psaila-Dombrowski, A. Turnbull, R. Ballinger, "Implications of Crevice Chemistry for Cracking of BWR Recirculation Inlet Safe-Ends," UK Corrosion 90, Surrey, October 29-31, 1990.

3.1.4.3 Fusion Reactor Structural Materials Development

A program is under way to develop advanced structural materials for fusion reactor applications. The program is focused on materials for structural and superconducting magnet applications. The program has a number of thrusts:

Development of Advanced Fracture Mechanics Methodology for Applications to Structural Analysis at Cryogenic Temperatures: A program is under way to develop J-Integral test methods for applications at temperatures as low as 4K. A facility has been designed and built for fatigue and fracture testing at 4K. Methods being developed will be applied to design and life prediction analysis of structural materials for fusion systems.

High Strength Low Coefficient of Expansion Structural Alloys for Cryogenic Service: The current carrying capacity of Nb_3Sn superconducting wire is strongly influenced by the state of strain in the conductor. For this reason it is important that the sheathing material used for wire structural support have the same thermal expansion coefficient as the conductor. The goal of this research program is to develop a new high strength low coefficient of expansion, alloy for use as sheathing material. A patent has been obtained for a new structural alloy, Incoloy 908, which promises to become the material of choice for niobium-tin superconducting magnets.

Structural Integrity of Copper/Inconel Composites for High Field Magnets: Due to the large Lorentz forces generated by high field magnets, it is necessary that additional structural support be provided. In many cases the additional structural support is provided for by using composite magnet design with the high strength support material being bonded to the current carrier, in most cases, copper. These magnets are operated in a pulse mode which results in cyclic stresses being generated. The purpose of this research program is to develop an understanding of the effect of cyclic loading on the integrity of the composite interfaces.

Investigators: Professor R. G. Ballinger; Dr. I. S. Hwang

Support: US Department of Energy, Office of Fusion Energy, Office of Basic Energy Science

Related Academic Subjects:

22.70J	Materials for Nuclear Applications
22.71J	Physical Metallurgy
22.72J	Corrosion: The Environmental Degradation of Materials
22.74J	Mechanical Behavior of Materials

Recent References:

M. Steeves et al., "Progress in the Manufacture of the U.S. DPC Test Coil." *IEEE Transactions on Magnetics*, Vol. 25, No. 2 (1989).

R.L. Tobler, R.P. Reed, I.S. Hwang, M.M. Morra, R.G. Ballinger, H. Nakajima, S. Shimamoto, "Charpy Impact Tests Near Absolute Zero." *Journal of Testing & Evaluation*, Vol. 19, No. 1 (1991), pp. 34-40.

I.S. Hwang, M.M. Morra, R.G. Ballinger, H. Nakajima, S. Shimamoto, and R.L. Tobler, "Charpy Absorbed Energy and J_{IC} as Measures of Cryogenic Fracture Toughness." *Cryogenics*, in press.

M.M. Morra, R.G. Ballinger, and I.S. Hwang, "The Relationship Between Processing, Structure, and Properties of a New High Strength, Low Coefficient of Expansion Alloy for Cryogenic Service," 1989 TMS Annual Meeting, Las Vegas, NV, February 27 - March 2, 1989.

M.M. Morra, I.S. Hwang, R.G. Ballinger, M.M. Steeves and M.O. Hoenig, "Effect of Cold Work and Heat Treatment on the 4°K Tensile, Fatigue and Fracture Toughness Properties of Incoloy 908." 11th International Conference on Magnet Technology (MT-11), Tsukuba, Japan, August 28 - September 1, 1989.

3.1.4.4 Irradiation Assisted Stress Corrosion Cracking

There is mounting evidence that the in-core radiation environment of light water power reactors can enhance the crack growth rate of core structural components. A basic understanding of this phenomenon is of importance in predicting the service performance of critical in-core structural components. A major project is currently underway at the Nuclear Reactor Laboratory which is aimed at obtaining fundamental understanding of IASCC and at obtaining the design window for structural materials which can experience IASCC.

Investigators: Professors O.K. Harling, R.G. Ballinger, M.J. Driscoll; Dr. G. Kohse

Support: Internal funds from the Nuclear Reactor Laboratory; nuclear utilities PSE&G and Duke Power, and EPRI have provided seed funds. Major funding has been obtained from EPRI and TEPCO.

Related Academic Subjects:

22.71J	Physical Metallurgy
22.39	Nuclear Reactor Operations and Safety

Recent References:

Project Staff, Nuclear Reactor Laboratory and Nuclear Engineering Department, "Irradiation Assisted Stress Corrosion Cracking and BWR Chemistry Studies, First Annual Progress Report to TEPCO/EPRI for Period September 1988-September 1989," Report No. MITNRL-035, October 1989.

Project Staff, Nuclear Reactor Laboratory and Nuclear Engineering Department, "Irradiation Assisted Stress Corrosion Cracking and BWR Chemistry Studies, Second Annual Progress Report to TEPCO/EPRI for Period September 1989-November 1990," Report No. MITNRL-043, November 1990.

O.K. Harling, G.E. Kohse, M.J. Driscoll, R.G. Ballinger, "In-Pile Facilities for LWR Materials and Chemistry Studies at the MIT Research Reactor," an invited paper presented at the 1991 JAIF International Conference on Water Chemistry, April 22-25, 1991, Fukui City, Japan.

3.1.4.5 Radioactive Corrosion Products in the Primary Coolant Systems of Light Water Power Reactors

High radiation exposures to workers during maintenance of the primary coolant systems of light water power reactors result in a significant financial cost, health and public relations concern. A technical team comprising several MIT disciplines is involved in a major research and testing project, with support from the nuclear industry, which is devoted to studying the processes involved in the production, activation, transport and deposition of radioactive corrosion products in LWR primary coolant systems. A major component of this work is the design and construction of in-core loops at MITR-II which are designed to simulate the primary coolant systems of PWRs and BWRs. These facilities are used for testing which is designed to elucidate basic mechanisms and to develop the technology needed to reduce radiation exposure and corrosion in LWR coolant systems.

Investigators: Professors O.K. Harling, M.J. Driscoll; Dr. G. Kohse

Support: Major support from the Empire State Electric Energy Research Corporation, the Electric Power Research Institute, and the Japanese Nuclear Power Engineering Center, and minor but significant support from several individual nuclear utilities, PSE & G/Duke Power/Boston Edison

Related Academic Subjects:

22.71J	Physical Metallurgy
22.39	Nuclear Reactor Operations and Safety
22.59	Principles of Nuclear Radiation Measurement and Protection

Recent References:

C.B. Lee, "Modeling of Corrosion Product Transport in PWR Primary Coolant," Ph.D. Thesis, Department of Nuclear Engineering, MIT, February 1990.

R.G. Sanchez, "Construction and Operation of an In-Pile Loop for PWR Dose Reduction Experiments," Ph.D. Thesis, Department of Nuclear Engineering, MIT, May 1990.

J.G. Outwater III, "Design, Construction and Commissioning of an In-Pile BWR Coolant Chemistry Loop," Sc.D. Thesis, Department of Nuclear Engineering, MIT, January 1991.

G.E. Kohse, R.G. Sanchez, M.J. Driscoll, M. Ames, and O.K. Harling, "In-Pile PWR Loop Coolant Chemistry Studies in Support of Dose Reduction," an invited paper presented at the 1991 JAIF International Conference on Water Chemistry, April 22-25, 1991, Fukui City, Japan.

3.1.4.6 Irradiation-Induced Decomposition of Fe-Ni and Fe-Mn Invar-type Alloys

Alloys based on Fe-35 Ni show remarkable resistance to irradiation-induced swelling until spinodal-type concentration fluctuations develop. We are conducting a theoretical and experimental study of phase decomposition in these alloys in order to develop materials for advanced fission and fusion reactors.

Investigators: Professor K.C. Russell; Dr. F.A. Garner (Westinghouse-HEDL)

Support: Department of Energy, NORCUS

Related Academic Subjects:

22.71J	Physical Metallurgy
22.73J	Radiation Effects in Crystalline Solids (no longer offered)
3.40J	Physical Metallurgy

3.1.5 Nuclear Chemical Engineering

A formal subject was not taught in this area for four years, but one is planned for the spring of AY 91-92, to be taught by Visiting Professor Alfred Schneider. However, research activities at the Nuclear Reactor Laboratory related to Nuclear Chemical Engineering have expanded. This work involves the use of in-pile loops to evaluate various aspects of PWR and BWR coolant chemistry: in the former the goal is to study means, such as pH optimization, to minimize buildup of radionuclides on ex-core surfaces; and in the latter, to better understand key radiolysis reactions, such as H_2O_2 production, and the basic chemistry of N-16 carryover in the steam phase.

Closely related materials research dealing with Irradiation-Assisted Stress Corrosion Cracking (IASCC), including constant extension rate testing of material in-pile, and tests of sensors to monitor the coolant environment for promotion of this phenomenon, is discussed elsewhere in this report.

Investigators (NED only): Professors O.K. Harling, R.G. Ballinger, and M.J. Driscoll; Drs. G.E. Kohse and I.S. Hwang; M. Ames, E. Cabello, R. Sanchez, J. Outwater, C.B. Lee, A. Esteves, V. Mason, P. Borys, M. Zhang, R. Medina, R. Rozier, L. Doboe

Support: Utility Organizations (EPRI, ESEERCO, MIT-EUP), and Japanese Sponsors (TEPCO, NUPEC) via the Nuclear Reactor Laboratory

Related Academic Subjects:

22.32	Nuclear Power Reactors
22.39	Nuclear Reactor Operations and Safety
22.59	Principles of Nuclear Radiation Measurement and Protection
22.70J	Materials for Nuclear Applications

Recent References:

G.E. Kohse, R.G. Sanchez, M.J. Driscoll, M. Ames and O.K. Harling, "In-Pile PWR Loop Coolant Chemistry Studies in Support of Dose Reduction," 1991 JAIF International Conference on Water Chemistry in Nuclear Power Plants, April 1991, Fukui City, Japan.

O.K. Harling, G.E. Kohse, M.J. Driscoll and R.G. Ballinger, "In-Pile Facilities for LWR Materials and Chemistry Studies at the MIT Research Reactor," 1991 JAIF International Conference on Water Chemistry in Nuclear Power Plants, April 1991, Fukui City, Japan.

A. Esteves, "Qualification of Miniature Canned Rotor Pumps for PWR In-Pile Loop Service," Nuclear Engineering Thesis, MIT Nuclear Engineering Department, January 1990.

J. Baeza, "Refinement of an In-Pile Loop Design for BWR Chemistry Studies," S.M. Thesis, MIT Nuclear Engineering Department, January 1989.

C.-B. Lee, "Modeling of Corrosion Product Transport in PWR Primary Coolant," Ph.D. Thesis, MIT Nuclear Engineering Department, February 1990.

R.G. Sanchez, "Construction and Operation of an In-Pile Loop for PWR Dose Reduction Experiments," Ph.D. Thesis, MIT Nuclear Engineering Department, May 1990.

R. Medina, "Measurement of Neutron Flux and Spectrum Averaged Cross Sections for an In-Pile PWR Loop," S.M. Thesis, MIT Nuclear Engineering Department, May 1990.

E.D. Cabello, "Decontamination Studies of Simulated PWR Primary Coolant System Components," S.M. Thesis, MIT Nuclear Engineering Department, May 1990.

P. Borys, "Activity Removal and Transport Studies in Support of PWR In-Pile Loop Operations," S.M. Thesis, MIT Nuclear Engineering Department, February 1991.

M. Zhang, "Measurement and Interpretation of Chemical and Radiochemical Data from PWR In-Pile Loop Runs," S.M. Thesis, MIT Nuclear Engineering Department, February 1991.

V.H. Mason, "Chemical Characterization of Simulated Boiling Water Reactor Coolant," S.M. Thesis, MIT Nuclear and Chemical Engineering Departments, May 1990.

J.O. Outwater, "Design, Construction and Commissioning of an In-Pile BWR Coolant Chemistry Loop," Sc.D. Thesis, MIT Nuclear Engineering Department, January 1991.

3.1.6 Quantum Thermodynamics

Research activity in the area of quantum thermodynamics is continuing under the supervision of Professor Elias P. Gyftopoulos.

3.1.6.1 Subjects of Instruction

The following graduate subjects of instruction are offered to students interested in the area of quantum thermodynamics.

22.571J General Thermodynamics, presents thermodynamics as a general theory of all physical phenomena in any system, large or small (including one point-particle having only one spatial degree of freedom), and in any state, equilibrium or not equilibrium. The concepts of system, property, state, energy, stability of equilibrium, adiabatic availability, available energy, entropy, temperature, chemical potential, pressure, work, nonwork, and heat are introduced in that order. A novel energy versus entropy diagram illustrates all the basic concepts. The results are applied to properties of substances, energy conversion systems, and chemical reactions.

22.572J Quantum Thermodynamics, presents a nonstatistical unified quantum theory of mechanics and thermodynamics for all systems, large or small, all states, equilibrium or not equilibrium, and including an equation of motion for reversible and irreversible processes. Self-contained review of necessary background. Applications to fermions, bosons, black-body radiation, electrons in metals, crystals, rate processes, and relaxation phenomena.

3.1.6.2 Foundations of Quantum Thermodynamics

Professor Gyftopoulos continued his research on the foundations of quantum thermodynamics. The emphasis of this research is on the general equation of motion of quantum thermodynamics, criteria for distinguishing between quantal and nonquantal uncertainties, and the general expression for entropy.

In October 1990, a textbook on *Thermodynamics: Foundations and Applications* by Professors Gyftopoulos and Gian Paolo Beretta was published by Macmillan.

Investigator: Professor E.P. Gyftopoulos

Support: None

Related Academic Subjects:

22.571J	General Thermodynamics
22.572J	Quantum Thermodynamics

Recent References:

E.P. Gyftopoulos and J.L. Park, "Are there Foolish Questions in Quantum Physics," Letter to the Editor, Physics Today, pp. 98-99, April (1989).

G.P. Beretta and E.P. Gyftopoulos, "What is the Third Law?" Proceedings Florence World Energy Research Symposium, May (1990).

G.P. Beretta and E.P. Gyftopoulos, "What is Heat?" Winter Annual Meeting, ASME, AES 20, pp. 33-41 (1990).

G.P. Beretta and E.P. Gyftopoulos, "Electromagnetic Radiation: A Carrier of Energy and Entropy Transfers," Winter Annual Meeting, ASME AES 19, pp. 1-6 (1990).

E.P. Gyftopoulos and G.P. Beretta, Thermodynamics: Foundations and Applications, Macmillan Publishing Co. (1990).

3.2 Plasmas and Controlled Fusion

3.2.1 Theoretical Plasma Physics

MIT has long been recognized as a center of excellence in the field of theoretical plasma physics, with particular emphasis on magnetic fusion. A substantial part of the overall theoretical effort is associated with faculty, research scientists, and students in the Nuclear Engineering Department. In an endeavor as complex as magnetic fusion, theory has two major roles. First, to provide direct support in the design, analysis of data, and predicted performance of existing experiments. Second, to provide fundamental insight into the behavior of magnetically confined plasmas to guide the future directions of the magnetic fusion program. In support of these goals, there are active research projects in the areas of alpha particle effects, MHD equilibrium and stability theory, transport theory both classical and anomalous, and nonlinear turbulence theory.

3.2.1.1 Subjects of Instruction

The Department offers the following subjects in the areas of Applied Plasma Physics and Fusion Technology.

22.061 Fusion Energy I is an undergraduate offering of graduate course 22.601. Both courses meet together for three lecture hours per week, but have different assignments.

22.062 Fusion Energy II is an undergraduate offering of graduate course 22.602. Both courses meet together, but assignments differ.

22.069 Undergraduate Plasma Laboratory is an undergraduate offering of course 22.69. Both courses meet together, but assignments differ.

22.601 Fusion Energy I introduces the basic nuclear physics and plasma physics for controlled fusion. Topics include fusion cross sections, ignition condition, break-even condition, Lawson criterion, elementary fusion reactor, required plasma parameters, definition of a plasma, single-particle orbits, Coulomb collisions, fluid model, magnetic fusion configurations, MHD equilibrium and stability, transport and heating.

22.602 Fusion Energy II discusses the basic engineering physics and technology of current fusion experiments and controlled thermonuclear reactors. Topics include operation of tokamaks, alternate concepts; systems analysis and design of power reactors, ignition experiments, hybrid reactors; magnet design, and heating technology, tritium handling, safety and environment. The course also contains an engineering design segment.

22.611J Introduction to Plasma Physics I is an introduction to plasma phenomena relevant to energy generation by controlled thermonuclear fusion and to astrophysics. Coulomb collisions and transport processes. Motion of charged particles in magnetic fields; plasma confinement schemes. MHD models; simple equilibrium and stability analysis. Two-fluid hydrodynamic plasma models; Wave propagation in a magnetic field. Introduces kinetic theory; Vlasov plasma model; electron plasma waves and Landau damping; ion-acoustic waves; streaming instabilities.

22.612J Introduction to Plasma Physics II deals with linear waves and instabilities in magnetized plasma; solutions of Vlasov-Maxwell equations in homogeneous and inhomogeneous plasmas; conservation principles for energy and momentum; negative energy wave; absolute and convective instabilities. Quasi-linear theory and conservation principles; evolution of unstable particle distribution functions. Collisional transport theory; Fokker-Planck equations; particle diffusion, thermal conductivity, and viscosity in magnetized plasma.

22.615J Theory of Plasma Confinement I deals with the theory and applications of ideal MHD to magnetic fusion systems. The subject includes a derivation of the MHD equations, illustrating the physics described by the model and range of validity. A basic description of equilibrium and stability of current magnetic fusion systems such as tokamak, stellarator/torsatron, and reverse field pinch is given.

22.616 Theory of Plasma Confinement II is a continuation of 22.615J. Theory and application of nonideal MHD theory including: resistive instabilities, tearing modes, resistive interchanges, nonlinear saturation, with applications to sawtooth oscillations and major disruption in a tokamak; finite Larmor radius stabilization of ideal MHD modes and rotationally driven instabilities.

22.63 Engineering Principles for Fusion Reactors is an introductory course in engineering principles and practices of systems relevant to controlled fusion. Topics covered include mechanism and technique for plasma production, vacuum engineering based on considerations of free molecular flow, surface physics and standard design practices, magnetic field generation by normal, cryogenic and superconducting coils; electrical, heat transfer and structural requirements, high voltage engineering and practices, methods of plasma heating; ion, electron and neutral beam production, microwave and laser systems, applications to fusion systems. The course also contains an engineering design segment.

22.64J Plasma Kinetic Theory, content varies from year to year. Typical subjects: the linearized Vlasov equation, Fokker-Planck and diffusion approximations for the average distribution function, autocorrelation functions, resonant and nonresonant diffusion, free energy, energy and momentum conservation, resonant wave coupling, non-linear Landau damping, strong turbulence theories. Selected applications to enhanced diffusion, stochastic acceleration, turbulent resistivity, shock waves, radio emission.

22.67 Principles of Plasma Diagnostics is an introduction to the physical processes used to measure the properties of plasmas, especially fusion plasmas. Measurements of magnetic and electric fields, particle flux, refractive index, emission and scattering of electromagnetic waves and heavy particles; their use to deduce plasma parameters such as particle density, pressure, temperature, velocity, etc., and hence the plasma confinement properties. Discussion of practical examples and assessments of the accuracy and reliability of different techniques.

22.69 Plasma Laboratory introduces the advanced experimental techniques needed for research in plasma physics and useful in experimental atomic and nuclear physics. Laboratory work on vacuum systems, plasma generation and diagnostics, physics of ionized gases, cryogenics, magnetic field generation, and other topics of current interest; brief lectures and literature references to elucidate the physical basis of the laboratory work.

3.2.1.2 Theory of Magnetically Confined Fusion Plasmas

There are two basic purposes for the theoretical studies of magnetically confined fusion plasmas. The first is to provide direct support for the experimental program at MIT. The second is to provide fundamental insights into the behavior of magnetically confined plasmas so that the future directions of the fusion program are guided along the most promising path. A summary of these activities is as follows:

Most of the effort is involved with tokamak research in the general areas of MHD equilibrium and stability, neoclassical and anomalous transport and α-particle physics.

In recent years the MHD theory has focused on two areas. First, a significant analytical and computational effort has been applied to the design of new experiments. In particular, detailed studies have been performed for Alcator C-Mod, VTF, BPX and ITER. The main area of interest is in the design of the PF system including elongation, divertors, feedback stabilization, resistive wall instabilities, and startup procedures. An innovative way to gain access to the regime of second stability has also been devised.

The second major area of interest involves the development of a number of ultra-fast numerical techniques for MHD and transport problems for between shot analysis on actual experiments. Such techniques include the determination of the shape of the plasma surface, the current and pressure profiles, the coil currents, and resistive wall vertical stability.

The transport theory has focused on neoclassical anomalous ion and impurity transport which plays a crucial role in sizing the next generation of tokamak experiments including those aimed at ignition.

The alpha physics studies are motivated by the national commitment to BPV which has elevated this topic from an academic discipline to one of immediate relevance for obtaining and maintaining the ignited state. Principal questions concern the α-effects on MHD stability and on bulk plasma energy confinement, besides the question of anomalous α-particle transport during the slowing down phase.

A substantial effort has also been devoted to the issues of optimized ignition experiments and burn control in ignited plasmas. These studies have shown that designs with high fields and larger aspect ratios may be more desirable than those currently under consideration.

Investigators: Professors J.P. Freidberg and D.J. Sigmar; Drs. E. Chaniotakis, F. Gang, C.T. Hsu, J. Kesner, B. Lane, and J. Ramos; R. Betti, R. Gormley, W. Stewart, and J. Wei

Support: US Department of Energy

Related Academic Subjects:

22.601	Fusion Energy I
22.602	Fusion Energy II
22.611J	Introduction to Plasma Physics I
22.612J	Introduction to Plasma Physics II
22.615J	Theory of Plasma Confinement I
22.616	Theory of Plasma Confinement II
22.64J	Plasma Kinetic Theory

3.2.1.3 Space Plasma Physics Theory

Activities in the space plasma physics group have focused on the theory of processes responsible for the emission of Whistler waves in the magnetosphere--a problem in non-linear plasma kinetic theory, and tearing processes in the magnetotail responsible for magnetic substorms. Research is also in progress in the development of novel space propulsion systems--the plasma rocket. Finally, much recent interest and effort is focusing on the development of logical, Boolean algorithms (or *cellular automation*) for simulating physics on the computer. These methods circumvent all of numerical analysis and raise the possibility of novel, massively parallel, computing techniques.

Digital Logic for Fluid Dynamics

This project is concerned with the development of algorithms in logic that can simulate realistic fluid dynamics. Such a "reduction of hydrodynamics to logic" has a strong philosophical motivation, of course, but its main purpose in this project is for the practical application of fluid dynamics simulation on the computer. It offers the promise of providing algorithms of sufficient simplicity that massively parallel computer architectures could be implemented to solve them in practical situations. This could open the door to the kind of massive parallelism that substantial improvements in fluid dynamics computing will require. The class of theories we develop are written in Boolean algebra--the language of the microchip--

and offer the hope of being directly implemented at the hardware level without all the extremely complex layers of software and numerical analysis that present floating point computations require.

Past work (in which we participated) on this subject--often called *lattice gas hydrodynamics*--has shown how many of the Boolean and lattice structure artifacts can be eliminated at the macroscopic level to give a simulation algorithm with surprising similarity to hydrodynamic behavior. Nonetheless, previously existing cellular automata still had major limitations--*as models for real fluid dynamics*. As a result no practical applications of cellular automata have been carried out to date.

Ongoing research by the authors has developed a new class of generalized cellular automata aimed at closing this gap. These automata have certain features that allow flexibility in tailoring the logic to create the desired macroscopic properties. In particular, these systems are endowed with a genuine *energy* that is distinct from mass and at the same time they are free of *all* the Boolean-lattice artifacts. Specifically, the macroscopic limit yields a system possessing isotropic pressure tensor, truly Galilean invariant flow equations, with allowance for compressibility, a proper scalar pressure reflecting energy equipartition, in addition to the energy transport equation with the ideal gas adiabatic constant. One limitation appears to be that the lattice required to give pressure isotropy is four dimensional, and although the projection to three dimensions gives the proper momentum equation, the specific heat ratio $(D + 2)/D$ in the energy equation carries the signature of the four dimensional energy. Thermal conductivity and viscosity coefficients remain to be worked out.

Our generalized cellular automata may have sufficient flexibility to improve that difficulty with small signal to noise that is known to be present in single speed automata (as articulated by Orszag and Yakhot) for practical applications. In any case, they have sufficient realism that a more accurate accounting of the computational requirements of practical simulations can be carried out. One purpose of the proposed work is to carry out the evaluation of the computational work, including the relative simplicity of the cellular automata operations and data structure as compared to floating point methods.

This research suggests innovative uses of computers for scientific computing. The originality of these uses lies in their non-numerical nature: they avoid the inaccuracies of floating-point arithmetic and bypass the need for numerical analysis. In the place of numerical analysis one has a kind of kinetic theory for discrete systems that links them to the continuum descriptions currently used in physics.

<u>Investigators</u>: Professor K. Molvig; C. Teixeira

<u>Support</u>: Office of Naval Research

<u>Related Academic Subjects</u>:

22.601	Fusion Energy I
22.602	Fusion Energy II
22.611J	Introduction to Plasma Physics I
22.612J	Introduction to Plasma Physics II
22.615J	Theory of Plasma Confinement I
22.616	Theory of Plasma Confinement II
22.64J	Plasma Kinetic Theory

3.2.2 Experimental Plasma Physics and Fusion System Technology

Experimental research is the mainstay of the national program to develop economically viable controlled fusion energy sources. Because of the complexities of the behavior of plasmas, only experiments can give sufficient information about the phenomenological behavior of plasmas in fusion confinement configurations to allow any confidence in the development of a fusion reactor. MIT has had a very strong fusion program for several decades, in which the Department of Nuclear Engineering has been a major participant. The experimental activities in controlled fusion and plasma physics are focused in the Institute's Plasma Fusion Center. A large part of this effort is in the experimental plasma confinement area, particularly the highly successful Alcator tokamaks. In addition, smaller efforts exist including studies of generation of electromagnetic radiation from sources such as the gyrotron and free electron laser. Students and faculty from the Department of Nuclear Engineering play a leading role in many of these areas.

3.2.2.1 Subjects of Instruction

Subjects of Instruction are the same as those listed in Section 3.2.1.1.

3.2.2.2 Experimental Plasma Physics

MIT's main program in experimental fusion plasma physics is the Alcator project. In the Spring of 1987, approval was received for the construction of the new experiment, Alcator C-MOD, a greatly modified and upgraded version of the Alcator C Tokamak. This machine has, in the Alcator tradition, very high magnetic fields for plasma confinement, but also strongly shaped cross sections including a divertor and will have auxiliary heating in the ion cyclotron range of frequencies. It will thus combine the ability to explore novel shaping and control issues with a very high performance for plasma confinement. It will allow plasma currents up to three mega-amps and plasma confinement parameters approaching those for the reactor regime.

In many respects Alcator C-MOD will serve as a scale prototype for the proposed national ignition experiment, BPX, and will provide the opportunity to study the many very important questions concerning BPX's operation and performance.

An important area where the Nuclear Engineering Department faculty and students are involved is the design and implementation of the magnetic field system for Alcator C-MOD. This involves the calculation of MHD equilibria and optimization of the control and programming of the machine, and leads into the interesting problem of reconstructing the equilibrium from measurements outside the plasma.

Another topic of key importance for experiments of this type is in the area of diagnostics. The Department has considerable involvement in a number of different diagnostic techniques which will be used for investigating the plasma performance, including cyclotron emission measurements, magnetic measurements, x-ray emission, fusion product measurements, and probe and edge diagnostics.

Smaller scale experiments are also conducted both within the Plasma Fusion Center and outside. Experiments of a more basic nature and investigations related to space plasma physics are actively pursued at the Fusion Center. In addition, collaborations have recently taken students, for example, to the JET tokamak.

Investigators: Professor I.H. Hutchinson; Drs. D.B. Montgomery, M.C. Lee and R. Petrasso; T. Hsu, C. Tsui, C. Kurtz, C.K. Li, C. Kurtz, A. Niemczewski, G. Tinios, J. Urbahn, and L. Wang

Support: US Department of Energy

Related Academic Subjects:

22.601	Fusion Energy I
22.602	Fusion Energy II
22.63	Engineering Principles for Fusion Reactors
22.67	Principles of Plasma Diagnostics
22.69	Plasma Laboratory

Recent References:

Granetz, R.S., Hutchinson, I.H., Gerolamo, J., Pina, W., Tsui, C., "Magnetic Diagnostics in Alcator C-MOD," Rev. Sci. Instrum. 61, 2967 (1990).

Hutchinson, I.H., "The Connected Presheath: One-dimensional Models of Neighboring Objects in Magnetized Plasmas," Physics of Fluids B 3, 847 (1991).

Kirkwood, R.K., Hutchinson, I.H., Luckhardt, S.C., Squire, J.P., "Measurement of Suprathermal Electrons in Tokamaks via Electron Cyclotron Transmission," Nuclear Fusion, Vol. 30, 431 (1990).

3.2.2.3 Fusion Reactor System Safety Studies

The overall objectives of these studies are the development of a methodology suitable for safety and environmental analysis of proposed fusion reactor power plants and the development of criteria to guide designs in order to ensure optimum safety as well as economic performance.

1) Magnet Safety Studies

Expanded methods for predicting quench front propagation in superconducting magnets have been developed. PQUENCH is a code for coils with epoxy impregnated windings. It employs a one-dimensional, logical coordinate system to solve the three-dimensional problem. The code can treat quench transients in a general configuration of multiple, inductively coupled coils, three-dimensional normal front propagation, and material properties that are dependent on the local magnetic fields. Thus far, the code has only been applied to simple solenoidal cases, but it has shown good agreement with measured data in the form of a characteristic quench time. Modifications to improve efficiency and modeling accuracy are underway in work being carried out at the Plasma Fusion Center.

2) Lithium-Lead Reaction Studies

In the past two years, attention has been given to kinetics of $Li_{17}Pb_{83}$ reactions with air and steam. Reaction kinetics with $Li_{17}Pb_{83}$ and dry air were performed at temperatures between 673 and 1373 K. Dry air was simulated using a 77% nitrogen and 23% oxygen mixture. The peak reaction rate occurred at 1073 K and was up to an order of magnitude smaller than previously determined peak lithium-air rates. Compared to the Li_{17} Pb_{83} reactions with steam (data from JRC-Ispra), the $Li_{17}Pb_{83}$-steam reaction rates followed the same trend but had a peak reaction rate five times higher and at a higher temperature.

The reaction rate of nitrogen was found to be a strong function of temperature that peaks at approximately 1073 K, while the reaction rate of oxygen remains relatively constant with increasing temperature after an initial jump that is presumably due to the complete melting of the lithium-lead. Although the steam peak occurs at a lower temperature (873 K), the reaction rates for $Li_{17}Pb_{83}$ in both steam and air follow the same trend of nearly doubling between 673 K and 873 K. This indicates that lithium-lead may react more violently and liberate more heat in an air environment than in a steam environment.

3) Performance Analysis of Plasma-Facing Components

A beryllium-coated copper divertor tube with axisymmetric cylindrical geometry was analyzed for lifetime performance for International Thermonuclear Experimental Reactor (ITER)-type conditions. Erosion of the plasma-facing surface due to plasma disruptions is expected to limit the beryllium coating lifetime to about 10-20 thermal quench disruptions (considering a peak energy deposition between 10-20 MJ/m^2, disruption time between 0.1-3.0 ms, and a 3.0-mm thick beryllium coating). Since several hundred disruptions are expected over the course of plasma physics experimentation, this design would require many beryllium surface rejuvenations. The results of other divertor designs using graphite and tungsten protection are similar, suggesting that a decrease in the allowable number of plasma disruptions or a quick and economical in-situ armor rejuvenation method will be required.

The advantages of the present design over the option of carbon tiles are the lack of brazed tiles, ease of fabrication, in-situ regeneration of the beryllium armor by plasma spray deposition (the technology for beryllium plasma spraying already exists), and the good plasma performance observed in current devices using beryllium, such as the Joint European Torus.

A thermal-hydraulic analysis revealed the need for enhancing coolant heat transfer at the divertor strike points where the heat flux from the plasma is highly peaked. Insertion of twisted tapes to promote swirl flow at these strike points proved satisfactory by increasing the heat transfer coefficient by more than 90% (from 59 to 113 kW/m^2-K) and allowing a 3.0-mm thick beryllium armor to remain below the desirable temperature safety limit of 1073 K.

An investigation of liquid metals as divertor surfaces has been initiated. It is hoped that such concepts will overcome the sputtering problem and allow for controlled tritium recoil.

4) MHD Pressure Drop

An investigation has been carried out in the conditions that may give rise to significant effects from nonuniformities on the pressure drop associated with liquid metal flow in self-cooled blankets.

Generally, uniform field and velocity conditions have been used in conceptual studies. Corrections due to nonuniform flow path area, magnetic field strength and flow direction have been proposed.

Investigators: Professors M.S. Kazimi and J. Meyer; Dr. R. Thome; L. Porter, M. Oshima, D. Hanchar, D. Lo, Y. Parlatan, T. Hechanova, S. Pappano, M. Koch, C.P. Liao

Support: US Department of Energy and EG&G Idaho

Related Academic Subjects:

22.38	Reliability Analysis Methods
22.602	Fusion Energy II
22.63	Engineering Principals for Fusion Reactors

Recent References:

M.S. Kazimi, "First Wall and Blanket Safety," A Chapter in Safety, Environmental Impact, and Economic Prospects of Nuclear Fusion, Brunelli and Knoepfel, Eds., Plenum Press, New York, 1990.

D.S. Barnett and M.S. Kazimi, "Modeling Lithium Reactions with Steam-Air Mixtures," Fusion Engineering & Design 11, 1989: 321-334.

J.E. Massidda, Y. Parlatan and M.S. Kazimi, "Passive Safety Considerations in Thermal Design of Fusion Blankets," presented at NURETH-4 Karlsruhe, Germany, October 1989.

Lisa J. Porter, "Upgrade of a Fusion Accident Analysis Code and Its Application to a Comparative Study of Seven Fusion Reactor Designs," S.B. Thesis, June 1989.

Marie Oshima, "Computation of Quench Propagation in Multiple Superconducting Coils," Engineer's Thesis, February 1990.

Tony E. Hechanova, "Thermo-Mechanical Performance of Beryllium-Coated Copper Divertors," S.M. Thesis, August 1990.

Deborah R. Hanchar, "Engineering Methods to Assess Magnetohydrodynamic Pressure Drop in Liquid Metal Fusion Blankets," Ph.D. Thesis, October 1990.

3.2.2.4 Plasma Engineering and Technology

This activity places particular emphasis on engineering physics and technology of plasmas in high magnetic fields. It includes work in tokamak fusion reactor design (devices with burning plasmas), high field magnet engineering, applications of advanced superconductors and development of plasma diagnostics using novel millimeter wave and far infrared laser technology. The main programs are:

1) Burning Plasma Experiment (BPX) Design

There is active participation in a number of aspects of the design of the BPX, the next major tokamak planned in the US fusion program. The objective of this device is to obtain self-heated deuterium-tritium plasma operation, a milestone that is analogous to the achievement of the self-sustained fission reaction by Fermi and co-workers. It will use high-field, high performance copper plate magnets. Members of the group are currently working on the BPX project in the areas of magnet design, heating, and burn control. Concepts for obtaining a higher performance/cost ratio are also being developed, with particular emphasis on very strong ohmic heating and use of high aspect ratios.

2) Systems Studies and Superconductor Technology

Concepts have been developed for engineering test reactors using high-field, state-of-the-art Nb_3Sn superconducting magnets. A number of advantages may be possible using high magnetic fields, leading to the possibility of lower-cost, simpler devices for engineering test reactor and demonstration reactor goals. Advanced high field magnet technology is being studied as a means to improve commercial reactor design. A super high field approach developed by the Plasma Engineering Group has been adopted on the basis for the national commercial reactor design effort. Potential advantages of this approach include smaller plasma volume, lower current and reduced current drive requirements, and higher density operation, leading to reduced sputtering problems.

3) Diagnostic Development

A concept has been developed for application of gyrotron scattering to measure simulated and actual alpha particle densities velocity distributions. It can also be used for basic transport studies. Experimental work is under way to utilize this device on the TFTR tokamak.

Investigators: Professor J.P. Freidberg; Drs. D. Cohn, L. Bromberg, P. Woskov, J. Williams, E. Chaniotakis, J. Machuzak, and J. Schwartz; D. Rhee, J. Wei, and A. Zolfaghari

Support: US Department of Energy

Related Subjects:

22.601	Fusion Energy I
22.602	Fusion Energy II
22.63	Engineering Principles for Fusion Reactors

3.3 Radiation Science and Technology

The Radiation Science and Technology Group is composed of the Applied Radiation Physics and Molecular Simulation program, the Radiological Sciences program, the Radiation Health Physics program, and the physical metallurgy part of the Nuclear Materials program (see section 3.1.4).

3.3.1 Applied Radiation Physics and Molecular Simulation

This program is concerned with experimental and theoretical studies of simple and complex fluid systems, solids with defects, and molecular properties of various condensed matter. The teaching part of the program consists of subjects in nuclear physics, nuclear and atomic collision phenomena, nuclear measurements, radiation interactions, statistical thermodynamics, and atomistic simulations, while the research part involves neutron and laser scattering spectroscopy, and atomistic simulations of materials properties and behavior.

3.3.1.1 Subjects of Instruction

22.02 Introduction to Applied Nuclear Physics, is an introductory subject to nuclear physics and neutron physics with emphasis on those aspects of the subject which are applied in nuclear engineering. Topics covered include elementary results of quantum theory and special relativity, detection of atomic and nuclear particles, properties of atomic nuclei; isotopes and isotopic masses; nuclear reactions; natural and artificially induced radioactivity; cross sections for nuclear reactions; alpha-, beta- and gamma-decay; nuclear models; shell-models; liquid-drop model; nuclear fission properties of fission and their relation to the feasibility of nuclear power and to its problems; slowing down and diffusion of neutrons; neutron induced chain reactions.

22.09 Principles of Nuclear Radiation Measurement and Protection, is the undergraduate offering of graduate subject 22.59.

22.111 Nuclear Physics for Engineers I, deals with basic nuclear physics for advanced students majoring in engineering. Basic properties of nucleus and nuclear radiation. Quantum mechanical calculation of bound states and transmission coefficients. Nuclear force and nuclear shell model. Nuclear binding energy and stability. Interaction of charged particles, neutrons, gammas with matter. Nuclear decays. Introductory nuclear reactions.

22.113 Nuclear and Atomic Collision Phenomena, principles and applications of classical and quantum mechanical theory of collision cross sections. Two-body central force collisions with applications to radiation damage. Detailed study of partial wave and phase shift analysis, and the Born approximation. Optical model of nuclear reactions. Charged particle scattering. Thermal neutron inelastic scattering. Basic connections between diffraction and imaging.

22.51 Interactions of Radiation with Matter, deals with the basic principles of interaction of electromagnetic radiation, thermal neutrons, and charged particles with matter. Introduction to classical electrodynamics, quantum theory of radiation field and time-dependent perturbation theory. Emphasis is on the development of transition probabilities and cross sections describing interaction of various radiations with atomic systems. Applications include emission and absorption of light, theory of gas lasers, Rayleigh, Brillouin, and Raman scattering, x-ray diffraction, photoelectric effect, Compton scattering, Bremsstrahlung, and interaction of intense light with plasma. The last part deals with use of thermal neutron scattering as a tool in condensed matter research.

22.52J Statistical Thermodynamics of Complex Liquids (Joint with the Physics and Chemical Engineering departments). Introductory course to modern topics in physics and chemistry of the liquid state, including supramolecular liquids and liquid crystals. Pair correlation function theory, mean field theory of phase equilibria and polymer solutions, theory of self assembly in surfactant-water (micellar) and surfactant-water-oil (microemulsion) systems. Concepts of broken symmetry, Goldstone mode and order-disorder phase transitions in liquid crystal systems, properties of nematic, smectic and hexatic phases of liquid crystals.

22.53 Statistical Processes and Atomistic Simulations. Statistical mechanics principles of equilibrium and time-dependent properties of condensed states of matter. Phase-space distributions, time correlations functions, kinetic equations. Free energy calculations. Stochastic processes. Continuum and molecular models for transport phenomena and phase transitions. Methods and applications of molecular dynamics and Monte Carlo simulations in statistical physics and materials science.

22.59 Principles of Nuclear Radiation Measurement and Protection, combines lectures, demonstrations, and experiments. It covers effects of radiation on persons; control of radiation exposure within applicable standards; theory and use of α, β, γ, and η detectors and spectrometers, use of isotopes, radiation shielding, and dosimetry. Includes demonstrations and experiments using the MIT research reactor, accelerators, and power reactors. Meets with undergraduate subject 22.09, but assignments differ.

Subject 22.111 is taken by practically all the graduate students in the Department. Most of the undergraduates take 22.09 and many will take 22.02. All the doctoral students in Applied Radiation Physics and Molecular Simulation will take 22.113, 22.51, 22.52J, 22.53, and 22.59.

3.3.1.2 Neutron Spectrometry and Molecular Dynamics in Solids and Fluids

Density fluctuations occur in all forms of matter because of the thermal motions of the atoms and molecules. Since these fluctuations result in space and time-dependent inhomogeneities in the system they can be observed directly by thermal-neutron scattering. In this way one has a powerful technique for studying molecular dynamics on a microscopic level (frequencies and wave-lengths of the order of 10^{13} Hz and one Angstrom).

The primary purpose of this program is to apply the technique of incoherent inelastic neutron scattering to problems of molecular vibrations in large organic molecules and hydrogen-bonded solids. In the scattering event, the neutron interacts mainly with the nuclei of the atoms composing the sample rather than with the surrounding electrons. Since neutron scattering cross sections are well known for most elements, the scattering can be modeled mathematically; that is, for a substance whose crystal structure is known, a set of assumed interatomic potential functions can be used to generate a predicted neutron-scattering spectrum. Comparison of the calculated spectrum with the observed spectrum then enables one to correct or refine the potential functions. A successful investigation confers two main benefits: (1) a set of validated potential functions for the substance investigated, which can then be used to gain insight about chemical behavior or to model more complex systems, and (2) a detailed description of the vibrational dynamics of the substance investigated.

The program described above can be resolved into two major branches--the experimental (acquisition of neutron-scattering spectra) and the computational (generation of calculated spectra and refinement of potential functions). On the experimental side, we have been doing incoherent inelastic neutron scattering with a high energy time-of-flight spectrometer at the Intense Pulse Neutron Source of Argonne National Laboratory. We have studied solid hydrocarbons such as benzene and butane and have recently completed measurements on supercooled water. The latter experiment is significant in that we have succeeded in observing the hydrogen bond dynamics of water. Computationally, we have evolved a rather complex program (LATDYN) which carries out lattice dynamics calculations within the framework of Born-von Karman theory. A number of less ambitious computer codes have been used to study individual molecules and single-chain polymers.

Investigators: Professor S.H. Chen; Dr. K.F. Bradley and P. LoNostro

Support: National Science Foundation (International, French-US Collaboration); US Department of Energy

Related Academic Subjects:

22.51	Interactions of Radiation with Matter
22.52J	Statistical Thermodynamics of Complex Liquids

Recent References:

M.C. Bellissent-Funel et al. and S.H. Chen, "Low Frequency Collective Modes in Dry and Hydrated Proteins," Biophys. J. 56, 713 (1989).

S.H. Chen, "Quasi-Elastic and Inelastic Neutron Scattering and Molecular Dynamics of Water at Supercooled Temperature," in Hydrogen-Bonded Liquids, p. 289-332. Edited by J.C. Dore and J. Teixeira, NATO ASI Series Vol. 329, Kluwer Academic (1991).

3.3.1.3 Quasielastic Light Scattering Studies of Ionic Micellar Solutions and Dense Microemulsions

A new technique for determining the Doppler frequency shifts in the scattered laser light from slowly moving particles has been developed. This "photon correlation spectroscopy" is a completely digital technique in the time domain whereby the intensity correlation function of the scattered light $<I(t)I(t+E)>t$ can be simultaneously measured at 256 values of the delay time τ by using a delay coincidence method. The accessible range for τ in this instrument is for 1 sec to 1 μsec which covers the useful range of fluctuation phenomena from neutron population in a reactor core to flow of particles in turbulent fluids. In the past, the method has been applied to the study of slow fluctuations of the concentration in a binary liquid mixture near the critical point with a great deal of success. We also applied this technique to the measurement of isotropic random motion of bacteria in liquid media and also to directed biased motions when a chemotactic agent is present. More recently, the critical slowing-down of concentration fluctuations in three-component ionic micellar solutions (lithium dodecyl-sulfate/butanol/water system) has been studied, and the critical exponents have been determined. We have also observed a glass-like transition in dense microemulsions (AOT/water/decane) by measuring the density fluctuations of microemulsion droplets when the volume fraction of the droplets are increased to above 0.6.

Investigators: Professor S.H. Chen; P. LoNostro; B. Carvalho and X.H. Guo

Support: National Science Foundation

Related Academic Subject:

22.51 Interactions of Radiation with Matter

Recent References:

C. Cametti, P. Codestefano, F. D'Arrigo, P. Tartaglia, J. Rouch and S.H. Chen, "Viscoelastic Behavior of Dense Microemulsions," Phys. Rev. A42, 3421-3426 (1990).

J. Rouch, N.M. Ziou, C. Cametti, P. Codastefano, P. Tartaglia, and S.H. Chen, "Light Scattering Investigation of Dense Microemulsions Above and Below the Percolation Threshold," J. Phys. Condens. Matter 2, SA353-SA357 (1990).

3.3.1.4 Small Angle Neutron Scattering Studies of Structure and Interaction of Micelles, Microemulsions, and Proteins

A new method of extracting the intermicellar structure factor for strongly interacting ionic micelles using SANS technique has been developed. The method has been applied to alkali dodecyl-sulfate micelles in both dilute and concentrated solutions. We were able to extract both the aggregation number of the micelle and its renormalized surface charge at all concentrations with good accuracy. A contrast variation method, which takes advantage of the large difference between scattering lengths of hydrogen and deuterium atoms, has also been used to study in detail the internal structure of small micelles.

Studies have been made of the recently found critical phenomena in a three-component microemulsion, AOT (a surfactant, sodium di-2-ethyl-hexyl-sulfosuccinate) + n-decane + water system. The main interest is in determining the nature of the critical point and its associated order parameter. Our SANS results have been analyzed by assuming critical concentration fluctuations of polydispersed microemulsion droplets. We obtained non-Ising-like values for the exponents Υ and η, while the size of the microemulsion droplets remains constant with 30 percent polydispersity. Recently, the structure of dense phases has also been determined.

Globular protein bovine serum albumin in solutions of different pH values have been studied. By varying the pH one can vary the surface charge of the protein and can thus vary the strength of interactions between protein molecules. We were able to determine the shape and size of the protein, its bound water content, as well as the surface charge. Interesting ordering phenomena have been seen at high protein concentrations.

We routinely use the small angle neutron scattering instruments at Oak Ridge, Brookhaven and NBS.

Investigators: Professor S.H. Chen; B. Carvalho, S.L. Chang, X.H. Guo

Support: National Science Foundation

Related Academic Subject:

22.51 Interactions of Radiation with Matter

Recent References:

X.H. Guo, N.M. Zhao, S.H. Chen and J. Teixeira, "Small Angle Neutron Scattering Study of the Structure of Protein-Detergent Complexes," Biopolymers, 29, 335-346 (1990).

T.L. Lin, S.H. Chen, N.E. Gabriel, M.F. Roberts, "SANS Study of Triglyceride Solubilization by Lecithin Micelles: A Direct Observation of Rod-to-Sphere Transition," J. Phys. Chem. 94, 855-862 (1990).

X.H. Guo and S.H. Chen, "Observation of Polymer-like Phase Separation of Protein-Surfactant Complexes in Solution," Phys. Rev. Lett. 64, 1979-1982 (1990).

X.H. Guo and S.H. Chen, "Reptation Mechanism in Protein-SDS Polyacrylamide Gel Electrophoresis," Phys. Rev. Lett. 64, 2579-2582 (1990).

D. Bratko, D. Wang, and S.H. Chen, "Spatial Correlations in Aqueous Protein Solutions," Chem. Phys. Lett. 163, 239-245 (1990).

S.H. Chen, S.L. Chang, and R. Strey, "Structural Evolution within the One-Phase Region of a Three-Component Microemulsion System: Water-n-decane-sodium-bisethylhexylsulfosuccinate (AOT)," J. Chem. Phys. 93, 1907-1918 (1990).

S.H. Chen, S.L. Chang, and R. Strey, "On the Interpretation of Scattering Peaks from Bicontinuous Microemulsions," Progr. Colloid. Polym. Sci. 81, 30-35 (1990).

S. Kreuger, S.H. Chen, J. Hofrichter and R. Nossal, "Small Angle Neutron Scattering Studies of HbA in Concentrated Solutions," Biophys. J. 58, 745-757 (1990).

T.L. Lin, M.Y. Tseng, S.H. Chen and M.F. Roberts, "Temperature Dependence of the Growth of Diheptanoylphosphatidylcholine Micelles Studied by Small-Angle Neutron Scattering," J. Phys. Chem. 94, 7239-7243 (1990).

S.L. Chang, S.H. Chen, R.L. Rill, and J.S. Lin, "Measurements of Monovalent and Divalent Counterion Distributions around Persistence Length DNA in Fragments in Solution," J. Phys. Chem. 94, 8025-8028 (1990).

X.H. Guo and S. H. Chen, "The Structure and Thermodynamics of Protein-SDS Complexes in Solution and the Mechanism of their Transports in Gel Electrophoresis Process," Chem. Phys. 149, 129-139 (1990).

K.F. Bradley, S.H. Chen, and P. Thiyagarajan, "Micellar Formation and Correlation in the Cavity of Porous Silica Glass," Phys. Rev. A42, 6015-6023 (1990).

P. LoNostro, G. Briganti, and S. H. Chen, "Structural Properties of Vesicles Produced from a New Bipolar Lipid," J. Colloid and Interf. Sci. 42, 214-223 (1991).

3.3.1.5 Molecular Simulation Studies of Materials Properties and Behavior

The overall objective of this group of projects, 3.3.1.5 - 3.3.1.9, is to develop molecular models, based on the techniques of molecular dynamics and Monte Carlo simulation, for applications to complex physical phenomena with emphasis on gaining insight into the properties and behavior of material systems at the atomic level. In the molecular dynamics approach, one integrates numerically the Newtonian equations of motion for a system of atoms using interatomic interaction potential functions constructed to be as realistic as possible. In the companion method of Monte Carlo, the same potential functions can be used, but the particle positions are generated by stochastic sampling rather than following Newtonian dynamics. There are two important advantages of the molecular simulation approach. First, a variety of physical properties can be calculated directly in terms of atomic structure and interatomic forces. Secondly, detailed microscopic information about structure and dynamics is obtained which is often not available by any other means, either theoretical or experimental.

Molecular simulations have no difficulty in dealing with processes that are highly nonlinear, inhomogeneous, or nonequilibrium. They are therefore particularly effective for treating problems that are not amenable to analytical studies. As supercomputers become increasingly more powerful and available, and with the advent of scientific visualization as a research tool, the scope and significance of simulation studies will grow correspondingly.

Current problems under investigation fall into three main areas: structural and dynamical properties of interfacial systems such as grain boundary solids and free surfaces, fracture and mechanical properties of crack-tip systems, and phase transitions such as melting, vitrification (liquid to glass), and amorphization (crystal to glass). Several projects are described separately below, and it is characteristic of these studies to involve collaborations with colleagues in other departments at the Institute or at research laboratories elsewhere. These external interactions have proved to be particularly beneficial, not only in gaining access to scientific expertise and resources not available at the Institute, but also in giving the students valuable exposure to different types of research environments.

Investigators: Professor S. Yip; K. S. Cheung; Drs. D. Wolf, and S.R. Phillpot (Argonne)

Support: Argonne National Laboratory, National Science Foundation

Related Academic Subjects:

22.113	Nuclear and Atomic Collision Phenomena
22.53	Statistical Processes and Atomistic Simulations

Recent References:

S.R. Phillpot, J.F. Lutsko, D. Wolf, and S. Yip, "Molecular Dynamics Study of Lattice-Defect Nucleated Melting in Silicon," Physical Review B 40, 2831 (1989).

J.F. Lutsko, D. Wolf, S.R. Phillpot, and S. Yip, "Molecular Dynamics Study of Lattice-Defect Nucleated Melting in Metals Using an Embedded Atom Method Potential," Physical Review B 40, 2841 (1989).

T. Nguyen and S. Yip, "Molecular Dynamics Study of a Bicrystal at Elevated Temperatures," Materials Science and Engineering A107, 15 (1989).

S.R. Phillpot, D. Wolf, and S. Yip, "How Do Crystals Melt?" Computers in Physics 3, 20 (1989).

D. Wolf, P.R. Okamoto, S. Yip, J.F. Lutsko, and M. Kluge, "Thermodynamic Parallels between Solid-State Amorphization and Melting," Journal of Materials Research 5, 286 (1990).

D. Wolf and S. Yip, "Interfaces Part I: Structure, Chemistry, Electronic Properties," MRS Bulletin, vol. XV, p. 21, September 1990.

D. Wolf and S. Yip, "Interfaces Part II: Mechanical and High-Temperature Behavior," MRS Bulletin, vol. XV, p. 23, October 1990.

S. Yip and D. Wolf, "Atomistic Concepts for Simulation of Grain Boundary Fracture," in Boundary Chemistry and Intergranular Fracture, G.W. Was and S. Bruemmer, Eds., Materials Science Forum, 46, 77 (1989).

S.R. Phillpot, D. Wolf, and S. Yip, "Effects of Atomic-level Disorder at Solid Interfaces," MRS Bulletin, vol. XV, p. 38, October 1990.

K.S. Cheung and S. Yip, "Brittle-Ductile Transition in Intrinsic Fracture Behavior of Crystals," Physical Review Letters 65, 2804 (1990).

K.S. Cheung, A.S. Argon, and S. Yip, "Activation Analysis of Dislocation Nucleation from Crack Tip in α-Fe," Journal of Applied Physics, 69, 2088 (1991).

S. Yip, "Simulation Studies of Interfacial Phenomena -- Melting, Stress Relaxation and Fracture," in Molecular Dynamics Simulations, F. Yonezawa, ed. (Springer-Verlag, Berlin, 1991), in press.

S.R. Phillpot, S. Yip, P.R. Okamoto, and D. Wolf, "Role of Grain Boundaries in Melting and Solid-State Amorphization," in Atomic-Level Properties of Interface Materials, D. Wolf and S. Yip, eds. (Chapman and Hall, London) to be published.

3.3.1.6 Molecular Dynamics Studies of Glassy States: Supercooled Liquids and Amorphized Solids

This project is concerned with the study of transport and fluctuation phenomena in simple fluids which undergo a liquid-glass transition under rapid cooling or compression, and the study of point defect migration and clustering in crystals which undergo a transition to amorphous structures under particle-beam irradiation. Molecular dynamics simulation is employed to investigate the nature of a dynamical transition in supercooled fluids which occurs at a temperature above the glass transition temperature; it is also used to follow the structural relaxation of crystal lattices into which self-interstitials have been introduced and thereby determine the mechanism of amorphization.

Investigators: Professor S. Yip; H. Hsieh and J. Wang; Dr. J.J. Ullo (Schlumberger-Doll)

Support: National Science Foundation, Argonne National Laboratory

Recent References:

J.J. Ullo and S. Yip, "Dynamical Correlations in Dense, Metastable Fluids," Physical Review A 39, 5877 (1989).

H. Hsieh and S. Yip, "Atomistic Simulation of Defect-Induced Amorphization of Binary Lattices," Physical Review B 39, 7476 (1989).

S. Yip and H. Hsieh, "Atomistic Simulation of Defect-Induced Structural Disordering and Amorphization," in *Science of Advanced Materials*, M. Meshii and H. Wiedersich, eds. (ASM, Metals Park, 1990), p. 121.

S. Yip, "Commentary on the Self-Consistent Model-Coupling Approximation," Journal of Statistical Physics 57, 665 (1990).

S. Yip, "Molecular Dynamics Studies of Glassy States: Supercooled Liquid and Amorphized Solids," in *Strongly Coupled Plasma Physics*, S. Ichimaru, ed. (Elsevier, Amsterdam, 1990), p. 149.

J.J. Ullo and S. Yip, "Dynamical Correlations in a Binary Metastable Fluid," Chemical Physics 149, 221 (1990).

3.3.1.7 Structural Relaxation in Glassy Polymers

This project is part of a University Research Initiative Program on the study of mechanical properties of structural polymers with Professor A.S. Argon (Mechanical Engineering) as the Principal Investigator and other Co-Investigators consisting of Professors R.E. Cohen and U.W. Suter (Chemical Engineering), and D.M. Parks (Mechanical Engineering). The objective is to study the nature of the glass transition in a polymeric system and local details of structural relaxation through a realistic molecular dynamics simulation model.

Investigators: Professor S. Yip; M. Sylvester

Support: Office of Naval Research/Defense Advanced Research Projects Agency

Recent References:

D. Deng, A.S. Argon, and S. Yip, "A Molecular Dynamics Model of Melting and Glass Transition in an Idealized Two-Dimensional Material," Philosophical Transactions of the Royal Society of London A 329, 549 (1989).

D. Deng, A.S. Argon, and S. Yip, "Topological Features of Structural Relaxations in a Two-Dimensional Model Atomic Glass - II," Philosophical Transactions of the Royal Society of London A329, 575 (1989).

D. Deng, A.S. Argon, and S. Yip, "Kinetics of Structural Relaxations in a Two-Dimensional Model Atomic Glass - III," Philosophical Transactions of the Royal Society of London A329, 595 (1989).

D. Deng, A.S. Argon, and S. Yip, "Simulation of Plastic Deformation in a Two-Dimensional Atomic Glass by Molecular Dynamics - IV," Philosophical Transactions of the Royal Society of London A329, 613 (1989).

M.F. Sylvester, S. Yip, and A.S. Argon, "Investigation by Atomistic Simulation of Structural and Dynamic Differences in the Glassy and Liquid States of Atactic Poly(propylene)," in *Computer Simulation of Polymers*, R.J. Roe, ed. (Prentice Hall, Englewood Cliffs, 1991), p. 105.

3.3.1.8 Interfacial Properties of Semiconductor Materials

The overall objective of this project, part of an MIT-IBM Joint Studies Program, is to study the structure, energetics, and mechanical behavior of surfaces of silicon using empirical interatomic potential functions. The specific problem of current interest which we have investigated is the question of relative stability of and the effects of stress relaxations on single- and double-stepped layer surfaces on Si(100).

Investigators: Professor S. Yip; T.W. Poon; Drs. P.S. Ho (IBM Watson) and F.F. Abraham (IBM Almaden)

Support: IBM Thomas J. Watson Research Center

Recent References:

T.W. Poon, "Atomistic Study of Equilibrium Structures on Si(100) Stepped Surfaces," Ph.D. Thesis, MIT (1990).

T.W. Poon, S. Yip, P.S. Ho and F.F. Abraham, "Equilibrium Structures of Si(100) Stepped Surfaces," Physical Review Letters 65, 2161 (1990).

T.W. Poon, F.F. Abraham, P.S. Ho and S. Yip, "Ledge Roughening on Si(100) Stepped Surfaces," Europhysics Letters, submitted.

T.W. Poon, S. Yip, P.S. Ho and F.F. Abraham, "Ledge Interactions and Stress Relaxations on Si(100) Stepped Surfaces," Physical Review B, submitted.

3.3.1.9 Molecular Dynamics Study of Icing on Cables and Structures

This project is part of a collaboration with Professor S. Shyam Sunder (Civil Engineering) with the goal of studying the formation and growth of interfacial bonds between ice and various metal and polymer substrates. Simulation results will be combined with laser micro-Raman spectroscopic measurements, to be performed at the Spectroscopy Laboratory at the Hawaii Institute of Geophysics, to gain understanding of the effects of physico-chemical parameters such as temperature, pressure, surface energy, freezing rate, and icing type.

Investigators: Professor S. Yip; N. Sonwalker

Support: National Science Foundation, Electric Power Research Institute

Recent References:

N. Sonwalker, S. Shyam Sunder and S. Yip, "Atomistic Simulation and Visualization of Thermal Disorder in Crystalline Ice," Proceedings of the 6th ASCE Engineering Mechanics Specialty Conference, Columbus, OH, May 20-22, 1991.

3.3.2 Radiological Sciences

Radiological science refers to the general field of radiation and radioisotope applications to biology, medicine, and, recently, materials science. The field includes radiation biophysics, diagnostic medical imaging, radiation therapy, some aspects of radiopharmaceutical chemistry, and neutron tomography. Research in this exciting field is rapidly expanding and interfaces with the important area of health care. Research opportunities exist at MIT as well as the local teaching hospitals.

3.3.2.1 Subjects of Instruction

The basic subjects of instruction in the radiological sciences field include the undergraduate subject, 22.04 Radiation Effects and Uses, and the three undergraduate/graduate subjects: 22.055/55J Biological and Medical Applications of Radiation and Radioisotopes, 22.056/56J Principles of Medical Imaging, and 22.057/57J Radiation Biophysics.

22.04 Radiation Effects and Uses, covers a wide range of material concerning ionizing radiation, its origins, uses, and hazards. Tours through facilities such as the MIT nuclear reactor and fusion center are included in the course. Lectures include discussions on the history of radiation research, cosmic rays, nuclear power and weapons, detection methods, biological hazards, food irradiation, and medical applications.

22.55J Biological and Medical Applications of Radiation and Radioisotopes, covers the principles of radiation production and interactions; radiation dosimetry with emphasis on applications and health hazards; shielding of beta, gamma, and neutron radiation from isotope and machine sources; detection and spectroscopy of beta, gamma, and neutron radiation; neutron activation analysis; production of radioisotopes and radiopharmaceuticals; and principles of nuclear medicine. The new undergraduate subject, 22.055, meets with graduate subject 22.55J, but assignments differ.

22.56J Principles of Medical Imaging. This course covers a broad range of topics in medical imaging including X-ray, nuclear medicine, ultrasound, NMR, emission and transmission computed tomography, and other modalities; two-dimensional and three-dimensional imaging techniques and displays; fundamentals of image formation, physiology of image perception, physics of radiation and ultrasound interaction and detection; physics of NMR; quantitation of images and reconstruction algorithms; medical applications, biological hazards; and cost/benefit analysis of imaging modalities. The new undergraduate subject, 22.056, meets with graduate subject 22.56J, but assignments differ.

22.57J Radiation Biophysics. Discusses ionizing radiation, ultraviolet radiation and heat and their effects on biological materials, cells and tissues. Examines *in vivo* and *in vitro* mammalian systems and explores mathematical models for cell survival, emphasizing prediction. Microstructural damage to cell components such as membranes, organelles, enzymes and DNA studied. Radiation syndromes in man, mutagenesis and carcinogenesis also investigated.

22.562 Advanced Biomedical Magnetic Resonance Seminar, is designed for students interested in advanced biomedical applications of magnetic resonance and who have already mastered the basic principles. A brief review is given of notation and terminology to be used in pulse sequence development. Applications of multidimensional NMR spectroscopy explored in liquid and solid state biosystems. State-of-the-art imaging techniques analyzed in detail, including fast scanning, flow imaging, and microscopy. Details of instrumentation also covered as time permits.

3.3.2.2 An Accelerator-Source of Epithermal Neutrons for Use in Neutron Capture Therapy

A three year collaboration to develop an epithermal neutron source using a new type of ion accelerator has been established with a local company called Science Research Laboratory to develop a versatile neutron irradiation facility for BNCT based on accelerator production of epithermal neutrons. A high current cascade tandem electrostatic accelerator (TCA) has been built at Science Research Laboratory. The TCA utilizes a recently developed high current negative ion source in conjunction with a high current solid state power supply to provide a compact, low cost, proton accelerator well suited for epithermal neutron production. The inherent simplicity and flexibility of this accelerator provide several features which are desirable for laboratory and clinical applications requiring neutron generation such as the application to NCT. Results of computational studies have indicated that this source of epithermal neutrons can deliver a therapeutic beam with safety and total therapy times commensurate with existing reactor-produced beams.

Investigators: Professors G.L. Brownell and J.C. Yanch

Support: US Department of Energy

Related Academic Subjects:

22.51	Interactions of Radiation with Matter
22.55J	Biological and Medical Applications of Radiation and Radioisotopes
22.56J	Principles of Medical Imaging
22.561J	Magnetic Resonance - Analytic, Biochemical and Imaging Techniques
22.57J	Radiation Biophysics

Recent References:

Yanch, J.C., X-L. Zhou, R.E. Shefer and R.E. Klinkowstein, "Accelerator-based epithermal neutron beam design for neutron capture therapy," accepted for publication by *Medical Physics*, 1991.

Yanch, J.C., X-L. Zhou and G.L. Brownell, "A Monte Carlo investigation of the dosimetric properties of monoenergetic neutron beams for neutron capture therapy," *Radiation Research*, **126**:1-20, 1991.

Yanch, J.C., X-L. Zhou, R.G. Shefer, R.E. Klinkowstein and G.L. Brownell, "The design of an accelerator-based epithermal neutron beam for boron neutron capture therapy," Proceedings of the Fourth International Symposium on Boron Neutron Capture Therapy, December 4-7, 1990, B. Allen, ed., Plenum Press, 1991.

Shefer, R.E., R.E. Klinkowstein, J.C. Yanch and G.L. Brownell, "Production of epithermal neutrons for BNCT with a tandem cascade accelerator," Proceedings of the Fourth International Symposium on Boron Neutron Capture Therapy, December 4-7, 1990, B. Allen, ed., Plenum Press, 1991.

Shefer, R.E., R.E. Klinkowstein, J.C. Yanch and G.L. Brownell, "A versatile accelerator source of epithermal neutrons for boron neutron capture therapy," in O.K. Harling, J. Bernard (Eds.), *Neutron Beam Design, Development and Performance for Neutron Capture Therapy*, Plenum Press, New York, 1989.

3.3.2.3 Isotope Sources of Epithermal Neutrons for Neutron Capture Therapy

The possibility of utilizing neutrons from the spontaneously-fissioning isotope ^{252}Cf is of real interest to hospitals and medical centers hoping to take advantage of NCT but who have no ready access to a nuclear reactor. A design study of the moderating and filtering assembly required to slow the ^{252}Cf neutrons down to a therapeutically useful energy indicates that a safe therapy beam can be developed with therapy times a factor of five lower than the times currently cited for reactor (and accelerator) beams.

Investigators: Professor J. C. Yanch; Dr. J. K. Kim (post-doctoral associate from Korea)

Related Academic Subjects:

22.51	Interactions of Radiation with Matter
22.55J	Biological and Medical Applications of Radiation and Radioisotopes
22.56J	Principles of Medical Imaging
22.561J	Magnetic Resonance - Analytic, Biochemical and Imaging Techniques
22.57J	Radiation Biophysics

Recent Reference:

Yanch, J.C., J.K. Kim and M.J. Wilson, "Design of a Californium-based epithermal neutron beam for neutron capture therapy," for submission to *Phys. Med. Biol.*, 1991.

3.3.2.4 Interstitial and Intracavity Brachytherapy using Radioisotopes

1. Beta-Emitters in the Treatment of Rheumatoid Arthritis

Surgical treatment of rheumatoid arthritis, a chronic disease affecting the joints, is painful, costly and requires a lengthy rehabilitation time. An alternative called "radiation synovectomy" requires the injection of beta-emitting radionuclides into the joint cavity. Using computer simulation the dose deposition in all areas of the affected joint have been calculated and the capacity for treating different-sized joints with different beta-emitters has been assessed. Tables providing rheumatologists with previously unavailable information regarding how much activity to administer as a function of maximum therapeutic dose to diseased areas while minimizing dose to health components have been developed.

Investigator: Professor J. C. Yanch

Support: Whitaker Health Sciences Fund

Related Academic Subjects:

22.51	Interactions of Radiation with Matter
22.55J	Biological and Medical Applications of Radiation and Radioisotopes
22.56J	Principles of Medical Imaging
22.561J	Magnetic Resonance - Analytic, Biochemical and Imaging Techniques
22.57J	Radiation Biophysics

Recent References:

Johnson, L.S. and J.C. Yanch, "Absorbed dose profiles for radionuclides of frequent use in radiation synovectomy," accepted for publication in *Arthritis and Rheumatism*, 1990.

Harling, O.K., R.G. Zamenhof, J.C. Yanch, R. Choi, G.R. Solares, R.D. Rogus, D.J. Moulin, L.S. Johnson, I. Olmez, S. Wirdzek, J.A. Bernard, C.I. Nwanguma, D.E. Wazer, S. Saris, C.B. Sledge and H. Madoc-Jones, "Boron neutron capture and radiation synovectomy research at the MIT research reactor," accepted for publication by *Nucl. Science Eng.*, 1991.

Johnson, L.S. and J.C. Yanch, "Absorbed dose profiles for radionuclides of frequent use in radiation synovectomy," *Health Physics*, **60** (Supp. 2): S9, 1991.

2. ^{252}Cf Implants for the Treatment of Solid Tumors

Detailed dosimetric calculations of the dose delivery profiles from ^{252}Californium implants in the brain and other tissues have been performed. Results have been separated into individual dose components and compared with experimental measurements carried out by collaborators in the New England Medical Center and the University of Kentucky. Data obtained as a result of the dosimetry study provide radiotherapists with the most detailed and up-to-date information for use in treatment planning for patient irradiation. Investigations into dose augmentation (via the neutron capture reaction) by the presence of ^{10}B in tumor cells have also been performed. Preliminary results indicate an 18% increase in tumor dose leading to almost 50% increase in tumor control (based on mammary cell carcinoma tumor control curves).

Investigators: Professor J.C. Yanch; Dr. R. Zamenhof (collaborator at Tufts-New England Medical Center)

Related Academic Subjects:

22.51	Interactions of Radiation with Matter
22.55J	Biological and Medical Applications of Radiation and Radioisotopes
22.56J	Principles of Medical Imaging
22.561J	Magnetic Resonance - Analytic, Biochemical and Imaging Techniques
22.57J	Radiation Biophysics

Recent Publications:

Zamenhof, R.G., J.C. Yanch, O.K. Harling, J. Wierzbicki, and J. Maruyama, "Comparison of dose distributions with ^{10}B augmentation near linear sources of ^{252}Cf obtained by experimental measurement and Monte Carlo simulation," Neutron Therapy Workshop, Kentucky, May 25-27, 1990.

Yanch, J.C., R.G. Zamenhof, J. Wierzbicki and Y. Maruyama, "Comparison of dose distributions with boron-10 augmentation near linear sources of ^{252}Cf obtained by Monte Carlo simulation and by experimental measurement," Proceedings of the Fourth International Symposium on Boron Neutron Capture Therapy, December 4-7, 1990, B. Allen, ed., Plenum Press, 1991.

3.3.2.5 Computer Simulation of Nuclear Medicine Imaging for Image Quantification

Simulation of all aspects of a realistic tomographic imaging situation in Nuclear Medicine has recently been undertaken using computer hardware and software available in the Whitaker College Biomedical Imaging and Computation Laboratory. Results compare extremely well both with theory and with real data acquired at the New England Medical Center with whom a collaboration has been set up. Now that the model has been verified it is being used to investigate the ability of a) different collimator geometries and b) scatter- and attenuation-correction algorithms to provide quantitatively accurate data with a higher signal-to-noise ratio. These investigations will ultimately lead to the development of new methods that will improve the quantitative information available in Nuclear Medicine Tomographic Images.

Investigators: Professor J. C. Yanch; A. Dobrzeniecki

Support: BRSG funding through MIT and a small pilot research grant from the Society of Nuclear Medicine

Related Academic Subjects:

22.44	Modeling and Simulation
22.56J	Principles of Medical Imaging
22.561J	Magnetic Resonance - Analytic, Biochemical and Imaging Techniques
6.341	Discrete-Time Signal Processing

Recent References:

Yanch, J.C., A.B. Dobrzeniecki, C. Ramanathan and R. Behrman, "Physically realistic Monte Carlo simulation of source collimator and tomographic data acquisition for emission computed tomography," submitted to *Physics in Medicine and Biology*, July 1991.

Yanch, J.C. and A.B. Dobrzeniecki, "Cone-beam SPECT for Cardiac Imaging - A Physically Realistic Model," accepted for presentation at Computers in Cardiology conference, September 1991.

Yanch, J.C. and A.B. Dobrzeniecki, "Monte Carlo simulation in SPECT: Complete 3D modeling of source, collimator and tomographic data acquisition," accepted for presentation at the IEEE Nuclear Science Symposium and Medical Imaging Conference, 1991.

3.3.2.6 NMR Microscopy

Pushing the fundamental limits of resolution of NMR imaging is the goal of this research. Included in this endeavor are biomedical applications of NMR microscopy. One subject under investigation is how the regional segregation of biochemical reactions inside cells and in small biosystems by physical barriers affects the biochemistry of life processes. A definition of the physico-chemical state of the intracellular milieu is essential to understanding biological chemistry and predicting behavior in living systems from data obtained in experiments performed in test tubes. In particular, the diffusion characteristics of major cellular biochemicals are under investigation to predict intracellular structural constraints from changes in diffusion characteristics compared with free solutions. Work is presently focused on rapidly metabolizing excitable cells from brain and muscle.

Investigators: Professor E. W. McFarland; Dr. J. L. Ackerman; S. Fricke, A. Mortara, and Y. Wu

Support: Whitaker Health Sciences Fund, MIT Sloan Fund

Recent Reference:

E.W. McFarland, M.J. Kushmerick, and L. Neuringer, "Chemical Exchange Magnetic Resonance Imaging," Magn. Res. Imaging 6:507-15 (1988).

3.3.2.7 Neutron Tomography

To utilize non-reactor neutron sources for imaging, high efficiency and high spatial resolution neutron detectors are required. A position-sensitive neutron detector is under investigation for two- and three-dimensional tomographic imaging of materials and complex assemblies. The detector system consists of an LiF-ZnS scintillator screen optically coupled to a cooled charge-coupled device (CCD). Practical resolution limits of the single screen system are calculated to be approximately μm, determined by the neutron beam divergence and the resolution of the scintillator screen. Contrast resolution in a $(200\ \mu m)^3$ volume element is calculated to be 1 percent of the cross-section in small samples. Initial images were made using the MIT Research Reactor as a thermal neutron source (nominal flux approximately 2.4×10^8 n°/cm-sec). Predictions for nonreactor-based sources are made using this preliminary data. The effects of scatter have been estimated and modelled using Monte Carlo and direct numerical calculations. These results were compared to measured data. The expected strong dependence on sample material has been observed. Two- and three-dimensional tomograms were obtained of phantoms and several demonstration objects, including a control valve and an oil well dolomite core sample. The spatial resolution in the images compared favorably to predictions, and it is expected that the final system will improve resolution by at least a factor of 10 over current technology.

Investigators: Professor E. W. McFarland; Dr. R. C. Lanza; G. W. Poulos and J. L. Uhle

Support: MIT Sloan Fund, NSF Presidential Young Investigator's Award to E. W. McFarland

Recent References:

R. Lanza, E. McFarland, and G. Poulos, "Neutron-computed Tomography Using Charge-coupled Devices," IEEE Nuclear Science 12/90.

E. McFarland, R. Lanza, and G. Poulos, "Multi-dimensional Neutron-computed Tomography with Cooled Charge-coupled Devices," IEEE Nuclear Science 2/91.

3.3.2.8 Boron Neutron Capture Therapy for Brain Cancer

A highly malignant type of brain cancer, glioblastoma, is fatal for 5000-6000 US residents each year. Metastatic melanoma of the central nervous system is another target of this research. Conventional modalities of treatment are not effective in treating these cancers. Recently a major project leading to clinical trials has been re-funded for an additional three years. The approach is to use neutron capture therapy at the MIT research reactor to selectively destroy the malignant cells in high grade astrocytomas. Initially about ten patients will be treated. If results are positive, expanded clinical trials will be initiated. Current efforts are focused on preclinical studies and on the preparation for clinical trials.

Investigators: Professor O. K. Harling; Dr. J. A. Bernard; medical collaborators at the Tufts New England Medical Center, Dr. H. Madoc-Jones and Dr. R. G. A. Zamenhof and associates

Support: US Department of Energy

Related Academic Subjects:

22.51	Interactions of Radiation with Matter
22.55J	Biological and Medical Applications of Radiation and Radioisotopes
22.56J	Principles of Medical Imaging

22.561J Magnetic Resonance - Analytic, Biochemical, and Imaging Techniques
22.57J Radiation Biophysics

Recent References:

Neutron Beam Design, Development, and Performance for Neutron Capture Therapy, Basic Life Sciences, Vol. 54, Otto K. Harling, John A. Bernard and Robert G. Zamenhof, eds., Plenum Press, NY (1990).

S.D. Clement, J.R. Choi, R.G. Zamenhof, J.C. Yanch and O.K. Harling, "Monte Carlo Methods of Neutron Beam Design for Neutron Capture Therapy at the MIT Research Reactor (MITR-II)," in: Neutron Beam Design, Development, and Performance for Neutron Capture Therapy, Basic Life Sciences, Vol. 54, Otto K. Harling, John A. Bernard and Robert G. Zamenhof, eds., Plenum Press, NY (1990), pp. 51-70.

J.R. Choi, S.D. Clement, O.K. Harling and R.G. Zamenhof, "Neutron Capture Therapy Beams at the MIT Research Reactor," in: Neutron Beam Design, Development, and Performance for Neutron Capture Therapy, Basic Life Sciences, Vol. 54, Otto K. Harling, John A. Bernard and Robert G. Zamenhof, eds., Plenum Press, NY (1990), pp. 201-218.

H. Madoc-Jones, D.E. Wazer, R.G. Zamenhof, O.K. Harling and J.A. Bernard, Jr., "Clinical Considerations for Neutron Capture Therapy of Brain Tumors," in: Neutron Beam Design, Development, and Performance for Neutron Capture Therapy, Basic Life Sciences, Vol. 54, Otto K. Harling, John A. Bernard and Robert G. Zamenhof, eds., Plenum Press, NY (1990), pp. 23-36.

R.G. Zamenhof, S.D. Clement, O.K. Harling, J. Brenner, D.E. Wazer, H. Madoc-Jones and J.C. Yanch, "Monte Carlo Based Dosimetry and Treatment Planning for Neutron Capture Therapy of Brain Tumors," in: Neutron Beam Design, Development, and Performance for Neutron Capture Therapy, Basic Life Sciences, Vol. 54, Otto K. Harling, John A. Bernard and Robert G. Zamenhof, eds., Plenum Press, NY (1990), pp. 283-306.

O.K. Harling, J.A. Bernard, and R.G. Zamenhof, "Critique of the MIT Workshop on Neutron Beam Design, Development, and Performance for Neutron Capture Therapy," an invited paper submitted at the Fourth International Symposium on Neutron Capture Therapy for Cancer, Biomedicine and Health, held in Sydney, Australia, December 4-7, 1990.

R.G. Zamenhof, H. Madoc-Jones, O.K. Harling, D. Wazer, S. Saris and J.C. Yanch, "The Neutron Capture Therapy Research Program at New England Medical Center and the Massachusetts Institute of Technology," an invited paper submitted at the Fourth International Symposium on Neutron Capture Therapy for Cancer, Biomedicine and Health, held in Sydney, Australia, December 4-7, 1990.

J.R. Choi, R.G. Zamenhof, J.C. Yanch, R. Rogus and O.K. Harling, "Performance of the Currently Available Epithermal Neutron Beam at the Massachusetts Institute of Technology Research Reactor (MITR-II)," an invited paper submitted at the Fourth International Symposium on Neutron Capture Therapy for Cancer, Biomedicine and Health, held in Sydney, Australia, December 4-7, 1990.

3.3.2.9 Determination of Sub-Cellular Distribution of Boron-10 for Application to Boron Neutron Capture Therapy

A program of preclinical study of BNCT continues. Studies are aimed at the development of techniques for determining the distribution of boron compounds in cells and tissue. The studies also include the dosimetry of boron capture and other radiation, development of new boron compounds, and improvement in radiation sources.

Investigators: Professor G.L. Brownell; T. Nguyen, M. Bhatia

Support: US Department of Energy

Related Academic Subject:

22.57J	Radiation Biophysics

3.3.2.10 Collaborative Projects with Massachusetts General Hospital (MGH)

Medical imaging is an area of increasing interest in diagnostic medicine. In collaboration with the MGH, programs are being developed in the area of positron tomography. The program involves development of new tomographic instruments having high resolution, development of new compounds, and biological and medical study.

A study is underway on the analysis of systems for highly automated production of radiopharmaceuticals. Such a system may result in a much wider application of positron imaging.

NMR imaging is playing an increasingly important role, and a number of various groups are interested in developing new and improved instruments. This topic is being included in future imaging courses.

Investigator: Professor G.L. Brownell, Dr. B. Rosen

Support: National Institutes of Health; US Department of Energy

Related Academic Subjects:

22.56J	Principles of Medical Imaging
22.561J	Magnetic Resonance - Analytic, Biochemical and Imaging Techniques

Recent References:

Brownell G.L., Burnham C.A., Stearns C.W., Chesler D.A., Brownell A-L., and Palmer M.: Development in high-resolution positron emission tomography at MGH. International Journal of Imaging Systems and Technology 1:207-217, 1989.

Burnham C.A., Kaufman D., Chesler D.A., Martin J. and Brownell G.L.: A Low-Z PET Detector. IEEE Trans. Nucl. Sci. Symposium, San Francisco, CA (Abstract), January, 1990.

3.3.3 Radiation Health Physics

Radiation Health Physics is dedicated to educating scientists and engineers in the study of all aspects of radiation interactions, measurement and effects on the human body. A strong foundation in basic engineering fundamentals plus specialized study in the hazards and benefits of radiation, environmental radiation transport, radiation shielding and the regulatory and legal aspects of radiation use lead to both careers and independent contributions in this diverse and pertinent field of study.

3.3.3.1 Subjects of Instruction

The following graduate subjects are offered to students specializing in the area of radiation health physics.

22.39 Nuclear Reactor Operations and Safety. Principles of operating nuclear reactor systems in a safe and effective manner. Emphasizes light-water reactor systems with transient response studies, including degraded core recognition and mitigation. Consequence analysis and risk assessment. Lessons from past accident experience. NRC licensing and regulations. Demonstrations: operation of the MIT research reactor, use of a PWR concept simulator. Optional laboratory section involves a project at the Nuclear Reactor Laboratory.

22.51 Interactions of Radiation with Matter. Basic principles of interaction of electromagnetic radiation, thermal neutrons, and charged particles with matter. Introduces classical electrodynamics, quantum theory of radiation, time-dependent perturbation theory, transition probabilities and cross-sections describing interaction of various radiations with atomic systems. Applications include theory of nuclear magnetic resonance; Rayleigh, Raman and Compton scattering; photoelectric effect; and use of thermal neutron scattering as a tool in condensed matter research.

22.55J Biological and Medical Applications of Radiation and Radioisotopes. Benefits and hazards of radiation. Principles of radiation production and interactions. Radiation dosimetry, emphasizing applications. Health effects. Shielding of beta, gamma, and neutron radiation from isotope and machine sources. Detection and spectroscopy of beta, gamma, and neutron radiation. Neutron activation analysis. Production of radioisotopes and radio-pharmaceuticals. Principles of nuclear medicine and imaging with radiation. Requires a comprehensive term paper and presentation.

22.57J Radiation Biophysics. Discusses ionizing radiation, ultraviolet radiation and heat and their effects on biological materials, cells and tissues. Examines *in vivo* and *in vitro* mammalian systems and explores mathematical models for cell survival, emphasizing prediction. Microstructural damage to cell components such as membranes, organelles, enzymes and DNA studied. Radiation syndromes in man, mutagenesis and carcinogenesis also investigated.

22.58 Seminar in Radiation Health Physics. Introduces many of the pertinent areas of research and concern in the field of Radiation Health Physics. Topics of weekly seminars include radiation shielding, waste management, environmental behavior of radioactivity, medical irradiations, methods of detection and dosimetry, dose reduction and the regulatory and legal aspects of radiation; student presentations will also be required.

22.59 Principles of Nuclear Radiation Measurement and Protection. Combines lectures, demonstrations and experiments. Covers effects of radiation on persons; control of radiation exposure within applicable standards; theory and use of α, β, γ and n detectors and spectrometers; use of isotopes, radiation shielding and dosimetry. Includes demonstrations and experiments using the MIT research reactor, accelerators and power reactors. Students have choices in the experiments they perform. This course has recently been revised to include more modules which explicitly deal with Health Physics.

22.77 Nuclear Waste Management. Introduces scientific and engineering aspects of the management of spent fuel, reprocessed high-level waste, uranium mill tailings, low-level wastes and decommissioning wastes. Fundamental processes and governing equations of radiation and radionuclide transport. Design principles and evaluation methods for geologic waste disposal systems. Interim storage, processing and transportation technologies. Review of nuclear waste management regulation.

22.32 Nuclear Power Reactors. Describes engineering and physical aspects of current nuclear power reactors. Discusses design details, including requirements for safety of light- and heavy-water reactors, high temperature gas-cooled reactors, liquid-metal cooled fast reactors, and other reactor concepts. Compares reactor characteristics both in class and by individual student projects. Discusses development problems and assesses potential for future improvements.

22.35 Nuclear Fuel Management. Principles of physics and engineering that govern and constrain the configuration, arrangement and time-dependent behavior of fuel for nuclear reactors. Emphasizes in-core and front-end aspects and light-water reactor applications. Economic optimization of fuel cycles, fuel design and assembly management, considering both long-term strategic goals and short-term tactics.

22.811 Energy, Electricity, and the Environment. Addresses the various environmental impacts of producing thermal and electric power with currently available technology. Compares impacts throughout both the fossil and nuclear fuel cycles. Topics include fuel resources and extraction, power station effluents, air pollution, global warming, alternative technologies, waste heat disposal, reactor safety and radioactive waste disposal.

22.812 Nuclear Energy Economics and Policy Analysis. A comprehensive assessment of the economic, environmental, political and social aspects of nuclear power generation and the nuclear fuel cycle. Quantitative applications of the principles of engineering economics; comparison of alternatives, using discounted cash flow methods. Technology assessment/policy analysis of institutional alternatives for R&D, management and regulation; includes nuclear power plant licensing, nuclear waste management and nuclear power and weapons proliferation.

Harvard School of Public Health:

ESP 261a,b Aerosol Technology. Covers the properties of suspended particles (dust, smoke, clouds) and the physical principles underlying their behavior. Topics include: particle motion due to gravitational, thermal and electrostatic forces; diffusion; impaction; coagulation; filtration; condensation and evaporation; optical properties; and sizing statistics. Laboratories cover optical and electron microscopy, sampling and mass concentration and particle size measurement. Required for concentrators in industrial hygiene and air pollution control.

ESP 271b Occupational and Environmental Radiation Protection. Covers biological effects of radiation; radiation epidemiology; radiation protection standards and regulations; laboratory, industrial and environmental sources of radiation; and methods of environmental and occupational radiation protection.

3.3.3.2 Effects of Radon on Human Genetic Material

Experimental determination of the ability of Radon daughters to produce point mutations in human β cells has begun. Radon gas is bubbled through a suspension of cells in medium. Dose-rate delivery and total dose are under experimental control. Using the technique of "mutational spectral analysis" the exact "fingerprint" of high-LET radiation on genetic material (if one exists) can be determined. Knowledge of what this fingerprint is will aid in assessing the radon exposure to excised human lung tissue (biopsy removal and necropsy).

Investigators: Professor J. C. Yanch, Professor W. Thilly (Center for Environmental Health Studies)

Support: application to National Cancer Institute, May 1991

Related Academic Subjects:

22.55J	Biological and Medical Applications of Radiation and Radioisotopes
22.57J	Radiation Biophysics
TOX 213	Genetic Toxicology
TOX 215	Molecular Carcinogenesis

3.4 Energy Economics and Policy

Full development of the Department's original and still prime role in applications of nuclear technology (fission, fusion and other radiation related disciplines) brings us into the areas of energy policy, environmental effects, national and international affairs, studies of the overall health of the nuclear and related sectors, power plant siting policies, regulatory procedures, and a number of fundamental issues that underlie how modern civilizations handle their problems.

These activities have continued during the past year and have had substantial influence both at MIT and elsewhere.

3.4.1 Subjects of Instruction

The basic subjects of instruction in the energy field include the undergraduate subject 22.08 Energy and the two graduate subjects 22.812 Nuclear Energy Economics and Policy Analysis and 22.81 Energy Assessment.

22.08 Energy, this subject deals with energy from a holistic point of view: provision, rational utilization and conservation, regulation, environmental effects, and impact on other societal sectors. Resources of petroleum, natural gas, coal, nuclear and other energy forms. Technologies of providing energy from these forms. Utilization of energy in various sectors: transportation, industrial, commercial, and domestic, including especially opportunities for increased efficiency and energy conservation. Regulatory, tax, and other institutional arrangements that effect production and use patterns. Environmental costs and opportunities associated with exercising various energy strategies, both existing and proposed. Domestic and international political, strategic, and economic implications. Meets with 22.81, but some assignments differ.

22.38 Reliability Analysis Methods, covers the methods of reliability analyses including fault trees, decision trees, and reliability block diagrams. Discusses the techniques for developing the logic diagrams for reliability assessment, the mathematical techniques for analyzing them, and statistical analysis of required experience data. Practical examples of their application to the risk assessment of nuclear power reactors and other industrial operations discussed.

22.81 Energy Assessment, is an introduction to the broad field of energy, including technological, social, environmental, economic, and political aspects. Energy provision, transformation, and utilization. Development of energy options for the future, and analyses of present regional, national, and international energy programs. Intended for graduate students entering energy fields in which energy is important, and who desire a holistic overview.

22.811 Energy, Electricity, and the Environment, assesses the various environmental impacts of producing thermal and electric power with currently available technology. Compares impacts throughout both the fossil and nuclear fuel cycles. Topics include fuel resources and extraction, power station effluents, waste heat disposal, reactor safety, and radioactive waste disposal.

22.812 Nuclear Energy Economics and Policy Analysis, presents a comprehensive assessment of the economic, environmental, political, and social aspects of nuclear power generation and the nuclear fuel cycle. Applications of the principles of engineering economics; comparison of alternatives using discounted cash flow methods. Technology assessment/policy analysis of institutional alternatives for R&D, management and regulation; topics include nuclear power plant licensing, nuclear waste management, and nuclear power and weapons proliferation.

22.82 Engineering Risk-Benefit Analysis, is offered as a School-wide Elective. Risk assessment, decision and cost-benefit analysis, and fault-tree methods for describing and making decisions about societal risks (nuclear reactors, dams, carcinogens, transport and disposal of hazardous materials) associated with large engineering projects. Balancing risks and benefits in situations involving human safety, environmental risks, and financial uncertainties. Presentations of major risk assessments and the public decision processes associated with them.

22.821 Engineering Systems Analysis, is offered as a School-wide Elective. Synthesis of analytic procedures for identification and selection of optimal systems. Review of economic framework for analysis. Systematic application of mathematical optimization to engineering problems. Evaluation procedures for single and multi-attributed problems covering decision analysis in addition to standard procedures. Application of this material to real problems. Use of microcomputer packages and expert systems based in Project Athena.

22.841 Nuclear Weapons and Arms Control: Technology and Policy Issues, is offered as a School-wide Elective. This course reviews nuclear weapons systems developments and efforts at arms control. Focuses on the interaction of technological factors with strategic concepts, intelligence assessments, and political judgement. Topics: nuclear weapons technology and effects, nuclear weapons proliferation, strategic defensive and offensive weapons, and analysis of current strategic arms programs. To the extent possible, experts who have played key roles in the topics covered are invited to give guest lectures.

22.843J Technology, Productivity and Industrial Competition is a new subject, jointly offered with the Sloan School, the Department of Political Science, and the Science, Technology and Society Program. This course analyzes the relationships between technological innovation, productivity growth, and industrial competitiveness, and discusses the key factors influencing the industrial performance of the US and other countries. The course draws heavily on the recent work of the MIT Commission on Industrial Productivity.

3.4.2 US Industrial Productivity

A major new program of research has been initiated which will continue the study of productivity and industrial performance begun by the MIT Commission on Industrial Productivity. The program involves faculty and students from across the Institute, and will be comprised of several activities including (1) research on the productivity and competitiveness of specific industries, (2) research projects addressing important aspects of industrial performance that cut across individual sectors; and (3) the development of new educational tools and resources for undergraduate and graduate programs.

Investigators: Professor R. K. Lester et al.

Support: Sloan Foundation

Recent References:

M.L. Dertouzos, R.K. Lester, R.M. Solow, and the MIT Commission on Industrial Productivity, Made in America: Regaining the Productive Edge, MIT Press, Cambridge, 1989.

The Working Papers of the MIT Commission on Industrial Productivity, MIT Press, Cambridge, 1989 (two volumes).

S. Berger, M. Dertouzos, R. Lester, R. Solow, and L. Thurow, "Towards a New Industrial America," Scientific American, June 1989, Vol. 260, No. 6.

3.4.3 Option Valuation of Flexible Energy Investments

Classical financial investment criteria are not well-suited to project investments that can be interrupted or modified by the investor during the lifetime of the project. The calculation of the net present value of a flexible investment requires sophisticated decision tree analyses, and raises difficult discount rate issues. In some cases it may be preferable to consider such investments as financial call options. Financial option theory can then be used to value these flexible investments.

Coal gasification offers an attractive way to use coal in an environmentally acceptable way and also potentially allows a natural gas-fired power plant to switch fuels from natural gas to coal in order to take advantage of changes in gas or coal prices. Using financial option theory we have analyzed a coal gasifier as an add-on investment to a gas-fired power plant of finite life. Our model yielded results that are substantially different from those of a classical NPV calculation. The flexibility to delay installing gasifier and to switch fuels following its installation were each found to produce significant economic value for the plant operator. Neither factor is accounted for in conventional NPV calculations.

We are currently applying option theory to the evaluation of environmental investment opportunities in the electric utility industry. We are specifically interested in the evaluation of a scrubber investment by a coal-burning utility that is required by regulation to reduce its sulfur dioxide emissions.

Investigators: Professor R. K. Lester; O. Herbelot

Support: Center for Energy Policy Research

Related Academic Subject:

22.812 Nuclear Energy Economics and Policy Analysis

Recent Reference:

O. Herbelot and R.K. Lester, "Option Valuation of Flexible Energy Investments: The Case of a Coal Gasifier," CEPR Working Paper, April 1991.

3.4.4 Cross-National Analysis of Nuclear Industrial Performance

An abundance of statistical and case study evidence indicates the presence of systematic variations in industrial performance in nuclear power plant design, construction, and operation within and among nations. By studying the origins of these differences, useful lessons can be drawn for nuclear industry practitioners seeking to bring their performance to worldwide levels of "best practice." Such studies can also provide more general insights into the effects of managerial, organizational, cultural, and other factors on productive performance across a range of industries. During the last two years, our research has continued to focus on the relationships between managerial and regulatory practices, industrial organization, and construction and operating performance in the United States, France, Japan, and West Germany. We have refined the statistical technique developed previously to quantify the contribution of "learning by using" to the improvement of operating performance, and have obtained results demonstrating the effects of industrial structure differences on learning in the nuclear power industries of France and the United States. We are currently extending this work to include Germany and Japan.

In the area of nuclear construction, we have continued our efforts to understand the reasons for variations in construction costs. We have extended our framework for analyzing the economic consequences of differences in the organization of power plant construction projects, and have made statistical estimates of trends in the ability of utilities to effectively monitor the activity of their agents from project to project and also of the economic costs associated with "agent switching," i.e., changes in the identity of architect-engineers and/or constructors contracting with utilities during or between projects.

Investigators: Professor R. K. Lester; M. J. McCabe and S. Norastheh

Support: MIT Center for Energy Policy Research

Recent References:

R.K. Lester and M.J. McCabe, "The Effect of Industrial Structure on Learning by Doing in Nuclear Power Plant Operation," April 1991 (in press).

M.J. McCabe and R.K. Lester, "Principals, Agents and the Learning Curve: The Case of Nuclear Power Plant Construction," presented at the American Economics Association Annual Meeting, New York, December 1990.

3.4.5 Nuclear Proliferation in the Middle East

Although there is widespread recognition of the grave consequences of the use of nuclear weapons in the Middle East, there also has been a strong and long-held tendency in both the US and Israel to avoid discussing the nuclear issue in a serious manner.

Admittedly, this view does have its political logic. The nature of the Arab-Israeli conflict makes it highly unlikely that any proposal for elimination of the nuclear threat, e.g., a nuclear weapons free zone, would be acceptable to all sides at the present time. Nevertheless, in the aftermath of the war in the Gulf, we believe that the time has come to reexamine this conventional wisdom. This is because the risks of nuclear use are increasing, and also because the current interest in a political settlement might provide a window of opportunity for fruitful discussions on the nuclear issue.

A study of the subject was started in April 1990.

Investigators: Dr. M. Miller and Dr. A. Cohen (Department of Philosophy, Tel-Aviv University, Israel)

Support: Rockefeller Brothers Fund, W. Alton Jones Foundation, Rockefeller Foundation, Ploughshares Fund, Prospect Hill Foundation

Recent References:

A. Cohen and M. Miller, "Nuclear Shadows in the Middle East: Prospects for Arms Control in the Wake of the Gulf Crisis," Strategic Studies, Spring 1991.

A. Cohen and M. Miller, "Defusing the Nuclear Mideast," The New York Times, May 30, 1991.

A. Cohen and M. Miller, "A Retrospective View of the Gulf War Nuclear Threat," Bulletin of the Atomic Scientists, July/August 1991.

3.4.6 Nuclear Waste Management

Worldwide prospects for greater acceptance of nuclear power may be linked to the successful development and deployment of systems for the disposal of high-level nuclear waste (HLW). Constraints on faculty availability have, in recent years, limited the extent of departmental involvement in this area, but a commitment has been made and several initiatives taken, including hiring a new tenure track assistant professor, to strengthen our activities in this area. In September 1991, Professor Alfred Schneider joined the faculty as a visiting professor whose primary interest is in this area. He will be teaching a revised version of the subject Nuclear Chemical Engineering.

Professor (emeritus) Driscoll, jointly with Professor Tester (Energy Laboratory/Chemical Engineering Department), is currently supervising an engineer's thesis student who is evaluating deep drill holes as an alternative scheme for HLW disposal.

Professor Lester continues to serve on the National Academy of Sciences Board on Radioactive Waste Management; he again taught subject 22.77 Nuclear Waste Management in the fall term 1990.

Professor Kazimi was appointed chairman in 1991 of the High-Level Waste Tank Advisory Panel for DOE. He and Dr. Charles Forsberg, a visiting scientist in the academic year 1990-91, collaborated on the assessment of the safety conditions of storage facilities for the high-level wastes at DOE sites. Professor Kazimi also supervised two S.M. theses in this area: one comparing radioactive waste from fusion and fast fission reactors, and the other, co-supervised by Professor Lidsky, evaluating the use of a fusion reactor to transmute HLW from a modular high temperature gas-cooled reactor.

Professor Kent Hansen, together with his colleagues at the Energy Laboratory, has developed and submitted to DOE a research proposal aimed at improved environmental management of DOE wastes, including work on the science of managing complex systems, technology to improve the functioning of the system, and policy issues related to how the different parties involved influence overall system behavior.

As discussed in the section on advanced nuclear power studies, Professor Lidsky and Golay and Dr. Miller have continued their assessment of the Integral Fast Reactor fuel cycle, which has a number of unconventional HLW streams.

The department continues as an approved site for graduate study by DOE Civilian Radioactive Waste Management Fellows. During academic years 1989-1990 and 1990-1991, two and one students have held these awards, respectively.

Investigators: Professors M. Kazimi, R. K. Lester, L. M. Lidsky, K. Hansen, M. J. Driscoll, J. Tester (E-Lab/Chem. Eng.); Drs. M. Miller, M. Weiss (E-Lab); W. Hollaway, M. Koch, B. Lal, W. S. Kuo

Support: Internal, DOE Waste Management Fellowships, DOE (ANL)

Related Academic Subjects:

22.35	Nuclear Fuel Management
22.77	Nuclear Waste Management

22.811	Environmental Impacts of Electricity (new title: Energy, Electricity, and the Environment)
22.812	Nuclear Energy Economics and Policy Analysis

Recent References:

M. Koch, "A Comparison of Radioactive Waste from Fast Fission and Fusion Reactors," S.M. Thesis, MIT Nuclear Engineering Department, September 1990.

B. Lal, "MHTGR Spent Fuel Transmutation in ITER," S.M. Thesis, MIT Nuclear Engineering Department, May 1990.

W.R. Hollaway, L.M. Lidsky and M.M. Miller, "The Role of Actinide Burning and the Integral Fast Reactor in the Future of Nuclear Power," Report No. MIT-ANP-TR-001, December 1990.

4. CURRICULUM

4.1 Degree Programs

The Department offers programs leading to the degrees of Bachelor of Science in Nuclear Engineering, Master of Science in Nuclear Engineering, Master of Science in Radiation Health Physics, Nuclear Engineer, and Doctor of Philosophy (or Doctor of Science) in Nuclear Engineering. The duration and objectives of these programs are quite different.

The objective of the bachelor's program in nuclear engineering is to provide students with a mastery of scientific and engineering fundamentals together with experience in their applications to problems in the field of nuclear engineering. This is accomplished through a curriculum under which a student completes general Institute requirements and a departmental program. The departmental program includes background subjects (in physics and mathematics); subjects in engineering principles (strength of materials, fluid mechanics, thermodynamics, heat transfer, and computer modeling); nuclear engineering specialty subjects (laboratory, applied physics, and design/systems); and an SB thesis project. In this manner, the student is prepared for immediate employment at the SB level in the nuclear industry, for further graduate level training in nuclear engineering, or for entry into medical school.

The objective of the master's program is to provide students who have had sound undergraduate training in physics, chemistry or engineering with the equivalent of one year of graduate education in nuclear engineering. Although full knowledge of the subject matter and techniques of nuclear engineering cannot be obtained in one year, graduates of this program are given a sound base of knowledge which prepares them either for employment on nuclear projects or for more advanced graduate education. Minimum requirements for the master's degree are two semesters of full-time graduate instruction including thesis. The majority of the candidates for this degree, however, need a full calendar year to complete course work and thesis. A two-year program leading to the master's degree in radiation health physics is also available.

The objective of the nuclear engineer's program is to educate students for a creative career in the design aspects of nuclear engineering. Minimum requirements are four semesters of full-time graduate instruction, including a substantial thesis concerned with engineering analysis, engineering design, or construction of a nuclear facility or device. Students in this program have sufficient time to learn advanced techniques for engineering analysis and design, and their creative abilities in these areas are developed through participation in engineering projects under faculty supervision.

The objectives of the doctoral program are to provide an advanced education in nuclear engineering and to challenge the student to become a leading and original contributor to her or his professional field. Students in this program must satisfactorily complete the following three requirements: 1) pass a general examination, 2) fulfill a major/minor requirement, which consists of obtaining an average grade of B or better in an approved program of advanced studies of not less than 60 credit hours, and 3) complete a major research investigation of sufficient scope and originality to constitute a contribution of permanent value to science and technology. Although no set time is specified for completion of the doctoral program, most students require from three to five years. Students completing the doctor's program in nuclear engineering are prepared and motivated to work on the frontiers of nuclear technology.

4.2 Fields of Study

Although each student's program of study is arranged to suit her/his individual interests and objectives, most programs fall into one of the nine fields of study listed below.

1) Reactor Physics
2) Reactor Engineering
3) Applied Plasma Physics
4) Fusion Reactor Technology
5) Applied Radiation Physics and Molecular Simulation
6) Radiological Science
7) Nuclear Materials Engineering
8) Nuclear and Alternate Energy Systems and Policy
9) Radiation Health Physics

Most candidates for the master's degree specialize either in some combination of reactor physics and reactor engineering under the more general heading of fission reactor technology, or in applied plasma physics, nuclear materials engineering, or applied radiation physics.

The fields listed above are appropriate for candidates for the doctor's degree. Doctoral candidates taking the General Examination required for that degree have the option of being examined in any one of these fields.

4.3 Subjects of Instruction

Subjects of instruction currently offered by the Nuclear Engineering Department are listed below. The subjects are divided into different areas for convenience. The introductory subjects 22.311 Energy Engineering Principles and 22.71J Physical Metallurgy are intended for graduate students who did not have the material as an undergraduate but need the material for graduate work. Subjects designated "J" are taught jointly with other departments, e.g., Aeronautics and Astronautics, Chemical Engineering, Civil Engineering, Electrical Engineering and Computer Science, Health Science and Technology, Materials Science and Engineering, Mechanical Engineering, Metallurgy, Ocean Engineering, Physics, and Political Science.

Undergraduate Subjects

22.U.R.	Undergraduate Research Opportunities Program
22.002	Management in Engineering
22.006	Computer Models of Physical and Engineering Systems
22.011	Seminar in Nuclear Engineering
22.012	Seminar in Fusion and Plasma Physics
22.013	Applications of Radiation in Science, Medicine, and Technology
22.02	Introduction to Applied Nuclear Physics
22.021	Nuclear Reactor Physics

22.03	Engineering Design of Nuclear Power Systems
22.031	Engineering of Nuclear Reactors
22.033	Nuclear Systems Design Project
22.04	Radiation Effects and Uses
22.055	Biological and Medical Applications of Radiation and Radioisotopes
22.056	Principles of Medical Imaging
22.057	Radiation Biophysics
22.061	Fusion Energy I
22.062	Fusion Energy II
22.069	Undergraduate Plasma Laboratory
22.070J	Materials for Nuclear Applications
22.08	Energy
22.082	Nuclear Energy Economics and Policy Analysis
22.084	Inventions and Patents
22.09	Principles of Nuclear Radiation Measurement and Protection
22.091	Special Topics in Nuclear Engineering
22.092	Engineering Internship

Graduate Subjects

Nuclear Physics

22.111	Nuclear Physics for Engineers I
22.113	Nuclear and Atomic Collision Phenomena

Nuclear Reactor Physics

22.211	Nuclear Reactor Physics I
22.212	Nuclear Reactor Physics II
22.213	Nuclear Reactor Physics III

Nuclear Reactor Engineering

22.311	Energy Engineering Principles
22.312	Engineering of Nuclear Reactors
22.313	Advanced Engineering of Nuclear Reactors
22.314J	Structural Mechanics in Nuclear Power Technology
22.32	Nuclear Power Reactors
22.33	Nuclear Engineering Design
22.35	Nuclear Fuel Management
22.36J	Two-Phase Flow and Heat Transfer
22.38	Reliability Analysis Methods
22.39	Nuclear Reactor Operations and Safety
22.40J	Advanced Reliability Analysis and Risk Assessment
22.571J	General Thermodynamics
22.572J	Quantum Thermodynamics

Numerical and Mathematical Methods

22.42	Numerical Methods in Engineering Analysis
22.44	Modeling and Simulation

Radiation Interactions and Applications

22.51	Interactions of Radiation with Matter
22.52J	Statistical Thermodynamics of Complex Liquids
22.53	Statistical Processes and Atomistic Simulations
22.55J	Biological and Medical Applications of Radiation and Radioisotopes
22.56J	Principles of Medical Imaging
22.561J	Magnetic Resonance - Analytic, Biochemical, and Imaging Techniques
22.562	Advanced Biomedical Magnetic Resonance Seminar
22.563J	Advanced Topics in Image Analysis for Medical Applications
22.57J	Radiation Biophysics
22.58	Seminar in Radiation Health Physics
22.59	Principles of Nuclear Radiation Measurement and Protection

Plasma and Controlled Fusion

22.601	Fusion Energy I
22.602	Fusion Energy II
22.611J	Introduction to Plasma Physics I
22.612J	Introduction to Plasma Physics II
22.615J	Theory of Plasma Confinement I
22.616	Theory of Plasma Confinement II
22.63	Engineering Principles for Fusion Reactors
22.64J	Plasma Kinetic Theory
22.67	Principles of Plasma Diagnostics
22.69	Plasma Laboratory

Nuclear Materials

22.70J	Materials for Nuclear Applications
22.71J	Physical Metallurgy
22.72J	Corrosion: The Environmental Degradation of Materials
22.74J	Mechanical Behavior of Materials
22.77	Nuclear Waste Management

Systems, Policy, and Economics

22.81	Energy Assessment
22.811	Energy, Electricity, and the Environment
22.812	Nuclear Energy Economics and Policy Analysis
22.82	Engineering Risk-Benefit Analysis
22.821	Engineering Systems Analysis
22.841	Nuclear Weapons and Arms Control: Technology and Policy Issues
22.843J	Technology, Productivity, and Industrial Competition
22.86	Entrepreneurship

General

22.901-4	Special Problems in Nuclear Engineering
22.911	Seminar in Nuclear Engineering (Fall)
22.912	Seminar in Nuclear Engineering (Spring)
22.92	Advanced Engineering Internship
22.921	Nuclear Power Plant Dynamics and Control
22.922	Computer Modelling and Visualization in Engineering Science
22.923	Environmental Risks and Benefits of Nuclear Power
22.93	Teaching Experience in Nuclear Engineering

Subjects offered by other departments of special interest to Nuclear Engineering students include:

Civil Engineering

1.146	Engineering Systems Analysis
1.52	Structural Analysis and Design
1.581	Dynamics of Structures and Soils
1.77	Water Quality Control

Mechanical Engineering

2.032	Dynamics
2.06J	Mechanical Vibration
2.092	Methods of Engineering Analysis
2.093	Computer Methods in Dynamics
2.14	Control System Principles
2.151	Advanced System Dynamics and Control
2.155J	Multivariable Control Systems II
2.20	Fluid Mechanics
2.25	Advanced Fluid Mechanics
2.301	Advanced Mechanical Behavior of Materials
2.41J	Thermal Power Engineering
2.55	Convective Heat and Mass Transfer
2.56	Conduction and Change of Phase Heat Transfer

Materials Science and Engineering

3.14	Physical Metallurgy
3.26J	Micro Mechanisms of Fracture
3.39J	Mechanical Behavior of Materials
3.54J	Corrosion - The Environmental Degradation of Materials

Electrical Engineering and Computer Science

6.013	Electromagnetic Fields and Energy
6.683	Operation and Planning of Electric Power

Physics

8.312	Electromagnetic Theory
8.321	Quantum Theory I
8.322	Quantum Theory II

8.511	Theory of Solids I
8.512	Theory of Solids II
8.641	Physics of High-Energy Plasmas I
8.642	Physics of High-Energy Plasmas II

Chemical Engineering

10.382	Synthesis and Design of Chemical Processing Systems
10.39	Energy Technology
10.50	Analysis of Transport Phenomena
10.52	Mechanics of Fluids
10.70	Principles of Combustion
10.88	School of Chemical Engineering Practice

Ocean Engineering

13.21	Ship Power and Propulsion
13.26J	Design of Thermal Power Systems

Economics

14.272	Industrial Organization II

Management

15.065	Decision Analysis
15.081	Introduction to Mathematical Programming
15.084J	Nonlinear Programming

Mathematics

18.085	Mathematical Methods for Engineers I
18.089	Review of Mathematics
18.175	Theory of Probability

4.4 Independent Activities Period

Professor Chen initiated a new IAP course called "Computer Modelling and Scientific Visualization in Engineering Science." This course offers three credits, having six 1 1/2-hour lectures combined with laboratory work. It uses the Silicon Graphic Personal Iris Computer System as the instruction tool and draws expertise from four areas of research represented by Professors Yip, Chen, Yanch, and McFarland.

4.5 Undergraduate Research Opportunities Program

The Undergraduate Research Opportunities Program is a special program to provide undergraduate students with research experience in the various laboratories and departments throughout MIT. Professor Ronald Ballinger is the Nuclear Engineering Department Coordinator.

4.6 Changes in Nuclear Engineering Subjects

Since our last Activities Report, dated August 1989, the Department has introduced eight new subjects of instruction. Listed below are the new subjects, as well as those subjects that have undergone a change.

A. Subjects Introduced Since Last Report

22.082	Nuclear Energy Economics and Policy Analysis
22.562	Advanced Biomedical Magnetic Resonance Seminar
22.563J	Advanced Topics in Image Analysis for Medical Applications
22.58	Seminar in Radiation Health Physics
22.72J	Corrosion - the Environmental Degradation of Materials
22.921	Nuclear Power Plant Dynamics and Control
22.922	Computer Modelling and Visualization in Engineering Science
22.923	Environmental Risks and Benefits of Nuclear Power

B. Subjects with Revised Content

22.35	Nuclear Fuel Management
22.615J	Theory of Plasma Confinement I
22.616	Theory of Plasma Confinement II

C. Subject with New Title

22.013	Applications of Radiation in Science, Medicine, and Technology

D. Renumbered Subjects

22.811	Energy, Electricity, and the Environment (formerly 22.37)
22.812	Nuclear Energy Economics and Policy Analysis (formerly 22.341)

E. Subjects No Longer Offered (since last Activities Report)

22.003	The Nuclear Age
22.088J	Human Factors in Design
22.43	Advanced Numerical Methods in Engineering Analysis
22.66	Plasma Transport Phenomena
22.73J	Radiation Effects in Crystalline Solids
22.913	Graduate Seminar in Energy Assessment (Fall)
22.914	Graduate Seminar in Energy Assessment (Spring)

4.7 Undergraduate Program

4.7.1 Description of the Undergraduate Program

The undergraduate program in nuclear engineering provides engineering and science education related to the peaceful applications of nuclear processes. In particular, the program prepares students for industrial careers in nuclear energy or in applied radiation (including medical technology). The program also prepares students for graduate study in nuclear engineering and related disciplines (including entry into medical schools).

The program provides various subject combinations to satisfy individual student preferences. Two specific "tracks" or options are available--a nuclear energy track and a track covering radiation for medicine and industry. Each track contains elements of both energy and radiation applications. Optional subject selections are available in the later stages of each track to permit concentrating on particular specialties of interest.

In the nuclear energy track, nuclear processes are those related to the production of electrical energy from the fission of heavy isotopes and from the fusion of light isotopes. Existing fission-based plants provide a major contribution to worldwide electrical energy production. In addition, future plants will benefit from exciting improvements from ongoing reactor innovation studies.

Fusion-based power plants are many decades away from commercial operation. The associated engineering and physics problems are extremely challenging. The nuclear energy track covers engineering for understanding systems for plasma physics experiments in the short term and for power plant applications in the long term.

The radiation for medicine and industry track relates to applications of nuclear processes in medical and industrial fields. Those applications include biomedical imaging for diagnosis of disease and radiation therapy for medical treatments. They also include imaging for industrial quality assurance, investigations of material content and structure using radiation, and data-taking in experimental research.

In either track, a student is educated in a combination of the departmental curriculum and MIT's General Institute Requirements. The MIT portion ensures that all undergraduates have taken subjects in fundamentals of sciences and mathematics and also in topics from the fields of humanities, arts, and social sciences. The departmental portion includes additional work in mathematics and science, subjects covering widely applicable engineering principles, subjects related to nuclear engineering specialties, and research efforts leading to an individual student thesis. This program gives preparation for immediate employment at the SB level in the nuclear industry, for further graduate level training in nuclear engineering, or for entry into medical school.

4.7.2 Reviews and Revisions of the Undergraduate Program

During calendar year 1990, we completed an extensive review of the Nuclear Engineering Department (NED) undergraduate program. The new program has been adopted and changes will become effective with the students who enter NED in fall term 1991. Highlights of, and rationale for, the changes are as follows:

- The three tracks or options in the former program (fission, fusion, and radiological sciences) are replaced by two tracks in the revised program ("nuclear energy" and "radiation for medicine and industry"). Fission and fusion have been combined to form a single track, "nuclear energy." There have always been many features in common for fission and fusion. Fewer differences remain in the new requirements and unification seems appropriate. The second track in the revised program ("radiation for medicine and industry") incorporates many of the medical and biomedical engineering aspects of the existing radiological sciences track. It is intended to add features of industrial applications such as imaging techniques for quality assurance and radiation investigations of material content and structure.

- The design content of the former fusion and radiological sciences areas has been upgraded by including all students in an expanded version of our existing design project subject (22.033). This subject has also been increased from 12 to 15 units for more design emphasis. Aspects of fission, fusion, and applied radiation will be incorporated in the design problems (only fission is involved in the existing subject).

- An objective for increased breadth in nuclear engineering topics is also achieved in the new program by requiring all students to take both 22.03 (engineering design of nuclear power systems) and 22.04 (radiation effects and uses). The former program, on the other hand, produces graduates that may have little acquaintance with power plant features or may not know details of radiation effects. The cost of this new breadth is judged to be acceptable. That cost is a decrease in depth by losing one or two advanced level nuclear engineering specialty subjects: engineering of nuclear reactors (22.031), fusion energy II (22.062), and/or principles of medical imaging (22.056). Two additional subjects have been deleted from the radiological sciences program: quantitative physiology organ transport systems (2.792J) and either biological and medical applications of radiation and radioisotopes (22.055) or radiation biophysics (22.057).

The revised program has more unity, more breadth in nuclear engineering, and more design content.

During fall term 1989, we had an accreditation evaluation of our undergraduate nuclear engineering program. The evaluation was performed by the Accreditation Board for Engineering and Technology (ABET) and paralleled evaluations of other programs in the MIT School of Engineering. We were reaccredited for three years and will have our next ABET evaluation visit in 1992. The revised design content in our new program conforms more closely to ABET requirements.

4.7.3 Subjects of Instruction

The following subjects are offered as nuclear engineering undergraduate subjects of instruction:

22.011 Seminar in Nuclear Engineering, surveys the range of topics covered by the Department. Introductory discussion of the basic phenomena of fission and fusion power, and related aspects of reactor design. The many applications of nuclear engineering for research in biology, earth sciences, medicine, and physics are discussed by guest lecturers from the appropriate discipline. A demonstration of the MIT Reactor as a research tool is given.

22.012 Seminar in Fusion and Plasma Physics, lecture and discussion introducing the range of topics covered under the fusion option. Introductory discussion of the economic and ecological motivation for the development of fusion power. Contemporary magnetic confinement schemes, theoretical questions, and engineering considerations are presented by expert guest lecturers. Concurrent work on the physics of the solar and terrestrial plasma environments also covered. Tour of the Plasma Fusion Center experimental facilities.

22.013 Applications of Radiation in Science, Medicine, and Technology, a series of wide-ranging lectures examining diverse current issues in the applications of radiation in science, medicine, and technology. Typical topics: medical imaging, radiation cancer therapy, neutron activation analysis, fission and fusion reactors, laser, neutron and synchrotron beam experiments, and computer modeling.

22.02 Introduction to Applied Nuclear Physics, introduces nuclear physics, emphasizing those aspects that are applied in nuclear engineering: elementary quantum theory, properties of atomic nuclei; natural and induced radioactivity; cross sections for nuclear reactions; alpha-, beta-, and gamma-decay. Nuclear models: shell-model, liquid-drop model, nuclear fission. Slowing down and diffusion of neutrons. Neutron-induced chain reactions. Thermonuclear reactions and the possibility of energy from nuclear fusion. Introduces radiation dosimetry.

22.021 Nuclear Reactor Physics, introduces fission reactor physics. Covers reactions induced by neutrons, nuclear fission, slowing down of neutrons in infinite media, diffusion theory, the few-group approximation, and point kinetics. Emphasizes the nuclear physics bases of reactor design and their relationship to reactor engineering problems. Three lecture hours per week meeting concurrently with 22.211, plus a separate recitation; assignments and quizzes are different from those in 22.211.

22.03 Engineering Design of Nuclear Power Systems, introduces nuclear engineering as applied to power plant design. Basic principles of nuclear physics, reactor physics, and environmental health physics; heat-transfer and energy utilization principles. Description of various fission and fusion reactors; ionizing radiation uses and health effects. Emphasizes reliability and reactor safety methods for improving design and operation of future reactors.

22.033 Nuclear Systems Design Project, group design project involving integration of reactor physics, control, heat transfer, safety, materials, power production, fuel-cycle management, environmental impact, and economic optimization. Provides student with opportunity to synthesize knowledge acquired in other subjects and apply this knowledge to practical problems of interest in the reactor design field. An undergraduate subject that meets with graduate subject 22.33. Same content, but assignments differ.

22.04 Radiation Effects and Uses, current problems in science, technology, health, and environment that involve radiation effects and their utilization. Medical and industrial applications of radioisotopes. Radiations in research. Laboratory demonstrations of methods and instruments in radiation measurements. Material presented is suitable for students interested in a general appreciation of the physical phenomena and their uses.

22.055 Biological and Medical Applications of Radiation and Radioisotopes, principles of radiation production and interactions. Radiation dosimetry, emphasizing applications. Health effects. Shielding of beta, gamma, and neutron radiation from isotope and machine sources. Detection and spectroscopy of beta, gamma, and neutron radiation. Neutron activation analysis. Production of radioisotopes and radiopharmaceuticals. Principles of nuclear medicine and imaging with radiation. An advanced undergraduate subject that meets with graduate subject 22.55J. Same content but assignments differ.

22.056 Principles of Medical Imaging, principles of medical imaging, including x-ray, nuclear medicine, ultrasound, NMR emission- and transmission-computed tomography, and other modalities. Two-dimensional and three-dimensional imaging techniques and displays. Fundamentals of image formation, physiology of image perception, physics of radiation and ultrasound interaction and detection, and physics of NMR. Quantification of images and reconstruction algorithms. An advanced subject that meets with graduate subject 22.56J. Same content but assignments differ.

22.057 Radiation Biophysics, Discusses ionizing radiation, ultraviolet radiation, and heat and their effects on biological materials, cells, and tissues. Examines *in vivo* and *in vitro* mammalian systems, and explores mathematical models for cell survival emphasizing prediction. Microstructural damage to cell components such as membranes, organelles, enzymes, and DNA studied. Radiation therapy, radiation syndromes in humans, mutagenesis, and carcinogenesis also investigated. An advanced subject that meets with graduate subject 22.57J. Same content but assignments differ.

22.061 Fusion Energy I, basic nuclear physics and plasma physics for controlled fusion. Nuclear physics, fusion cross sections, ignition condition, break-even condition, Lawson criterion, elementary fusion reactor, required plasma parameters. Plasma physics: definition of a plasma, single-particle orbits. Coulomb collisions, fluid model, magnetic fusion configurations, MHD equilibrium and stability, transport and heating. Meets three lecture hours a week with 22.601, but with different assignments and exams.

22.069 Undergraduate Plasma Laboratory, basic engineering and scientific principles associated with experimental plasma physics. Investigates vacuum pumping phenomena and gauge operation, normal and superconducting magnetic field coils, microwave interactions with plasmas, laboratory plasma production including electrical breakdown phenomena, Langmuir probe characteristics and spectroscopy. Meets with 22.69, but assignments differ.

22.070J Materials for Nuclear Applications, introductory subject for students who are not specializing in nuclear materials. Applications and selection of materials for use in nuclear applications. Radiation damage, radiation effects, and their effects on performance of materials in fission and fusion environments. Meets with 22.70J, but assignments differ.

22.08 Energy, energy from a holistic viewpoint. Provision, rational utilization and conservation, environmental effects, policy, and impact on other sectors. Resources, technologies of conversion and utilization. Assessment of both deployed and proposed energy systems and technologies. Includes economic, social and historic perspectives. Intended for third- and fourth-year students interested in entering the energy field. Meets with 22.81, but some assignments differ.

22.082 Nuclear Energy Economics and Policy Analysis, an undergraduate subject that meets with graduate subject 22.812.

22.09 Principles of Nuclear Radiation Measurement and Protection, combines lectures, demonstrations, and experiments. Covers effects of radiation on persons, control of radiation exposure within applicable standards, theory and use of α, β, γ and η detectors and spectrometers, use of isotopes, radiation shielding, and dosimetry. Includes demonstrations and experiments using the MIT research reactor, accelerators, and power reactors. Meets with graduate subject 22.59, but assignments differ.

22.091 Special Topics in Nuclear Engineering, for undergraduates who wish to conduct a one-term project of theoretical or experimental nature in the field of nuclear engineering, in close cooperation with individual staff members. Topics and hours arranged to fit students' requirements.

22.092 Engineering Internship, provides academic credit for the first two Work Assignments of XXII-A students affiliated with the Engineering Internship Program. Students register for this subject twice. Students must complete both Work Assignments in order to receive the academic credit for this subject. Enrollment limited to students registered in Course XXII-A.

4.8 Engineering Internship Program

The Engineering Internship Program is available on a competitive basis in most engineering departments. It provides a strong combination of work and study experiences. The program is intended to lead to both a bachelor's and master's degree after the student's fifth year at MIT. The student has four work assignments at a single participating company (in the summers after the second, third, and fourth year, and during the fall term of the fifth year). The original acceptance to the program is competitive--the student must be accepted by a participating company after a review of qualifications and a campus interview.

The student is paid by the company for the work; however, it is intended that the assignments be valid learning experiences and not only a way to make money. The program provides for completing an SM thesis as part of the final work assignment. The student works under the supervision of both a mentor at the company and a faculty advisor at MIT.

Essentially all of our undergraduates, with only few exceptions, have or are participating in the program. Companies which have placed students from the Nuclear Engineering Department are Brookhaven National Laboratory, Commonwealth Edison Company, Boston Edison Company, EG&G Company, and the Los Alamos National Laboratory. The program has often provided a stepping stone for eventual employment of our students. In several cases former students in the department and participants in the EIP Program are now in research and management positions in the companies for which they worked during their tenure at MIT.

4.9 Undergraduate Seminar Program

The Undergraduate Seminar Program is an Institute-wide program which offers an opportunity for students to interact with faculty members in small, informal class settings. Seminars vary tremendously both in style and topic. Some are oriented around small, informal class discussions while others may bring in speakers, go out on field trips or involve extensive laboratory projects. The following Undergraduate Seminars have been offered by the Nuclear Engineering Department since our last Activities Report: Controlled Fusion (K. Molvig); Nuclear Science and Engineering: A Sampling (K. Hansen); Applications of Radiation in Science, Medicine, & Technology (S. Yip); Nuclear Power (M. Golay); Design Your World Energy System for the 21st Century (M. Driscoll).

5. RESEARCH FACILITIES

5.1 MIT Reactor

On July 1, 1976, the MIT Reactor was designated an Institute facility under the responsibility of the Vice President for Research, and Professor Otto K. Harling was appointed Director of the newly formed Nuclear Reactor Laboratory (NRL). This ended a 16-year period of operation during which the reactor was under the supervision of the Nuclear Engineering Department. During that time the MITR logged 63,083 hours at full power and 250,445 megawatt hours.

While the reactor (now the MITR-II) is no longer in the Nuclear Engineering Department, there is a close relationship between the NRL and the NED, which continues to be a major user of the facility. Programs in nuclear materials, in-pile coolant chemistry studies including corrosion and dose reduction, computer control for reactors, and medical applications--described earlier in this report--depend heavily upon MITR-II. In addition, the reactor is used in teaching NED academic subjects, such as 22.32 Nuclear Power Reactors, 22.33 Nuclear Engineering Design, 22.313 Advanced Engineering of Nuclear Reactors, 22.59/09 Principles of Nuclear Radiation Measurement and Protection, and 22.314J Structural Mechanics in Nuclear Power Technology. As the director of the NRL and a member of the NED faculty, Professor Harling is strongly interested in developing NED projects and uses of the MITR-II.

The MIT Reactor has operated since 1958; and neutrons and gamma rays produced by the reactor have been used by many investigators for a great variety of research projects in physics, chemistry, geology, engineering, and medicine. On May 24, 1974, the reactor was shut down to make pre-planned modifications that were designed to modernize the reactor and to enhance the neutron flux available to experimenters. The successful modification was completed by the summer of 1975, and start-up procedures were carried out during the fall of 1975. Operation up to power levels of 2,500 kW were continued until November 1976. Since November 1976 the reactor has been in routine operation at the 5,000 kW power level.

The modified reactor core is more compact than the former core and is cooled by light water instead of by heavy water. The new core is surrounded by a heavy water reflector. The core is undermoderated and delivers a high output of fast neutrons to the heavy water reflector, where the neutrons are moderated and the resulting thermal neutrons trapped to produced the desired high flux. The beam ports of MITR-II are extended into the heavy water reflector beneath the core to give experimenters a high flux of thermal neutrons with low background of fast neutrons and gamma rays. To provide the desired 5 MW of thermal power (in a more compact core) a new design of fuel plate with longitudinal ribs has been developed. Fuel elements contain 15 plates and are rhomboidal in cross section for assembly into a hexagonal close-packed core.

The modification makes use of all of the existing reactor components except the reactor tank, fuel elements, control rods and drives and top shield plugs. Parts of the former reactor that remain include the graphite reflector, thermal shield, biological shield, beam ports, heat exchangers, pumps, cooling towers, and containment building.

Engineering studies and experiments on aspects of the new core have provided many opportunities for student research and participation and give unique practical training. Topics investigated by students include reactor beam port and reflector configuration, fluid flow measurement on a hydraulic mock-up heat transfer measurement and theoretical calculation on finned plates, safety analysis and fuel management studies, and construction, startup and checkout operation of the modified reactor. Recent studies are in the area of experimental-facility design, fuel management, advanced control systems, and material corrosion behavior under conditions simulating PWR and BWR environments.

Currently NED students are assisting in engineering studies of future options to modify and improve the MITR.

Researchers at the NRL have received financial support from DOE, EPRI, ESEERCO, NSF, NIH, MIT, Hitachi, Toshiba, GE, several nuclear utilities and the Japanese Nuclear Power Engineering Center.

5.2 Computing Facilities

Students in the Nuclear Engineering Department have access to a wide variety of computer systems both within the department and at shared facilities throughout the campus. The campus network includes the MIT Supercomputer CRAY X-MP EA/464, which has four processors and 64-Megaword memory.

The campus network has expanded into the NW12/NW13 area of the campus and in the Fall '91 a second PROJECT ATHENA workstation cluster will become operational in an expanded departmental computer facility in NW12-326. This new cluster will complement the existing ATHENA cluster in the 24-023A facility.

Each departmental cluster additionally has a MicroVAX III running VAX/VMS, several Macintosh and 386 generation machines, laser printers and plotters. They are maintained solely for the use of Nuclear Engineering students. There are four Silicon Graphics systems and four Sun workstations, as well as several other systems available to students through research facilities provided by faculty members.

All code work completed by graduating students is collected in and distributed from a departmental code library along with widely used reactor design and analysis codes. In addition students are given advice, assistance, and instruction in the use of these codes and available computer tools.

5.3 Nuclear Engineering Department Teaching Laboratories

The Nuclear Engineering Department teaching laboratories are specially equipped rooms in Buildings NW12-133 and NW13-133. The NW12-133 room is used for 22.09/59 Principles of Nuclear Radiation Measurement and Protection. This laboratory combines lectures, demonstrations, and experiments done by the students. Subjects covered include the principles of health physics and radiation protection, and instruction in safe laboratory procedures for working with radioactive substances. The students use a variety of modern radiation detectors to measure α, β, γ, and n radiation. Some of the experiments in the laboratory use the MIT Nuclear Reactor.

During the final few weeks of this course the student must do an individual project of his or her own choosing. These projects must involve a nuclear radiation measurement of some type. The student is expected to plan and carry out the measurement with a minimum of help from the instructor.

The Undergraduate Plasma Laboratory (22.069) and the Graduate Plasma Laboratory (22.69) in NW13-133A provide basic engineering and scientific principles associated with experimental plasma physics. A variety of small experiments by which students can gain experience in the laboratory techniques of plasma and fusion physics are carried out investigating basic vacuum pumping phenomena and gauge operation, normal and superconducting magnet field coils, microwave interactions with plasmas, laboratory plasma production including electrical breakdown phenomena, Langmuir probe characteristics and spectroscopy. The graduate course introduces the advanced experimental techniques needed for research in plasma physics and useful in experimental atomic and nuclear physics. Laboratory work on vacuum systems, plasma generation and diagnostics, physics of ionized gases, lasers, cryogenics, magnetic field generation, and other topics of current interest including control of experiments and acquisition of data by personal computers is covered. Brief lectures and literature references to elucidate the physical bases of the laboratory work are included.

6. DEPARTMENT PERSONNEL

6.1 Faculty

Mujid S. Kazimi

Professor of Nuclear Engineering; Head of the Department; B.S. '69 University of Alexandria, Egypt; M.S. '71, Ph.D. '73 (nuclear engineering) MIT; Safety aspects of nuclear plants and waste facilities; reactor engineering.

Ronald G. Ballinger

Associate Professor of Nuclear Engineering and Materials Science & Engineering; S.B. '75 WPI; S.M. '77 (nuclear), S.M. '78 (materials science), Sc.D. '82 (nuclear materials engineering) MIT; Corrosion and fatigue; stress corrosion cracking behavior in nuclear systems; fuel behavior modeling.

Manson Benedict

Institute Professor Emeritus; Professor of Nuclear Engineering; B. Chem. '28 Cornell; S.M. '32, Ph.D. '35 (physical chemistry) MIT; Processing of nuclear materials; isotope separation; reactor fuel cycles; nuclear power economics.

Gordon L. Brownell

Professor of Nuclear Engineering; Head, Physics Research Lab., Massachusetts General Hospital; B.S. '43 Bucknell; Ph.D. '50 (physics) MIT; Biomedical applications; radiation dosimetry; radioisotope applications; effects of radiation on materials; bioengineering.

Sow-Hsin Chen

Professor of Nuclear Engineering; B.S. '56 National Taiwan University; M.S. '58 National Tsing-Hua University; M.S. '62 University of Michigan; Ph.D. '64 (physics) McMaster University; Applied neutron physics and spectroscopy; applications of laser light scattering to biological problems.

Michael J. Driscoll

Professor Emeritus of Nuclear Engineering; B.S. '55 Carnegie Tech; M.S. '62 University of Florida; Ph.D. '66 (nuclear engineering) MIT; Nuclear fuel management; economics and systems engineering.

Jeffrey P. Freidberg

Professor of Nuclear Engineering; B.E.E. '61, M.S. '62, Ph.D. '64 (electrical physics) Polytechnic Institute of Brooklyn; Theoretical plasma physics.

Michael W. Golay

Professor of Nuclear Engineering; B.M.E. '64 University of Florida; Ph.D. '69 (nuclear engineering) Cornell University; Reactor engineering; fluid mechanics; environmental and safety problems of nuclear power.

Elias P. Gyftopoulos

Ford Professor of Engineering; Professor of Nuclear and Mechanical Engineering; Dipl. in ME & EE '53 Athens; Sc.D. '58 (electrical engineering) MIT; Thermodynamics; reliability analysis, energy conservation.

Kent F. Hansen

Professor of Nuclear Engineering; S.B. '53, Sc.D. '59 (nuclear engineering) MIT; Nuclear energy policy and management; nuclear plant operations and simulation.

Otto K. Harling

Professor of Nuclear Engineering; Director, Nuclear Reactor Laboratory; B.S. '53 Illinois Institute of Technology; M.S. '55 University of Heidelberg; Ph.D. '62 (physics) Penn State University; Research reactor applications; experimental materials research; neutron scattering.

Allan F. Henry

Professor of Nuclear Engineering; B.S. '45, M.S. '47, Ph.D. '50 (physics) Yale; Reactor physics; kinetics and design methods.

Ian H. Hutchinson

Professor of Nuclear Engineering; Head, Toroidal Confinement Division, PFC; B.A. '72 Cambridge University; Ph.D. '76 (plasma physics) Australian National University; Experimental plasma physics; controlled fusion.

Irving Kaplan

Professor Emeritus of Nuclear Engineering; A.B. '33, A.M. '34, Ph.D. '37 (chemistry) Columbia; Nuclear physics; reactor analysis; reactor physics measurements; history of science and technology.

David D. Lanning

Professor of Nuclear Engineering; B.S. '51 University of Oregon; Ph.D. '63 (nuclear engineering) MIT; Reactor engineering; reactor operations and safety.

Richard K. Lester

Professor of Nuclear Engineering; B.S. '74 Imperial College University of London; Ph.D. '79 (nuclear engineering) MIT; Nuclear power economics and policy analysis; nuclear waste disposal.

Lawrence M. Lidsky

Metcalfe Professor of Nuclear Engineering and the Liberal Arts; Codirector, MIT's Context Initiatives; B.E.P. '58 Cornell; Ph.D. '62 (nuclear engineering) MIT; Advanced fission and fusion reactor system designs.

John E. Meyer

Professor of Nuclear Engineering; B.S. '53, M.S. '53, Ph.D. '55 (mechanical engineering) Carnegie Institute of Technology; Structural mechanics; heat transfer and fluid flow.

Kim Molvig

Associate Professor of Nuclear Engineering; B.S. '70 Cornell; Ph.D. '75 (physics) University of California; Theoretical plasma physics.

Norman C. Rasmussen

McAfee Professor of Engineering; Professor of Nuclear Engineering; A.B. '50 Gettysburg; Ph.D. '56 (physics) MIT; Reactor safety; reliability analysis.

Kenneth C. Russell

Professor of Metallurgy and Nuclear Engineering; Met.E. '59 Colorado; Ph.D. '64 (nuclear engineering) Carnegie Institute of Technology; Radiation effects on materials.

Alfred Schneider

Visiting Professor of Nuclear Engineering; B.Ch.E. '51 Cooper Union, New York; Ph.D. '58 (chemical engineering) Polytechnic University, New York; Nuclear chemical engineering; nuclear fuel cycle; radioactive waste management; nuclear safety.

Nathan O. Siu

Associate Professor of Nuclear Engineering; B.S. '77, S.M. '80, Ph.D. '84 (nuclear engineering) UCLA; Risk and reliability analysis; systems modeling.

Neil E. Todreas

Professor of Nuclear Engineering; B. and M.Mech.E. '58, Cornell; Sc.D. '66 (nuclear engineering) MIT; Reactor engineering; reactor thermal analysis; heat transfer and fluid flow.

Jacquelyn C. Yanch

Assistant Professor of Nuclear Engineering and Whitaker College; Class of 1958 Assistant Professor; B.S. '81 (psychology), B.S. '83 (health and radiation physics), M.S. '85 (health and radiation physics) McMaster University; Ph.D. '88 (physics) University of London; Nuclear medical imaging; computational modelling in both therapy and image restoration; radiation health physics; neutron dosimetry.

Sidney Yip

Professor of Nuclear Engineering; B.S. '58, M.S. '59, Ph.D. '62 (nuclear engineering) University of Michigan; Atomistic simulations; condensed matter sciences; statistical mechanics; neutron scattering.

6.2 Complete Listing of Nuclear Engineering Department Personnel (as of August 1991)

Professors
M. Benedict (Institute Emeritus)
G.L. Brownell
S.H. Chen
J.P. Freidberg
M.W. Golay
E.P. Gyftopoulos (joint w/Mechanical)
K.F. Hansen
O.K. Harling (Dir., NRL)
A.F. Henry
I.H. Hutchinson
I. Kaplan (Emeritus)
M.S. Kazimi (Department Head)
D.D. Lanning
R.K. Lester
L.M. Lidsky
J.E. Meyer
N.C. Rasmussen
N.E. Todreas
S. Yip

Associate Professors
R.G. Ballinger (joint w/MS&E)
K. Molvig
N.O. Siu

Assistant Professor
J. Yanch (joint w/Whitaker)

Senior Lecturer
F.X. Masse*

Senior Research Engineers
D.B. Montgomery (joint w/PFC)
J.E.C. Williams (joint w/NML)

Principal Research Engineer
J. Bernard (joint w/NRL)

Senior Research Scientists
D.R. Cohn (joint w/PFC)
T.H. Dupree (joint w/Physics and Professor Emeritus)
M.M. Miller
D.J. Sigmar (joint w/PFC)

Principal Research Scientist
R. Lanza

Research Scientists
M.J. Driscoll (joint w/NRL and Professor Emeritus)
M.C. Lee (joint w/PFC)
P. Stahle

Research Staff
R.M. Morton (Mgr., Computer Facilities)

Administrative Officer
J.B. deVries Gwinn

Administrative Staff
C.M. Egan (Graduate Office Administrator)

Support Staff
L. Arduino
P. Cornelio
A. Hudson
E. Kehoe
M. Levine
D. Lewis
L. Miltner
E. Parmelee
G. Rook
A. Sloan
L. Suter

Research Affiliates
J. Ackerman
V. Manno
S. Patz
B. Rosen
D. Trent
W.E. Vesely
R. Zamenhof

*Mr. Masse holds the primary appointment of Radiation Protection Officer at the Medical Department and the Bates Linear Accelerator Center.

6.2.1 Complete listing of jointly held faculty and academic research staff appointments in the NED, the loci of which are other departments, labs, and/or centers

Name	Appointment Title	Locus
D. Bruce Montgomery	Associate Director, PFC Senior Research Engineer, joint PFC/NED	PFC
D.R. Cohn	Head, Fusion Systems and Technical Division, PFC Senior Research Scientist, joint PFC/NED	PFC
J.E.C. Williams	Head, Magnet Technology Division, FBNML Senior Research Engineer, joint FBNML/NED	FBNML
K.C. Russell	Professor, Materials Science and Engineering, joint w/NED	MS&E
D.J. Sigmar	Senior Research Scientist, joint PFC/NED Deputy Director, PFC	PFC

6.3 Complete List of Graduate Student Staff (as of Spring 1991)

Teaching Assistants

Bhatia, Mickey
Chang, Szu-Li (1/2)
Cubukcu, Erol
Ferri, Matthew
Fox, James
Herbelot, Olivier
Hilton, Bruce
Hopkins, Philip
Koch, Mathias
Kwak, Sangman
Mohamed, Amr
Parlatan, Yuksel
Poulos, George (1/2)
Tang, Meijie (1/2)
Uhle, Jennifer
Vacca, Luigi
Wilson, Michael

Research Assistants

Acosta, Cris
Ames, Michael
Barakat, Abdel
Bieri, Robert
Carney, Charles
Chang, Szu-Li (1/2)
Choi, Richard
Chu, Tak Sum
Chun, John
Credit, Kimberly
Dehbi, Abdelouahab
Doboe, Lou
Dobrzeniecki, Andrew
Duraski, Robert
Fricke, Stanley
Gavrilas, Mirela
Gormley, Robert
Gorur, Raghav
Graf, Michael
Grimm, Terry
Guimaraes, Alex
Gung, Chen-Yu
Guo, Xuan Hui
Hasanein, Hisham
He, Weiguo
Hechanova, Tony
Hejzlar, Pavel
Hoppel, Bernice
Hsu, Thomas
Huang, Xudong
Huang, Yuhao

Research Assistants (cont'd)

Hushek, Stephen
Iqbal, Asjad
Iverson, Erik
Jacqmin, Robert
Jang, Chang-heui
Jerng, Dong Wook
Johnson, Leigh
Kim, Keung Koo
Klann, Raymond
Kubali, Volkan
Kupfer, Kenneth
Kurz, Christian
Kwok, Kwan
Lee, Kookjong
Li, Chjikang
Liao, Chungpin
Lierzer, James
Lovett, Phyllis
Martin, Jerry
Martin, John
Michael, David
Moore, Gregory
Moriarty, Daniel
Moulin, Damien
Murphy, John
Neuder, Michelle
Nguyen, Tien
Niemczewski, Artur
O'Donnell, Jeff
Offutt, Martin
Ouyang, Meng
Panych, Lawrence
Pendergast, Ken
Poulos, George (1/2)
Ramanathan, Chan
Redmond, Everett
Reese, Timothy
Rhee, David
Rogus, Ron
Rozier, Robert
Shajii, Ali
Shatilla, Youssef
Shi, Shuanghe
Siddique, Mansoor
Solares-Hernandez, Guido
Sorci, Joseph
Tang, Meijie (1/2)
Teixeira, Chris
Tinios, Gerasimos
Tsui, Chi-Wa
Urbahn, John

Research Assistants (cont'd)

Vergara, Julio
Vilece, Ken
von Jako, Chris
Wang, Dan
Wang, Jinghan
Wang, Ling
Wang, Pei-Wen
Wei, Jiann
Wu, Yaotang
Yoo, Chan
Zerkle, Michael
Zhu, Hui
Zolfaghari, Ali

7. STUDENTS

Chapter 7 presents a statistical summary of the Department from its inception (Table 7.1), the number of applications for fall admission since 1975 (Table 7.2), and statistical information about the 142 full-time graduate students registered in the Department during the spring term 1991. Table 7.3 catalogues the background of these graduate students according to their profession and country. It also contains a listing of the colleges attended by our domestic students prior to their graduate admission.

As noted in our last Activities Report, a large percentage of our graduate students enter the Department with a nuclear engineering background. This is followed by physics, electrical engineering, mechanical engineering, and engineering physics majors.

The distribution of schools from which our domestic students are drawn is very widespread. Approximately 16% of our domestic graduates entered the Department with degrees from MIT. Our international student population represents 49% of our total graduate enrollment for the spring term 1991.

Table 7.4 summarizes the various sources of financial support available for the spring term 1991. With assistance from the nuclear industry and other organizations, we have been able to maintain our level of support as in previous years.

The distribution of activities of our graduates is given in Table 7.5. The breakdown among the categories of National Laboratories, Teaching, and Industry has changed very little since our last Activities Report. A larger percentage of our recent graduates are pursuing further study. Figure 7.1 summarizes the distribution of types of first employment of our graduate students through June 1991.

Table 7.1 DEPARTMENTAL STATISTICS (Summary)

Academic Year Sept-June	September Registration: Under-graduate	Graduate	Special	Total	Degrees Granted: B.S.	S.M.	Nucl.E.	Doctoral	Total	No. of Faculty	No. of Subjects
51 - 52		none								1	-
52 - 53	none	in	nuclear				none			2	4
53 - 54	-	8	-	8	-	4	-	-	4	2	5
54 - 55	-	20	-	20	-	13	-	-	13	2	5
55 - 56	-	46	-	46	-	10	-	-	10	3	6
56 - 57	-	74	-	74	-	32	-	-	32	5	7
57 - 58	-	93	1	94	-	31	-	2	33	6	8
58 - 59	-	95	6	101	-	44	-	7	51	8	12
59 - 60	-	102	6	108	-	32	-	5	37	10	14
60 - 61	-	112	10	122	-	25	1	7	33	10	16
61 - 62	-	118	8	126	-	34	-	11	45	13	17
62 - 63	-	109	8	117	-	27	1	12	40	15	20
63 - 64	-	103	10	113	-	20	2	13	35	15	21
64 - 65	-	124	6	130	-	24	3	14	41	16	24
65 - 66	-	125	6	131	-	30	3	15	48	16	25
66 - 67	-	122	6	128	-	28	11	22	61	18	26
67 - 68	-	132	4	136	-	27	2	13	42	17	27
68 - 69	-	127	3	130	-	35	6	14	55	18	28
69 - 70	-	128	-	128	-	31	8	22	61	20	28
70 - 71	-	111	3	114	-	27	4	14	45	19	37
71 - 72	-	117	1	118	-	20	2	19	41	20	35
72 - 73	-	115	1	116	-	29	5	14	48	18	42
73 - 74	-	127	2	129	-	32	12	8	52	19	49
74 - 75	-	138	7	145	-	38	4	7	49	19	52
75 - 76	20	182	2	204	-	39	8	24	71	22	58
76 - 77	33	188	2	223	2	37	10	23	72	24	61
77 - 78	47	170	3	220	11	57	18	20	106	23	63
78 - 79	41	172	1	214	11	40	10	15	76	19	58
79 - 80	39	170	1	210	11	40	8	19	78	21	55
80 - 81	35	154	2	191	10	34	7	20	71	24	62
81 - 82	37	154	1	192	6	25	3	19	53	23	64
82 - 83	33	164	0	197	12	28	4	15	59	24	67
83 - 84	27	164	3	194	9	36	11	29	85	26	70
84 - 85	18	162	0	180	8	27	2	18	55	24	71
85 - 86	25	148	0	173	9	28	3	30	70	24	80
86 - 87	20	150	1	171	6	32	3	20	61	24	82
87 - 88	22	148	0	170	3	29	5	13	50	22	85
88 - 89	28	150	1	179	6	29	3	13	51	21	78
89 - 90	26	149	1	176	8	26	4	19	57	22	84
90 - 91	14	149	3	166	4	26	1	21	52	22	87
				TOTALS	116	1126	164	537	1943		

Table 7.2

Applications for Graduate Admission
to MIT Nuclear Engineering Department

Fall Semester	Applicants
1975	149
1976	136
1977	139
1978	123
1979	105
1980	114
1981	99
1982	123
1983	85
1984	82
1985	78
1986	88
1987	72
1988	79
1989	72
1990	97
1991	107

Table 7.3

Background of Graduate Students Registered in Nuclear Engineering Department (Spring 1991)

By Profession (142)

Aerospace Engineering (2)
Applied Mathematics (1)
Applied Mechanics (1)
Applied Physics (1)
Applied Science (1)
Basic Science (1)
Biomedical Engineering (3)
Biophysics (1)
Civil Engineering (1)
Electrical Engineering (7)
Electrical Engineering/Computer Science (2)
Electrical Science and Engineering
Engineering Physics (5)
Engineering Science (1)
Finance (1)
Geological Engineering (1)
Marine Engineering (2)
Mechanical Engineering (6)
Mechanics (1)
Metallurgy (1)
Nuclear Engineering (71)
Nuclear Engineering/Physics (1)
Nuclear Instrumentation (1)
Nuclear Physics (1)
Physical Chemistry (1)
Physics (20)
Physics/Biology (2)
Physics/Math (2)
Physics/Mechanical Engineering (1)
Precision Instrument (1)
Systems Management (1)

By College (US citizens only) (73)

Bates College (1)
Brigham Young University (1)
Cornell (3)
Georgia Institute of Technology (2)
Iowa State University (2)
Kansas State University (1)
Marquette University (1)
MIT (19)
North Carolina State (1)
North Park College (2)
Northeastern (1)
Penn State (1)
Princeton (1)
Purdue (2)
Rensselaer Polytechnic Institute (4)
Rice University (1)
State University of New York (1)
Texas A&M (1)
United States Naval Academy (3)
University of Arizona (2)
University of California (6)
University of Cincinnati (1)
University of Colorado (1)
University of Connecticut (1)
University of Illinois (2)
University of Lowell (2)
University of Maryland (2)
University of Michigan (3)
University of Notre Dame (1)
University of Southern California (1)
University of Tennessee (1)
University of Virginia (1)
University of Wisconsin (1)

Table 7.3 (continued)

By Country (142)

Algeria (1)
Austria (1)
Canada (4)
Chile (1)
Czechoslovakia (1)
Egypt (3)
France (3)
Germany (1)
Greece (1)
Guatemala (1)
India (4)
Iran (2)
Italy (2)
Japan (2)
Korea (5)
Pakistan (2)
People's Republic of China (10)
Philippines (1)
Poland (1)
Republic of China (17)
Turkey (6)
United States of America (73)

Table 7.4

Sources of Financial Support
(as of Spring Term 1991)

Research Assistantship (88)
Teaching Assistantship (18)
DOE Civilian Radioactive Waste Management Fellowship (1)
DOE Magnetic Fusion Energy Technology Fellowship (2)
DOE Nuclear Engineering and Health Physics Fellowship (5)
National Academy for Nuclear Training Fellowship (2)
Theos Thompson Fellowship (1)
Manson Benedict Fellowship (1)
Schlumberger Fellowship (1)
Sherman Knapp Fellowship (1)
Wolfe Fellowship (1)
NRC/Ford Fellowship (1)
NASA Fellowship (1)
Space Fellowship (1)
MEMP/HST (1)
United States Army (2)
United States Navy (2)
Government of Japan (2)
Government of Turkey (2)
Government of the Republic of China (5)
Self-supported (4)

Table 7.5

Activities of Nuclear Engineering Department Graduate Students

(Place of first employment--information current as of June 1991)

US Industry and Research (464) (27.6%)

Apollo Computer
Aerodyne Research Inc.
Aerojet Nuclear
Air Research Mfg. Co.
Allis Chalmers (2)
American Electric Power
Amer. Science and Eng.
APDA (2)
Assoc. Planning Res.
Atomics Int. (10)
AT&T Bell Labs (2)
Avco (6)

Babcock & Wilcox (8)
Battelle Columbus
Battelle Northwest (12)
Bechtel (5)
Bendix
Berkeley Research Associates
Bettis (4)
Booz, Allen & Hamilton
Boston Edison (2)
Brigham and Women's Hospital
Burns & Roe (3)

California Oil
Colonial Management Associates
Combustion Eng. (21)
Commonwealth Edison (16)
Computer Processing
Conn. Mutual Life Ins.
Consolidated Edison (4)
Consultant
Consumers Power
Cornell University (research)
Creare Research & Development (3)

Detroit Power Co.
Devonrue
Direct Energy Con. Lab.
Douglas United Nucl. (2)
Draper Lab
Duke Power & Light (2)
Dyntech R/D Co.

Ebasco (2)
Edgerton, Germ. & Grier
EDS Nuclear
EG&G (8)
Energy Awareness
EPM, Inc. (4)
EPRI
Exxon Research & Eng.

Fauske & Associates, Inc. (2)

GA Technologies
General Atomic (6)
General Dyn., Elec. Boat (7)
General Electric (30)
Georgia Power Co.
Grumman Space
Gulf General Atomic (18)

Hercules
Hewlett-Packard
Hughes (5)
Hybrid Systems
Hanford Eng. Dev. Lab

IBM (4)
Industrial Tech. Services Inc.
Inst. for Defense Analysis (3)
Internuclear Co.
Isotopes, Inc.

Jackson & Moreland
Jet Propulsion Lab

Lane Wells
A.D. Little (4)
Lockheed
Long Island Lighting Co.

Table 7.5 (continued)

Management & Tech. Cons.
Martin-Marietta (3)
Mass. General Hospital (7)
Maxson Electric
McDonnell-Douglas
McKinsey & Co. (2)
Medisys
MIT (research) (35)
Mobil Oil
Monsanto
MPR Associates (3)

National Nuclear Corp. (2)
National Academy of Eng.
New England Medical Center
New England Nuclear Corp.
New England Power Service Co. (2)
New York Law Firm
North American Rockwell (2)
Northeast Utilities Serv. (4)
Northern Research & Eng. (3)
Nortronics
Nuclear Fuel Service (2)
Nuclear Mater. & Equipment
Nuclear Products
Nuclear Utility Services (4)
NUS Corporation (2)
NUTECH Engineers

Perkin-Elmer Co.
Philco
Pickard, Lowe & Garrick (2)
Planning Research Corp.
Princeton (research) (5)
Public Service Elec. & Gas
Purdue (research)

Radiation Tech.
Rand Corp.
RCA Research Lab
Resources for the Future

S3 Technologies
Salomon Brothers
Sanders Corp.
Schlumberger International
Science Applications (8)
Scientific Data Systems
Siemens Medical Systems
Sloan Kettering Mem. Hospital
Smithsonian Astrophys. Obs.
Southern Calif. Edison (4)
Spire Corp.
Stanford Research Institute
S.M. Stoller Assoc.
Stone & Webster (15)
Systems Sci. & Eng.
Systems Control

Texaco
Texas Instruments
Texas Utilities
Thermo Electron (2)
TWR Systems (2)

Union Carbide
United Aircraft (3)
United Eng. & Constr. (2)
United Nuclear (5)
U. of California (research) (3)
U. of Maryland (research)
U. of Texas (research)
U. of Wisconsin (research) (2)

Vacuum Industries

Wastechem
Watkins-Johnson
Westinghouse (32)
Wisconsin Electric

Yale (research) (2)
Yankee Atomic (19)

<u>National Laboratories (112) (6.7%)</u>

Argonne (19)
Brookhaven (7)
Knolls Atomic Power (22)
Lawrence Livermore (8)
Lawrence Radiation (5)
Los Alamos (19)
Oak Ridge (18)
Sandia (9)
Savannah River (5)

Table 7.5 (continued)

Further Study (303) (18.1%)

MIT (259)
Other (44)

US Government (239) (14.2%)

Atomic Energy Commission (22)
Air Force (17)
Army (91)
Army Nuc. Def. Lab.
Army Research Lab. (2)
Ballistic Research Lab
CIA (3)
Coast Guard
Dept. of Commerce
Dept. of Energy
Energy Res. & Dev. Admin. (5)
Environmental Prot. Agency (2)
NASA
National Bureau of Standards
National Institutes of Health
Naval Research Lab
Navy (78)
Nuclear Regulatory Commission (6)
Office of Science & Technology Policy
Peace Corps
Picatinny Arsenal
Dept. of Public Health

Teaching (73) (4.3%)

American Univ. (Washington, D.C.)
Brooklyn College (CCNY)
California Institute of Technology
California State (Long Beach)
Carnegie-Mellon University
Case Institute
Catholic University of America
Cornell
El Rancho High School
Georgia Institute of Technology
Howard University
Iowa State
Kansas State
Lehigh
Lowell Tech (4)
Loyola University
Mass. Maritime Academy
Michigan State University
MIT (13)
New York University
Northeastern University (2)
Northwest Nazarene
Pennsylvania State
Princeton
Purdue
Radford College
Rensselaer Polytech.
Swarthmore
Texas A & M (2)
US Military Academy
University of British Columbia
University of California (9)
University of Florida (2)
University of So. Florida
University of Illinois (5)
University of Kentucky
University of Missouri (2)
University of New Hampshire
University of Texas
University of Washington
University of Wisconsin (2)

Foreign (280) (16.7%)

Algeria (4)
Argentina (8)
Belgium (10)
Brazil (31)
Canada (16)
Chile (16)
Columbia, S.A. (2)
England (2)
France (29)
Germany (5)
Greece (6)
India (13)
Indonesia
Iran (26)
Israel (4)
Italy (5)
Japan (22)

Table 7.5 (continued)

Jordan
Korea (13)
Libya (1)
Malaysia (2)
Mexico
Morocco
Nigeria
Norway
Pakistan (4)
People's Republic of China
Philippines (2)
Poland
Republic of China (18)
Saudi Arabia
Spain (14)
Switzerland (8)
Turkey (5)
Venezuela (5)

<u>Not Reported (209) (12.4%)</u>

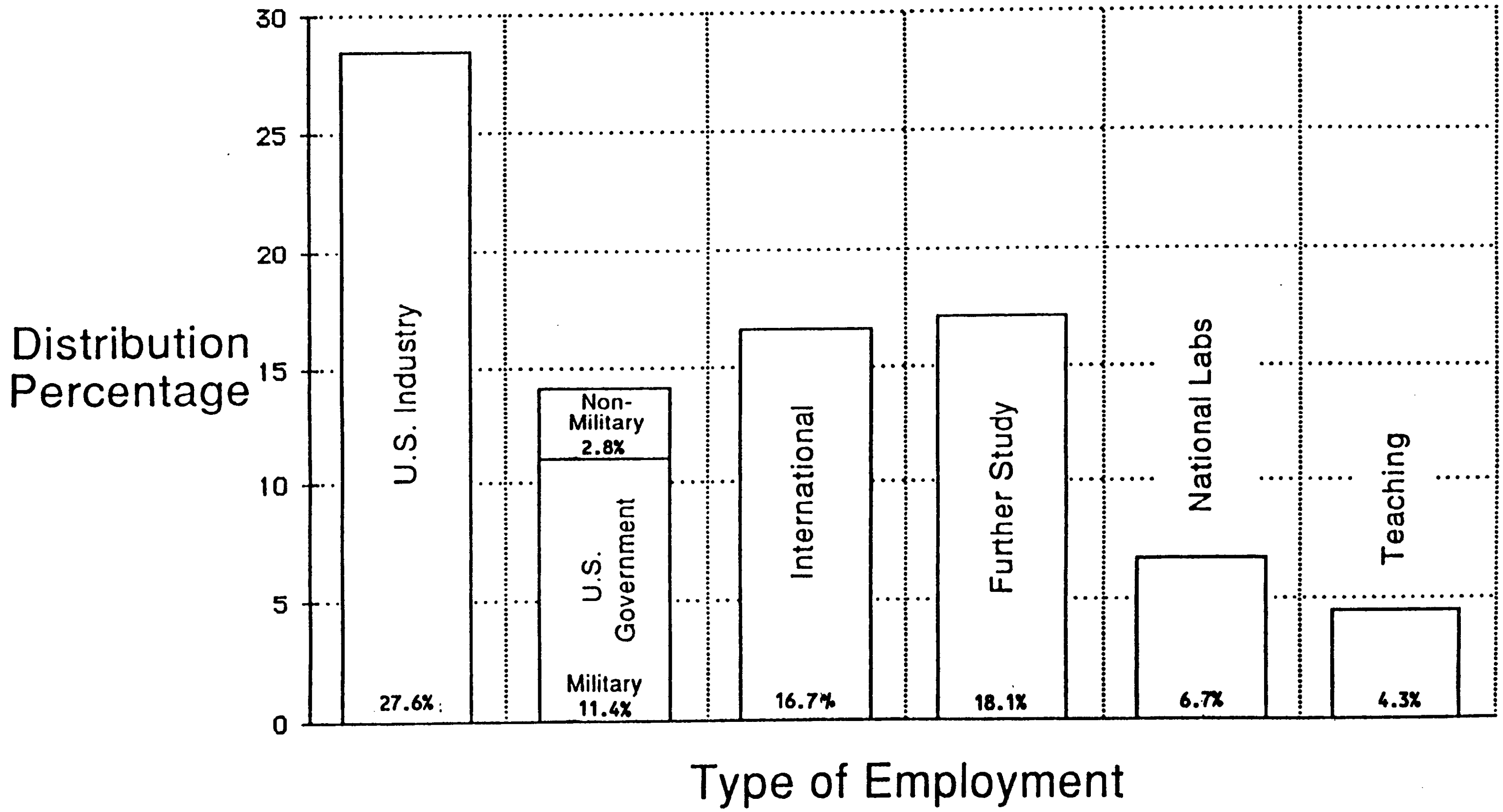
TOTAL 1680*

*Records from early years are incomplete

Figure 7.1

Distribution of First Place of Employment of Nuclear Engineering Graduates*

(as of June 1991)



*Excludes 209 (12.4%) Students Not Reporting

8. LIST OF GRADUATE THESES (SEPTEMBER 1989 TO JUNE 1991)

AUTHOR DEGREE / DATE	TITLE	THESIS SUPERVISOR
G. E. Broadbent SM 9/89	A Rule-Based Approach to PWR Reload Pattern Development	M. Driscoll
T. J. Farish ScD 9/89	A Magnesium Vapor Jet Neutralizer	R. Post
S. S. Hakkarainen PhD 9/89	Submillimeter Wave Harmonic Gyrotron	R. Temkin
T. Hiltz SM 9/89	Reducing Diagnostic Error in Nuclear Power Plant Operations	M. Golay
R. K. Kirkwood PhD 9/89	Measurement of Suprathermal Electrons by Cyclotron Transmission in the Versator II Tokamak	I. Hutchinson
V. Leung SM 9/89	Study of the Thermodynamics of Ion Solubilization in Water-in-Oil Microemulsions - A Technique for Metal Ion Removal From Waste Stream	S-H. Chen
K. L. Meyers SM 9/89	Information Technology and Nuclear Power - A Policy for Organizational Change	K. Hansen
Y. Parlatan SM 9/89	The Impact of Blanket Design on Activation and Thermal Safety	M. Kazimi
C. C. Petty PhD 9/89	Confinement of Multiply Charged Ions in an ECRH Mirror Plasma	D. Smith
A. Z. Tanker ScD 9/89	Generalized Reactor Kinetics Parameters for the Quadratic Analytic Nodal Method	A. Henry

AUTHOR DEGREE / DATE	TITLE	THESIS SUPERVISOR
B. N. Aviles PhD 2/90	Digital Control Strategies for Spatially-Dependent Reactor Cores with Thermal-Hydraulic Feedback	D. Lanning J. Bernard
A. A. R. Esteves NE/SM 2/90	Qualification of Miniature Canned Rotor Pumps for PWR In-Pile Loop Service	M. Driscoll O. Harling
J. C. Gehin SM 2/90	Nodal Method for Hexagonal Graphite and D2O Cores	A. Henry
O. Herbelot SM 2/90	Superconducting Cable Joint Resistance	M. Hoenig
C. Lee PhD 2/90	Modeling of Corrosion Product Transport in PWR Primary Coolant	M. Driscoll
M. V. McMahon SM 2/90	Fuel Burnup Effects on the Performance of a Reactor Power Controller	J. Meyer
M. Oshima NE 2/90	Computation of Quench Propagation in Multiple Superconducting Coils	M. Kazimi R. Thome
C. G. Owens SM 2/90	Passive Decay Heat Removal Approaches for Light Water Reactors	N. Todreas
M. J. Psaila-Dombrowski PhD 2/90	Modeling of Crack and Crevice Chemistry in Light Water Reactors	R. Ballinger
R. D. Rogus SM 2/90	An Os-191 → IR-191m Generator Using a Naturally Abundant Osmium Target	O. Harling
J. Schwartz PhD 2/90	Design and Stability of a High Field (>20T) Toroidal Field Coil Using Advanced Superconducting and Structural Materials	D. Cohn

AUTHOR DEGREE / DATE	TITLE	THESIS SUPERVISOR
K. W. Wenzel PhD 2/90	Measurements of Injected Impurity Transport in TEXT Using Multiply Filtered Soft X-Ray Detectors	R. Petrasso
K. L. Yuracko PhD 2/90	Transporting Spent Nuclear Fuel: A Framework for Decision-Making	N. Rasmussen
W. E. Casey SM 6/90	Transient Thermal-Hydraulic Analysis of a Packed Particle Bed Reactor Fuel Element	J. Meyer
E. D. Cabello SM 6/90	Decontamination Studies of Simulated PWR Primary Coolant System Components	M. Driscoll O. Harling
K. S. Cheung PhD 6/90	Atomistic Study of Dislocation Nucleation at a Crack Tip	S. Yip
W. G. He SM 6/90	The Dependence of Human Deductive Capabilities Upon Problem Complexity	M. Golay
T. D. Ippolito SM 6/90	Effects of Variation of Uranium Enrichment on Nuclear Submarine Reactor Design	D. Lanning M. Miller
L. S. Johnson SM 6/90	EGS4 Monte Carlo Evaluation of Dosimetry in Radiation Synovectomy	J. Yanch
W. A. Krueger PhD 6/90	Plasma and Neutral Gas Jet Interactions in the Exhaust of a Magnetic Confinement System	K. Molvig T. Yang
B. Lal SB/SM 6/90	MHTGR Spent Fuel Transmutation in ITER	M. Kazimi
W. Luangdilok PhD 6/90	Flow Reversal Under Mixed Convection Conditions in Rod Bundles	N. Todreas
J. S. Machuzak PhD 6/90	Millimeter-Wave Electron Cyclotron Emission and Collective Thomson Scattering Diagnostics in the Tara Tandem Mirror Experiment	P. Woskov

AUTHOR DEGREE / DATE	TITLE	THESIS SUPERVISOR
V. H. Mason SM 6/90	Chemical Characterization of Simulated Boiling Water Reactor Coolant	M. Driscoll
K. A. McNeil SB/SM 6/90	The Behavior of Ag-In-Cd Control Rods During Severe Accidents	R. Ballinger
R. Medina SM 6/90	Measurement of Neutron Flux and Spectrum Averaged Cross-Sections for an In-Pile PWR Loop	M. Driscoll O. Harling
M. R. Palmer PhD 6/90	Spatial Resolution in Positron Emission Tomography: The Fundamental Limits	G. Brownell
E. L. Redmond II BS/SM 6/90	Monte Carlo Methods, Models, and Applications for the Advanced Neutron Source	A. Henry
K. A. Roberts SM 6/90	Mixed Field Dosimetry in Realistic Head Phantoms Using an Epithermal Beam at MITR-II	O. Harling R. Zamenhof
R. G. Sanchez PhD 6/90	Construction and Operation of an In-Pile Loop for PWR Dose Reduction Experiments	M. Driscoll O. Harling
G. Sasson SM 6/90	Probabilistic Risk Assessment in the Design Process	N. Siu
C. M. Steele SM 6/90	Quantitative Investigation into the Time Dependent Effects of Constant Nodal Discontinuity Factors in Coarse Mesh Finite Difference Reactor Transient Calculations	A. Henry
W. A. Stewart NE/SM 6/90	A Method for Estimating Tokamak Poloidal Field Coil Currents Which Incorporates Engineering Constraints	J. Freidberg

AUTHOR DEGREE / DATE	TITLE	THESIS SUPERVISOR
F. A. Tarantino PhD 6/90	The Development of Cross Sections from Bilinear Variational Theory for Use in Few-Group Transient Analysis	A. Henry
D. Wang SM 6/90	Computer Simulation Studies of the Structural Characteristics of (111) Twist Boundaries in Gold	S. Yip
F. M. G. Wong PhD 6/90	Fatigue, Fracture, and Life Prediction Criteria for Composite Materials in Magnets	R. Ballinger
J. J. Zhang NE/SM 6/90	High Resolution Gas Scintillation Proportional Camera in Nuclear Medicine	R. Lanza
X-L. Zhou NE/SM 6/90	A Design of an Accelerator-Based Epithermal Neutron Beam for Boron Neutron Capture Therapy	J. Yanch
J. W. Bates SM 9/90	Analysis of Discontinuities in Explosively Bonded Plates Using Ultrasound	R. Thome
E. A. Chaniotakis PhD 9/90	Ignition and Burn Control Characteristics of Thermonuclear Plasmas	J. Freidberg
J. H. Chun SM 9/90	Modeling of BWR Water Chemistry	R. Ballinger
T. E. Hechanova SM 9/90	Thermo-Mechanical Performance of Beryllium-Coated Copper Divertors	M. Kazimi
M. Koch SM 9/90	A Comparison of Radioactive Waste from Fusion and Fast Fission Reactors	M. Kazimi
J. C. McLoughlin SM 9/90	A Comparison of Methods for Monitoring Low Airborne Concentrations of Argon-41 and Tritium, with MIT-PFC Design Applications	G. Brownell F. McWilliams

AUTHOR DEGREE / DATE	TITLE	THESIS SUPERVISOR
S. W. Pappano SM 9/90	Environmental Impacts of the Modular High Temperature Gas-Cooled Reactor	D. Lanning M. Golay
T. W. Poon PhD 9/90	Atomistic Study of the Equilibrium Structures of the Si(100) Stepped Surfaces	S. Yip
P. Borys SM 2/91	Activity Removal and Transport Studies in Support of PWR In-Pile Loop Operations	M. Driscoll O. Harling
M. A. Cheema SM 2/91	Environmental Health, Risk Analysis and Safety Aspects of Nuclear Magnetic Resonance and Spectroscopy Systems	G. Brownell
V. N. Dang SM 2/91	Improved Methods for Simulation-Based Risk Assessment	N. Siu
S. M. Flank SM 2/91	Nuclear Power as Metaphor: Public Acceptability and the Future of Nuclear Power	K. Hansen
G. Fu ScD 2/91	Experimental and Analytic Evaluation of Gas-Cooled Reactor Cavity Cooling System Performance	N. Todreas M. Driscoll
D. R. Hanchar PhD 2/91	Engineering Methods to Assess Magnetohydro-dynamic Pressure Drop in Liquid Metal Fusion Blankets	M. Kazimi
M. G. Houts PhD 2/91	Out-of-Core Thermionic Space Nuclear Reactors: Design and Control Considerations	D. Lanning
S. H. Kim SM 2/91	Magnetic Susceptibility Effects in Magnetic Resonance Imaging of Bone Marrow	B. Rosen
T. Kiryaman SM 2/91	Non-Linear Analysis and Control of Switched-Mode Power Converters	M. Ilic
R. C. McKinstry III PhD 2/91	Ultrafast NMR Imaging of Brain Water Mobility	B. Rosen

AUTHOR DEGREE / DATE	TITLE	THESIS SUPERVISOR
A. Mortara SM 2/91	An Improved Probe Design for NMR Microscopy	E. McFarland
F. R. M. Mujica Fernandez SM 2/91	Lattice Gas Wind Tunnel	K. Molvig
J. O. Outwater III ScD 2/91	Design, Construction and Commissioning of an In-Pile BWR Coolant Chemistry Loop	O. Harling M. Driscoll
S. A. Parra SM 2/91	Simulating Light Water Reactor Start-up Transients Using a Point Kinetics Model with a Precalculated Reactivity-Table	A. Henry D. Lanning
J. J. Winebrake SM 2/91	An Analysis of Transfer Mechanisms for Federally Funded Research and Development	R. Tabors
M. Zhang SM 2/91	Measurement and Interpretation of Chemical and Radiochemical Data from PWR In-Pile Loop Runs	M. Driscoll O. Harling G. Kohse
T. G. Achorn SM 6/91	The Potential Role of New Technology for Enhanced Safety and Performance of Nuclear Power Plants Through Improved Service Maintenance	K. Hansen
C. G. Acosta PhD 6/91	Dynamic Event Tree for Accident Sequence Analysis	N. Siu
C. E. Carney, Jr. PhD 6/91	Analytical Treatment of Diffusion in Steady State Free Precession NMR Techniques	G. Brownell
S-L. Chang PhD 6/91	Study of Ion Distribution Around Cylindrical Polyelectrolytes and Microstructure of Bicontinuous Microemulsions by Small Angle X-ray and Neutron Scattering	S-H. Chen

AUTHOR DEGREE / DATE	TITLE	THESIS SUPERVISOR
J-H. R. Choi ScD 6/91	Development and Characterization of an Epithermal Beam for Boron Neutron Capture Therapy at the MITR-II	O. Harling
A. A. Dehbi PhD 6/91	The Effects of Noncondensable Gases on Steam Condensation Under Turbulent Natural Convection Conditions	M. Kazimi M. Golay
X-H. Guo PhD 6/91	The Structure and Phase Transition of Protein-SDS Complexes in Solution and the Transport Mechanism in SDS-Page	S-H. Chen
J. A. Izatt PhD 6/91	Pulsed Laser Ablation of Calcified Biological Tissue: Physical Mechanisms and Clinical Applications	M. Feld
R. T. Klann SM/SB 6/91	Utilizing Radiation Heat Transfer to Increase the Power Density in a Gas-Cooled Reactor	L. Lidsky
K. C. Kupfer PhD 6/91	Chaotic Dynamics and Transport Induced by Waves in Plasmas	A. Bers
K. S. Kwok PhD 6/91	Automated Startup of Nuclear Reactors: Reactivity Estimation, Computer System Development, and Experimental Evaluation	D. Lanning J. Bernard
S. H. Lau NE 6/91	Experimental Evaluation of Trajectory Tracking Methodologies for Control of Reactor Power	D. Lanning J. Bernard
K-S. Liang PhD 6/91	Experimental and Analytical Study of Direct Contact Condensation with Steam in Water	P. Griffith
C. M. Martin SM/SB 6/91	The Design of a High Temperature Gas Reactor Fuel Testing Facility for MITR-II	D. Lanning L. Lidsky
J. L. Martin PhD 6/91	DABLE: A Facility for Measuring Fission Product Transport in Gas-Cooled Reactors	L. Lidsky

AUTHOR DEGREE / DATE	TITLE	THESIS SUPERVISOR
J. Matsumoto SM 6/91	Electrochemistry of Intermetallic Phases in Ni-Ci-Fe Alloys in Aqueous Environment	R. Ballinger
T. Nguyen PhD 6/91	Subcellular Distribution and Microdosimetry Studies for Boron Neutron Capture Therapy	G. Brownell B. Teischer
M. C. Offutt SM 6/91	Nuclear Magnetization Transfer Studies of Metabolic Reaction Rates in Mouse Brain	E. McFarland
K. D. Pendergast PhD 6/91	Theoretical and Experimental Research on a High-Power, High-Frequency Cyclotron Autoresonance Maser	R. Temkin
S. Shi SM 6/91	Electronic Structure of the Palladium-Hydrogen System	K. Johnson
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C. Yoo SM 6/91	Plasma Confinement Optimization of the Versatile Toroidal Facility for Ionospheric Plasma Simulation Experiments	M-C. Lee