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ACTIVITIES IN NUCLEAR ENGINEERING AT MIT



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

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1. INTRODUCTION

This report has been prepared by the personnel of the Nuclear Engineering Department at M.I.T. 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, including medical applications; 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 include radiological sciences, radiation health physics, condensed matter sciences, 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, 1986, departmental faculty supervised a research volume of \$3,676,828, including 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 150 domestic and international students during the academic year 1986-87. Of this number, approximately 51% expressed interest in the fission area, 26% were involved in plasma and controlled fusion, 18% registered in the radiation program, and 5% in energy economics and policy. In September 1986, our undergraduate enrollment totaled 20 students.

The Department awarded 55 advanced degrees during the academic year 1986-87. This included 20 doctorates, 3 nuclear engineers, and 32 masters of science degrees. Six bachelor degrees were awarded, four of which were joint SM/SB degrees.

Table 1Enrollment in M.I.T. Nuclear Engineering DepartmentFall Semester*

1973	127
1974	138
1975	202
1976	221
1977	217
1978	213
1979	209
1980	189
1981	191
1982	197
1983	194
1984	180
1985	173
1986	171

*Source: Bruce Report, July 1987 (for AY 1973/74 to 1985/86)

Table 2Applications for Graduate Admission
to M.I.T. Nuclear Engineering DepartmentFall Semester

1972	88
1973	102
1974	128
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

1.2 Graduate Student Financial Aid

During the fiscal year ending June, 1987, approximately 80% of our graduate student body was 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 ABZ Inc., the ACF Foundation, Inc., the Athena Engineering Curriculum Development, the Jerry McAfee Chair in Engineering, the Pickard, Lowe & Garrick, Inc., and the Schlumberger Doll Research Center. In addition, the department receives an annual allocation from the MIT Graduate School College Work Study Program.

Scholarship support was also provided through the generosity of the Latin American Scholarship Program of American Universities, the Andrew W. Mellon Foundation, the MIT Graduate and Professional Opportunities, the Graduate Engineering Minority, and the Technology and Policy (Rabinowitz Fellowship) Programs, the National Aeronautics and Space Administration, the National Institutes of Health, the National Science Foundation, the Rockwell International, the TRW, and the United States Departments of the Army, Energy, and the Navy.

In response to the need for more financial aid for graduate students, the Department established an Endowed Emergency Financial Aid Fund for Nuclear Engineering Department students in May of 1986. This fund was created with a generous bequest from the estate of the late Professor David J. Rose and a gift contribution from Professor Irving Kaplan. The financial aid officer of the Nuclear Engineering Department is responsible for the timely identification and resolution of financial difficulties that Nuclear Engineering Department students may encounter. This newly established endowed fund will greatly assist the financial aid officer in discharging this responsibility.

International support was provided by the countries: Brazil, Canada, Chile, Republic of China, France, Japan, Korea, Nigeria, Pakistan, Saudi Arabia, and Turkey. Industrial and laboratory support was provided by the Consolidated Edison of New York and the Battelle Northwest.

1.3 Organization of Activities Report

Section 2 of this report contains a summary of developments within the Department since December 1985. 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 theses submitted to the Department during the period February 1986 through June 1987.

2. SUMMARY OF DEVELOPMENT SINCE DECEMBER 1985

Section 2 summarizes developments within the Department since our last Activities Report. It includes academic programs, special summer activities, the Department's contribution to the Institute-at-large, outside professional activities, changes in the faculty, and recent honors to the faculty.

2.1 Academic Program

As mentioned in our last report, the faculty and graduate students have held considerable discussion regarding review of the department curriculum and the associated structure of the doctoral qualifying examination. As a result of these discussions, the faculty voted to issue a revised list of graduate courses and qualifying examination requirements, as well as institute a major requirement for PhD/ScD candidates in addition to the already existing minor requirement. This new policy has been in effect since September 1986.

In addition to the above, other changes in the nuclear engineering curriculum that have occurred since our last report are mentioned below. During the fall semester 1985, Professors Michael Driscoll and Richard Lester introduced a new course, 22.341 Nuclear Energy Economics and Policy Analysis. Another new graduate selection, 22.113 Nuclear and Atomic Collision Phenomena was presented during the spring semester 1987. The Department's basic laboratory course in nuclear measurements was reorganized by Professors Otto Harling and Norman Rasmussen. This new subject, 22.09/59 Principles of Nuclear Radiation Measurement and Protection was successfully taught for the first time during the spring term 1987. Also during the same semester, Professor Ian Hutchinson updated the subjects 22.069 Undergraduate Plasma Laboratory and 22.69 Plasma Laboratory to include work on lasers and cryogenics. A spring offering, 22.062/602 Fusion Energy II was revised by Professors Jeffrey Freidberg and Dr. Daniel Cohn. In this new version, they devoted a large effort to the explanation of how existing fusion experiments are built and operated from a technological point of view.

The Engineering Internship Program continues to be a valuable educational experience for our students. During the year, participants in this program have received on-the-job training at Brookhaven National Laboratory, EG&G, and Stone & Webster.

2.2 Student Activities

The MIT Student Chapter of the American Nuclear Society (ANS) continues to be a vital link between the student body and the Nuclear Engineering Department administration and faculty. In addition to planning monthly student/faculty dinner meetings, a departmental picnic, and a holiday party, the Student Chapter scheduled a weekly departmental seminar series. For each seminar, a guest speaker was invited to present his/her research in nuclear science and engineering. The ANS also participated in departmental orientation activities and organized intramural teams for sporting events.

2.3 Faculty Activities

The Nuclear Engineering Department faculty continue to participate in

various activities, both on- and off-campus. A summary of their accomplishments since our last report is presented below.

A special two-week summer course entitled "Nuclear Power Reactor Safety," was presented during the summers of 1986 and 1987. Under the direction of Professors Norman Rasmussen and Neil Todreas, this offering attracted members of the US nuclear industry as well as those of the international community. Also during the summers of 1986 and 1987, Professor Allan Henry offered the program "Modern Nodal Methods for Analyzing Light-Water Reactors." This week-long course was well attended and well received.

Faculty involved in the Nuclear Power Plant Innovation Project have participated in various seminars and workshops regarding this research. Professor Lawrence Lidsky gave an invited paper at the International Nuclear Engineering Symposium on the Development and Use of Small and Medium Size Power Reactors in the Next Generation. This symposium was held at Tokai University in November 1986. He has also testified before several congressional subcommittees regarding the virtues of the MHTGR and its potential role in the future of US nuclear power. Professor Lester has also contributed to various workshops and seminars concerned with US power reactor research and development goals, such as the NSF Workshop on Innovative Electric Power Systems that was held in June 1986.

Professor Michael Golay led the Energy Laboratory's Electric Utility Program nuclear workshop. This workshop focused upon problems of operating nuclear power stations reflecting the importance of increasing plant availability as the current generation of plants grows older.

Several Nuclear Engineering faculty members were invited to chair and/or present papers at professional meetings during the year. Professor Henry was a member of the Program Committee for the American-European Nuclear Society Topical Meeting on Reactor Physics and Mathematics. He also chaired a session and presented a paper at the meeting held in Paris.

In April 1986, Professor Todreas was co-chairman of the 2nd International Topical Meeting on Nuclear Power Plant Thermal Hydraulics and Operations that was held in Tokyo, Japan. During the same month, Professor Sidney Yip was invited to speak at an international meeting on computer simulation and the glass transition that was held at Oxford University. He also presented lectures on simulation studies in materials science during a three-week travel in the People's Republic of China under a grant from the Marion and Jasper Whiting Foundation.

In August 1986, Professor Sow-Hsin Chen was chairman of the Gordon Conference on "Water and Aqueous Solutions" that has been held every two years for the last 20 years. In February, he was invited to speak at the International Winter School in Les Houches, France.

At the invitation of Professor Mujid Kazimi, European and Japanese researchers attended an international workshop on safety aspects of lithium that was held at MIT during the summer of 1986. The following September, he presented the results of his work on severe accident phenomena at a Specialists' meeting organized by the Center for Studies of Nuclear Installation at EPRI.

He was also a US delegate to the workshop on fusion safety research convened by the International Atomic Energy Agency at Culham, England, in November 1986.

Professor Kent Hansen was an invited speaker at a forum entitled "Beyond Chernobyl: The Future of Nuclear Power." This on-campus presentation was arranged by MIT's Technology and Culture Seminar. The activities of a National Research Council committee to assess the costs and benefits of US university research reactors were launched with Professor Otto Harling providing one of the keynote addresses.

Professor Harling directed a series of short courses on nuclear technology which make use of the MIT Research Reactor. These courses have been well received by pre-college teachers and will continue to be offered with the US Department of Energy providing the necessary financial support.

Changes in some faculty administrative responsibilities have taken place since our last report. Graduate admissions, formerly reviewed by Professor David Lanning, are currently handled by Professor Jeffrey Freidberg. He is also chairman of the Department's admission's committee. On June 30, 1986, Professor Sidney Yip completed his term of duty as financial aid officer. Professor Mujid Kazimi has now assumed this responsibility. Professor Michael Driscoll continues to serve as Graduate Recruiting Officer. Professor Allan Henry represents the Department on the Committee on Graduate School Policy (CGSP). Professor John Meyer, who chaired the Committee on Undergraduate Students, also served as the faculty advisor for the honorary Alpha Nu Sigma Society. Professor Nathan Siu is the faculty advisor for the ANS Student Chapter. Professor Ron Ballinger continued to supervise the Undergraduate Research Opportunities Program, the Engineering Internship Program, and also served as the Undergraduate Financial Aid Officer. Departmental IAP activities were organized by Professor Schor. The NED Safety Committee and its Computer Committee were chaired by Professor Todreas.

In addition to Departmental obligations, Nuclear Engineering faculty have actively contributed to both School of Engineering and Institute activities throughout the year. Professor Norman Rasmussen continues to serve as Chairman of the MIT Committee on Reactor Safeguard, and is also a member of the Plasma Fusion Center's Visiting Committee and the Institute Council on Environmental Health and Safety.

Professor Richard Lester was appointed as Executive Director of the MIT Commission on Industrial Productivity, a group of 17 senior faculty members and administrators charged by President Gray with the task of exploring the role of the nation's universities in helping to overcome the problem of weak productivity growth in US industry. He is also a member of the Committee on International Institutional Commitments.

Professor Elias Gyftopoulos continued his services as Faculty Chairman of the MIT Sustaining Fellows Program. He also served as Chairman of the Interschool Working Group on Context Subjects, and was a member of the Killian Faculty Achievement Award Selection Committee for 1987-88.

Besides serving as departmental CGSP representative, Professor Henry holds membership on the Institute's Advisory Committee on Shareholder

Responsibility. Professor Lidsky has been selected to chair the Institute Committee on Curricula. Professor Yip is a member of the Committee on Student Affairs.

Also during the year, Professor Gordon Brownwell participated in the Committee on Radiation Exposure to Human Subjects. Other faculty appointed to Institute committees include Professors Kim Molvig and Golay. Professor Molvig is a member of the Faculty Club Advisory Board, and Professor Golay serves on the Committee on Outside Professional Activities.

Professor Otto Harling directs operation of the interdepartmental Nuclear Reactor Laboratory and is a member of the MIT Committee on Reactor Safeguard. Additional faculty members serving on this committee include Professor Ron Ballinger, David Lanning, and Mujid Kazimi.

During the past year, Nuclear Engineering faculty have participated in various activities in the professional community. Professor Rasmussen is a member of the National Science Board. He continues as a member of the Scientific Advisory Committee for the Cleanup of TMI-2. He recently chaired the Committee on Hydrogen Combustion of the National Research Council. He continues as Chairman of the LNG Safety Committee of Cabot Corporation, and as a member of the Board of Trustees of Northeast Utilities.

Professor Lanning continues to serve on the Safety Audit Committee at Northern States Power Co., the Nuclear Safety Review and Audit Committee at Boston Edison, and the Source Term Review Group for Stone & Webster Engineering Corporation. Professors Lanning and Todreas were appointed by the National Academy of Sciences/National Research Council to serve on the "Committee to Assess Safety and Technical Issues at DOE Reactors." Professor Todreas is chairman of the EG&G TMI-2 Accident Analysis Industry Review Group and he also serves on the B&W utility owner group Independent Advisory Board for the owner's safety performance and improvement program.

Professor Golay is a member of the Atomic Industrial Forum. Professor Hansen continues to serve on the Energy Research Advisory Board Panel on Civilian Nuclear Power, and on the Scientific Advisory Committee to the Idaho National Engineering Laboratory. He was recently selected a member of the National Research Council's Commission on Engineering and Technical Systems.

Professor Russell began service on the Program Advisory Committee of the Los Alamos Meson Production Facility. Besides serving on the advisory committee for the DOE's Magnetic Fusion Technology Fellowship Program, Professor Kazimi is a member of a DOE panel that will assess the economic, safety, and environmental aspects of fusion energy utilization in the next century. Dr. Daniel R. Cohn served on the National Academy of Sciences panel on Fusion Hybrid Reactors. Professor Jeffrey Freidberg was appointed to the executive committee of the annual Magnetic Fusion Sherwood Theory Conference. He also served as chairman of the Program Selection Committee for the Spring 1987 meeting in San Diego.

American Nuclear Society committee positions are held by Professors Henry, Driscoll, and Schor. Professor Henry is a member of the Program Committee of the Mathematics and Computation Division. Professor Driscoll completed his terms (1985-87) as a member of the Executive Committee of the

Fuel Cycle and Waste Management Division. He has also been appointed a member of the review committee for the Applied Physics Division at Argonne National Laboratory. Dr. Daniel R. Cohn served as Chairman of the Fusion Energy Division of the American Nuclear Society.

Two faculty are represented on editorial review boards. They are Professor Todreas on the thermal design section of the Journal of Nuclear Engineering and Design and Professor Henry on Nuclear Science and Engineering.

Two new textbooks have been published by fusion faculty members. A textbook "Plasma Diagnostics" by Professor Ian Hutchinson and one on "Ideal Magnetohydrodynamics" by Professor Jeffrey Freidberg.

Honors were bestowed upon several faculty since our last report. The MIT Student Chapter of the ANS presented its Outstanding Teacher Award to Professor Jeffrey Friedberg for the academic year 1985-86; for the academic year 1986-87, Professor Allan Henry was selected for this award.

Professor John Meyer received an Alumni Merit Award from Carnegie Mellon University. Professor Ken Russell was elected a Fellow of the American Society for Metals. Professor Elias Gyftopoulos was named a Fellow of the American Society of Mechanical Engineers. Professor Sow-Hsin Chen received the US Senior Scientist Award from the Humboldt Foundation in West Germany.

3. RESEARCH AND EDUCATIONAL ACTIVITIES

3.1 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.

3.1.1 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 and 22.212. Those whose special interests lie in the general area of nuclear reactor physics also take 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.

22.41: Numerical Methods of Radiation Transport, deals with the mathematical methods for the solution of neutron/photon transport problems: detailed development of discrete ordinates and Monte Carlo methods for applications in radiation shielding. Discussion of iteration techniques for solution of coupled difference equations. Group projects on solving original transport problems by design and implementation of computer codes are required.

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.

22.43: Advanced Numerical Methods in Engineering Analysis, covers advanced computational methods used in analysis of nuclear reactor engineering problems studies. Emphasizes the solution of multidimensional problems and non-linear equations using modern iterative techniques. Topics include finite difference and finite elements formulations with applications to incompressible and compressible flows. Introduction to numerical turbulence modeling. Additional special topics covered depending on the interests of the class.

3.1.2 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.

(1) Nodal Schemes

If, for purposes of obtaining critical eigenvalue and gross power distributions, a reactor can be represented as composed of large homogeneous nodes, there is no need to compute flux distributions throughout the nodes. Since physically real heterogeneities have been homogenized in the mathematical model, average reaction rates are the only calculated quantities having a true physical significance. Finite difference methods provide a very wasteful way of analyzing such a reactor since many mesh points must be used in a node to insure accuracy of the average nodal fluxes; yet, once the full core solution is obtained all the extra information specifying detailed flux shapes in the nodes is simply integrated out. Nodal methods circumvent this difficulty by treating the average nodal fluxes themselves directly as unknowns. Calculations are faster both because there are many fewer unknowns and because (with few unknowns) it becomes practical to use more powerful numerical iteration schemes. This situation makes it practical to solve three-dimensional reactor problems for both static and transient situations.

Because of the advantages just cited, we have developed a two-group nodal method, embodied in the computer code QUANDRY, as the main framework for our analysis of thermal reactor problems. Production versions of that code have been created at N.U.S. and at S. Levy Co. (with EPRI support) and an extension of the code embodying many improvements has been created by Studsvik of America.

During the past year we have coded a special nodal scheme in R-Z geometry which makes use of a quadratic representation of the flux rather than the analytical procedure embodied in QUANDRY. The intent is to apply this model to the analysis of graphite moderated reactors. For such an application the numerical solution methods used in QUANDRY are inefficient, and at present we are examining alternative schemes.

(2) Homogenization and Dehomogenization

Nodal methods deal with average fluxes and average reaction rates throughout an entire node. Hence it is necessary to determine homogenized cross sections as input to the nodal code. If one then wishes to determine power levels in individual fuel pins within a given node, it is necessary to reconstruct a detailed heterogeneous flux shape for that node.

We have previously developed accurate homogenization procedures based on the use of discontinuity factors and have explored methods of reconstructing pin powers from the nodal solutions. The reconstruction procedure worked well for PWR's but was a bit expensive to apply. A more efficient method has now been developed and successfully tested for several fuel cycles for PWR's. An attempt to improve the efficiency of previously developed schemes for reconstructing pin powers in BWR's was only partially successful.

The first effort to develop a "supernodal" method (node sizes = $40 \times 40 \times 60 \text{ cm}^3$) has been completed. The scheme, which involves reconstructing "fine-node" fluxes (node sizes: $10 \times 10 \times 15 \text{ cm}^2$) from the supernodal results in order to compute changes in cross sections due to feedback effects, predicts quite accurately changes in flux shape and criticality due to

xenon redistribution during power maneuvering.

(3) Modeling Kinetics Behavior

Since QUANDRY is a two-group, three-dimensional, time-dependent code which incorporates a thermal-hydraulic feedback model, it is an excellent tool for numerical testing of more approximate models. During the past year we have developed and tested a number of simpler models ranging from the conventional point kinetics scheme to several two-group, one-dimensional models. In all cases, these approximate methods have been derived directly from the matrix equations that define QUANDRY. Results suggest strongly that certain theoretical models now being used for transient analysis by utilities should be reexamined.

In order to test the validity of the two-group diffusion theory model for simulating transient behavior, we have programmed a one-dimensional, multigroup, P-1, nodal scheme to serve as a numerical standard. Both regular flux weighted and bilinear (flux-adjoint) weighted two-group schemes will be tested against this standard.

Other kinetics modeling efforts include the extension of the supernodal method to transient description and the continued exploration of the solution of kinetics equations using a parity simulator rather than a digital computer.

Finally, we have developed new numerical methods for solving the point kinetics equations in real time. A spin-off of this development has been an idea for an improved reactivity meter less noisy than those in current use. Preliminary work on this idea has been encouraging. However, more work needs to be done.

Investigators: Professor A.F. Henry; students E.J. Ashburner, A.F.V. Dias, R.G. Gamino, P.W. Kao, M. Kim, P.J. Loughton, K.R. Rempe, A.Z. Tanker, E. Tanker, and M.L. Zerkle.

Support: MIT Energy Laboratory Utility Program; D.O.D.; Sandia National Laboratory; Studsvik of America; Westinghouse Electric Corp.

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
- 22.43 Advanced Numerical Methods in Engineering Analysis

Recent References:

R.G. Gamino and A.F. Henry, "The Application of Supernodal Methods to 3-D PWR Analysis," paper presented at Session 10 of the International Topical Meeting on Advances in Reactor Physics, Mathematics and Computation, 27-30 April 1987, in Paris, France; Proceedings of the Conference, Volume 2, p. 875.

T.A. Taiwo and A.F. Henry, "Perturbation Theory Based on a Nodal Model," Nuclear Science and Engineering, Vol. 92, 34-41, 1986.

R.G. Gamino, "The Development and Application of Supernodal Methods to PWR Analysis," Ph.D. Thesis, Nuclear Engineering Department, MIT, May 1986.

K.R. Rempe, "Analysis of Zion-2's First Cycle of Operation with Nodal Methods," S.M. Thesis, Nuclear Engineering Department, MIT, June 1986.

A.G. Parlos, "Non-Linear Multivariable Control of Power Plants Using the Unknown-but-Bounded Modeling Methodology," Sc.D. Thesis, Nuclear Engineering Department, MIT, 1986.

A.G. Parlos, "Non-Linear Multivariable Control of Nuclear Power Plants Based on the Unknown-but-Bounded Disturbance Model," article accepted for publication in the IEEE Transactions on Automatic Control.

J. Bernard, D. Lanning, J. Meyer, and A. Henry, "Application of the Reactivity Constraint Approach to the Transient Control of Spacecraft Reactors," paper presented at the 4th Symposium on Space Nuclear Power Systems, Albuquerque, NM, January 12-16, 1987.

K.F. Hansen, E.V. Depiante, P.J. Laughton, J.E. Meyer, and A.F. Henry, (Nuclear Engineering, MIT), L.H. Mweene, (Electrical Engineering Computer Science Energy Laboratory, MIT), "Parity Simulation: An Electronic Approach to Simple Flow Systems," Computers in Mechanical Engineering, pp. 25-33, January 1987.

A.F.V. Dias, "Systematic Derivation, From 3-D Nodal Equations, of Simpler Models for Describing Reactor Transients," Ph.D. Thesis, Nuclear Engineering Department, MIT, May 1987.

E.J. Ashburner, "Real Time Solutions to the Point Kinetics Equations," S.M. Thesis, Nuclear Engineering Department, MIT, August 1986.

W.H.G. Francis, "A Systematic Treatment of Earlier Nodal Methods Using the Analytic Nodal Method," Ph.D. Thesis, Nuclear Engineering Department, MIT, May 1986.

3.1.3 LWR and LMR Fuel Management and Fuel Cycle

Because of declining subject enrollment, 22.35 Nuclear Fuel Management, will in the future be offered only every other year. Research is also at a reduced level. On the positive side, 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 accepted for publication by the ANS.

Recent LWR fuel management research has focused on the development of simple algorithms and strategies for the optimization of core reload assembly arrangements. In the LWR fuel cycle area, assessments of the prospects for reprocessing confirmed that it is unattractive under present economic and technological conditions, but might become interesting if fuel can be driven to ultra-high burnup ($\cong 70,000$ MWD/MT), because of the higher residual fissile content of the spent fuel. An energy analysis and environmental impact assessment of uranium recovery from seawater showed that the major

impediment for this technology lies in high product costs compared to current terrestrial ores.

An independent assessment of ANL's Integral Fast Reactor (IFR) fuel cycle for LMR's and its economics, was also carried out. It was found that this pyrometallurgical/electrochemical approach to reprocessing and recycle is indeed attractive if its projected system construction and operating costs can be realized. In the R & D area, the major uncertainty identified was the cost of the program required to qualify its unique waste forms for repository acceptance. This may be facilitated if the potential of the IFR scheme for actinide recycle/transmutation can be exploited. Another unresolved issue is the source and cost of the fissile inventory for initial startup of an IFR (or other type) LMR; our evaluation indicated that this could make ultra-long-life cores (15-30 years) economically less attractive than concepts refueled every 1-2 years.

Investigators: Professors. M.J. Driscoll, R.K. Lester; Dr. M. Miller; Messrs. G. Abu-Zaied, K. Elmediouri, V.E. Pareto, E.L. Taylor, R.W. Fieldhack, D.J. Merzke, Y.F. Khalil, W.A. Stewart.

Support: Primarily internal; \$25,000 from ANL during 1986.

Related Academic Subjects:

22.212 Nuclear Reactor Physics II
22.213 Nuclear Reactor Physics III
22.35 Nuclear Fuel Management

Recent References:

G. Abu-Zaied, "Control of PWRs Using Moderator Displacement and Fuel Assembly Reconstitution," Sc.D. Thesis, Nuclear Engineering Department, MIT, December 1985.

R.W. Fieldhack, "The Fuel Cycle Economics of PWR Extended Burnup," S.M. Thesis, Nuclear Engineering Department, MIT, December 1985.

K. Elmediouri, "Development and Evaluation of Algorithms for PWR Fuel Assembly Shuffling," Nuclear Engineer's Thesis, Nuclear Engineering Department, MIT, July 1987.

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

V.E. Pareto, "Reprocessing as an Alternative to Storage of Spent Nuclear Fuel," Ph.D. Thesis, Nuclear Engineering Department, MIT, June 1986.

D.J. Merzke, "Net Energy and Environmental Impact Analysis for the Recovery of Uranium from Seawater," S.M. Thesis, Nuclear Engineering Department, MIT, May 1987.

Y.F. Khalil, W.A. Stewart, and M.J. Driscoll, "Waste Disposal Aspects of the IFR Concept," MITNPI-TR-010, April 1987.

E.L. Taylor, "A Comparative Analysis of LMR and LWR Fuel Cycle Economics," Nuclear Engineer's Thesis, Nuclear Engineering Department, MIT, May 1987.

3.2 Reactor Engineering

Because of the important and the world wide 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.

3.2.1 Subjects of Instruction

A total of eighteen subjects of instruction are offered under the category 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 U.S. 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.

22.05: Introduction to Engineering Economics, introduces methods used by engineers for the economic analyses of alternatives. Topics covered include time-value-of-money mechanics; present worth and rate-of-return methodology; dealing with depreciation and taxes, inflation, and escalation; levelized cost; replacement and retirement problems. Also, component cost modeling, economy-of-scale and learning-curve effects, cost-risk-benefit analysis, insurance, and other probabilistic application are presented.

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 deal 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; 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 five other engineering departments (Civil, Mechanical, Materials, Ocean, and Aero/Astro) 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 both 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.

22.341: 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. 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.

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.

22.36J: Two-Phase Flow and Boiling 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.

22.37: Environmental Impacts of Electricity, 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.

22.38: 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 of safety analyses performed in nuclear and non-nuclear areas.

22.43: Advanced Numerical Methods in Engineering Analysis, covers advanced computational methods used in analysis of nuclear reactor engineering problem studies. Emphasizes the solution of multi-dimensional problems and non-linear equations using modern iterative techniques. Topics include finite difference and finite elements formulations with applications to incompressible and compressible flows. Introduction to numerical turbulence modeling. Additional special topics covered depending on the interests of the class.

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, take various choices from the advanced engineering subjects.

3.2.2 Flow Distribution and Heat Convection in Rod Bundles

An experimental and analytical program has been continuing at MIT on investigation of flow distribution and heat convection mechanisms in bare and wire-wrapped bundles. The effort in this program has been split among the three major flow and heat transfer regimes: forced convection, mixed convection and flow recirculation.

Work has been completed on the forced convection area and emphasis has been placed on the mixed convection and flow recirculation areas. In the mixed convection area analytical and numerical studies were made concerning the effect of buoyancy on fully-developed friction factors and Nusselt numbers for mixed convection flow through geometries exhibiting azimuthal symmetry and also for geometries associated with bare rod bundles. It was found that buoyancy effects could drastically alter the fluid velocity profile, rendering forced convection analyses inaccurate for mixed convection flows. A modified friction factor was developed for application in lumped parameter codes where only the bulk-averaged temperature is known for each node. The behavior of the modified friction factor as a function of the Gr_q/Re parameter was found to be significantly different from that of the conventional friction factor. For the rod bundle analysis, cell-averaged friction factors and Nusselt numbers were developed for geometries that correspond exactly to the conventional definition of interior and edge subchannels. The results can therefore be directly used in a subchannel code. Finally, the analyses are compared to experimental data, where available. The modified friction factor predicted the data for the heated circular tube with upflow better than the conventional friction factor since bulk-averaged properties were used to calculate the friction pressure drop in the experiment.

Attention was also directed at developing a predictive theory for the single bundle frictional pressure drop characteristics under decay power conditions. The key phenomena modeled were the global and local flow re-distribution due to buoyancy for a wide spectrum of radial power profiles and for the geometric arrangements of practical design and analysis interest. A correlating procedure has been proposed to assess the local, global and skew buoyancy effects. The bundle mixed convection friction factor correlation has been formulated as the product of the relevant bundle buoyancy multipliers and the corresponding isothermal bundle friction factors. The effects of interacting subchannel flows, developing mixed convective flow, wire wrapping and transition from laminar regime have been included. The predicting correlations have been validated against the experimental data from the MIT 19 rod bare and wire-wrapped bundles and against the literature data.

Finally, in the flow recirculation area, emphasis has been placed on improving our understanding of the causes of flow recirculation, the phenomenology (or topology) of the recirculation flow patterns and the stability of this regime (stable, steady but unstable, periodic, unsteady). In particular, under sufficiently low flow conditions, flow recirculation, which may cause undesirable temperature excursions, is more likely to occur in geometries with large power skews. In order to assess this possibility of temperature excursion, experimental temperature measurements and computer simulations were performed on fuel and blanket rod arrays.

The results of this study permitted the following conclusions to be drawn regarding flow recirculation:

- (a) The recirculation flow pattern and temperature distribution are primarily determined by the key parameter $Gr_{\Delta t_B}^2/Re$ and boundary conditions; (b)

Flow recirculation around a heat source is an intrinsically unstable condition. Therefore, steady recirculation flow under this condition is impossible. It can be established only if internal or external heat sinks exist; (c) Under low flowrate conditions, recirculation characteristics are not sensitive to the wrapping wire effects such as friction drag, swirl flow, and conduction shape factor as the results from COMMIX-1A for steady state and COBRA-WC for transient calculations indicate. Rather, the amount of heat loss plays the dominant role in determining the recirculation flow pattern; (d) Since the coolant temperature exhibits self-limiting regulation behavior, blanket assemblies overheating will not occur under steady state recirculation conditions.

Investigators: Professors N.E. Todreas, W.M. Rohsenow (Mechanical Engineering); Messrs. V. Iannello, T.-T. Huang, and K. Suh.

Support: Power Reactor Development Corporation (Japan), Westinghouse and General Electric

Related Academic Subjects:

- 22.312 Engineering of Nuclear Reactors
- 22.313 Advanced Engineering of Nuclear Reactors

Recent References

V. Iannello, K.Y. Suh, and N. Todreas, "Mixed Convection Friction Factors in Flow Channels," Topical Report, PNC/MIT-20TR and GE/MIT-2TR, December 1986.

K.Y. Suh, N. Todreas, and W. Rohsenow, "Mixed Convective Low Flow Pressure Drop in Vertical Rod Assemblies - Part I: Predictive Model and Design Correlation; Part II: Experimental Validation," Paper prepared for Symposium on Natural Circulation, ASME Meeting, Boston, MA, December 1987.

3.2.3 Mixed Convection in Multiple Parallel Channels Connected Only at Plena

Liquid metal reactor (LMR) systems are currently being investigated to evaluate their behavior under conditions of decay heat removal. Under these conditions, mixed convection exists through the core since the flow rates are low and thus the buoyancy term in the momentum equation is significant. The energy and momentum equations must therefore be solved in a coupled manner. In current LMR designs, assemblies are enclosed and thus the vessel can be modeled as a system of parallel channels connected only at the top and bottom plena.

Under forced convection conditions, the interassembly flow distribution is controlled by the orificing scheme. As the flow regime in the assemblies change from forced to mixed convection, the flow distribution will change. In general, assemblies with higher power would be expected to draw more flow because of the greater temperature rise and the associated density reduction. If the flow entering and leaving the vessel is very low, it is possible that the flow in the low power assemblies will either stagnate or reverse direction, potentially leading to high clad and/or coolant temperatures. In order to evaluate safety margins for core cooling, accurate flow distribution models are necessary.

Analytical, numerical, and experimental studies were made regarding the effect of buoyancy on the thermal hydraulic behavior of a parallel channel system. For such conditions, the velocity and temperature fields are distorted, rendering forced convection analyses inaccurate. The buoyancy will cause a redistribution of flow between and within channels; multi-dimensional recirculating flows may also develop.

A one-dimensional time independent model was developed to predict the buoyancy-induced flow redistribution between channels and was incorporated into a small code. The code was used to predict the behavior of a Liquid Metal Fast Breeder Reactor (LMFBR) core during natural circulation of the primary sodium loop. The analysis predicts that the temperature rise in the hot channel is reduced by 31% due to the flow redistribution.

A small, three-channel experiment was conducted. This apparatus was used to study the redistribution; the stability of mixed convection in parallel channels; the conditions leading to flow stagnation in a heated channel, intra-channel flow recirculation patterns during flow stagnation; flow recirculation patterns at the channel exit; and the effect of flow orificing on peak channel temperatures. To date, based on these experiments the onset of a recirculating flow at the exit of a heated channel was related to the channel exit-upper plenum temperature difference and channel flowrate using an annular channel test section. A correlation was developed to predict this recirculation onset condition. In addition, a qualitative study was made of the manner in which a heated channel reverses from upflow to downflow using injected dye to visualize the flow field.

Investigators: Professor N. Todreas; Mr. V. Iannello

Support: General Electric

Related Academic Subjects

- 22.312 Engineering of Nuclear Reactors
- 22.313 Advanced Engineering of Nuclear Reactors

Recent References

V. Iannello, "Mixed Convection in Vertical Parallel Channels Connected at Upper and Lower Plena," Ph.D. Thesis, Nuclear Engineering Department, MIT, February 1986.

V. Iannello and N. Todreas, "Mixed Convection in Parallel Channels with Application to the Liquid Metal Reactor Concept," paper presented at the National Heat Transfer Conference, Pittsburgh, PA, August 1987.

3.2.4 Natural Circulation for Decay Heat Removal

Nearly all of the advanced reactor designs under study in the U.S. rely upon rejection of decay heat to ambient air by natural convection as an ultimate resort, to achieve inherent, passive safety. LMR designs (SAFR, PRISM) use this approach for guard vessel cooling, and the latter also for heat removal from the steam generator shell; the small modular high-temperature gas-cooled reactor (MHTGR) now has natural convection, air-cooled panels in the annular space around its vessel; and small PWR designs rely upon natural convection cooling of the containment under severe post-accident conditions.

The department has focused on this generic technology as an important application and extension of its traditional fission engineering expertise in the thermal-hydraulic field, involving as it does, the coupling of all three modes of heat transfer—conduction, convection, and radiation—at the interface between free and forced convection near the transition between laminar and turbulent flow.

In a series of three thesis projects, a numerical model, embodied in a computer program, has been developed to analyze the performance of such systems for LMR applications, and limiting cases have been verified against classical analytical/experimental results. A sound foundation for continuing work in this area has been established, including formal liaison with ANL, where a full-scale experimental mockup has recently gone into operation. Extension of our work to HTGR and LWR applications is also being pursued.

Investigators: Professors. M.J. Driscoll, A.L. Schor, N.E. Todreas; Messrs. M.S. Boehle, D.A. Bushko, G. Fu, E.L. Taylor.

Support: DOE, via Westinghouse Advanced Energy Systems, ORNL, Rockwell International; at a total of approximately \$60,000/year.

Related Academic Subjects:

- 22.313 Advanced Engineering of Nuclear Reactors
- 22.43 Advanced Numerical Methods in Engineering Analysis

Recent References:

M.S. Boehle, "An Improved Method for the Computation of Passive Heat Removal for LMRs," S.M. Thesis, Nuclear Engineering Department, MIT, January 1987.

D.A. Bushko, "A Computational Model of Natural Convection Air Cooling for Nuclear Reactors," S.M. Thesis, Nuclear Engineering Department, MIT, May 1987.

3.2.5 Advanced Computational Methods for Single- and Two-Phase Flows

There is a continuous demand for increasingly more powerful, computer-based simulation capabilities for reactor system analysis. The objective of this research program is the development of advanced numerical methods and their application to the thermal hydraulic analysis of various systems and components. A number of activities have been initiated or continued during the past year.

1) Stable numerical methods for one-dimensional two-phase flow

Most computer codes for nuclear reactor analysis approximate the partial differential equations describing two-phase flow by a set of finite difference equations on a staggered mesh. The method used to difference the equations strongly affects the numerical stability of the computational algorithm. In particular, the time level chosen for the set of dependent variables govern the way that any numerical disturbance (e.g., round-off error) propagates in space and time within this numerical system. Explicit numerical schemes suffer from a time step restriction imposed by sonic propagation. The very high sound speed in pure liquid or nonequilibrium, two-phase mixtures limits the maximum time step allowed for numerical stability to the rate at which a pressure pulse can transit a grid cell (typically 10^{-6} to 10^{-5} sec). In using these schemes, the large number of time steps required for a calculation offsets the benefits of the relatively small amount of computation per step — especially for machines without array processing capability. At the other extreme, implicit schemes are generally unconditionally stable. Hence, the time step need only be controlled by the accuracy desired for the calculation. Unfortunately, implicit schemes require a relatively large amount of computation per time step, greatly reducing the savings of using larger steps.

A compromise between these extremes has led to the use of semi-implicit schemes in which only the terms governing phenomena with short transient times (e.g., sonic propagation) are treated implicitly.

Such schemes must use a time step limited by the shortest convective transport time across any mesh cell in the problem domain. The time steps used in analyzing two-phase flows with high velocities (e.g., sodium vapor under boiling conditions) are particularly sensitive to this restriction. Time steps limited to a few milliseconds can result from the small mesh spacings typically used to model the core region.

Although semi-implicit numerical schemes have been popular, the convective Courant condition leads to time steps that are frequently less than those required to preserve the accuracy of the calculation.

We have developed a numerical method for two-phase flow in which mass and energy convection are treated implicitly. Theoretical analysis and computational testing have suggested that the method is unconditionally stable for subsonic flows. The method has been implemented in an experimental, one-dimensional version of the sodium boiling code THERMIT-4E. A slightly larger amount of computation per time step is required due to the evaluation or

a more complex Jacobian matrix, but larger (and hence fewer) time steps are possible, giving a substantial net reduction in computational time.

We are applying the new scheme to various transients and plan to expand the ideas to multidimensional configurations.

2) Advanced Power Plant Condenser Modeling

The objective of this new project is the development of a best estimate two-dimensional, two-phase flow model for the simulation of power plant condensers. The model uses mixture mass, mixture energy and separate phasic momentum equations, being supplemented by a number of constitutive equations. Thermal equilibrium on the saturation line between coexisting phases is assumed. While not currently considered, the flow of non-condensable gas will be incorporated.

A computer code, THERMIT-4E for condensers, has been developed based on the existing code, THERMIT-4E. Using a semi-implicit scheme, THERMIT handles implicitly pressure pulse propagation and local effects characterized by short time constants, while dealing explicitly with convective transport associated with longer time constants. Major modifications have been made to the existing THERMIT to adapt it to power plant condensers: improvement of geometric representation capability for complicated problem domains including boundary conditions, extensive change of the constitutive equations and replacement of equations of state.

Two series of experimental simulations have yielded very encouraging results. The first series of simulations indicated that the code runs adequately even under severe calculation conditions. The second series of simulations has been performed for comparison between the calculations results and existing experimental data which were taken in a staggered tube bundle for three flow directions, i.e., horizontal, downward and upward flow. The comparison showed reasonable agreement in general, especially for the horizontal and the downward flow. However, it also pointed out the possibility of refinement by further investigation of the constitutive equations with regards to interfacial and wall friction and the effects of inundation and vapor shear on the condensation heat transfer.

The current model lays the foundation for improved condenser design and performance monitoring.

3) Transient heat pipe analysis

The resurrection of the space nuclear power program has refocused interest on the development of high-temperature heat pipes. Space electric power systems are often limited by the mass of the waste heat rejection component. Utilizing heat pipes for the transfer of heat from the power conversion system to the radiator has several significant advantages over conventional pump loops:

- o minimization of fluid mass due to low liquid inventory
- o minimization of radiator surface area due to the nearly isothermal heat transport characteristic of a two-phase system

- o passive heat removal capability
- o greater system reliability against a loss-of-fluid-accident due to micrometeoroid penetration.

At present, the analysis techniques for predicting heat pipe performance are steady-state, one-dimensional, semi-analytical treatments. These models are further limited to consideration of uniform axial and azimuthal heat addition and rejection. For space radiator applications the uniform heat removal assumption is inappropriate due to the interaction of the radiator panel with the heat pipe. In addition, the transient response of the heat pipe radiator is important. Some of the expected transients include:

- o reactor power change
- o acceleration-induced body forces (evasive maneuvers)
- o startup and shutdown

To address these issues, this project initiated the development of a three-dimensional transient finite-difference computer code for heat pipe analysis.

Key technical issues to be resolved are:

- o Treatment of the surface tension term in the two-fluid equations. A two-pressure model may be needed.
- o Courant time step limit: to resolve the sonic flow limit a reasonably sized axial mesh will be needed with the consequence of small explicit time steps. To overcome this and allow for the computation of transients in a moderate amount of computer time, an effort will be made to solve the two-fluid equations implicitly.

The resulting computer code will constitute a major advancement in the currently available analytical capabilities for heat pipe modeling.

4) Simulation Software Development For Nuclear Engineering Education

In June 1985, we began the initial development phase of a project to implement, adapt and expand an existing simulation package - DSNP (Dynamic Simulator for Nuclear Power Plants) as an aid to teaching courses in Nuclear Engineering. The work is being sponsored within the Institute-wide ATHENA project, whose aim is the study of the use of computers in education. In our field, there is a growing need to use numerical simulation to demonstrate basic engineering principles in the context of complex nuclear reactor systems.

The main objectives of this project are:

- a) implementation of the DSNP package in the ATHENA computing environment, achieving full compatibility with the UNIX operation system.
- b) development of an interactive capability, which will greatly facilitate classroom use.

- c) development of graphics support for display of simulation results.
- d) tailoring the DSNP package to the educational requirements and needs of our department.
- e) assessment of the DSNP generic educational capabilities, formulation of curriculum development projects and identification of future code development needs.

It is our belief that the ability to rapidly conduct sensitivity studies and demonstrate intricate and often subtle functional relationships will constitute a much appreciated educational aid.

Investigators: Professor A.L. Schor; Messrs S. Free, M. Houts, J. Kelly, Y. Fujitani.

Support: Hitachi Corporation, Battelle Northwest Laboratory, MIT Project Athena.

Related Academic Subjects:

22.36J	Two-Phase Flow and boiling heat transfer
22.42	Numerical Methods in Engineering Analysis
22.43	Advanced Numerical Methods in Engineering Analysis

Recent References:

H. Ninokota and A.L. Schor, "An Unconditionally Stable Numerical Scheme for Sodium Boiling Simulation," Proceedings of the International Conference on Computational Mechanics, Tokyo, Japan, May 1986.

J. Sasson and A.L. Schor, "Nonlinear Effects in Two-Phase Flow Numerical Modeling," Proceedings of the 12-th Meeting of the Liquid Metal Boiling Working Group, Ispra, Italy, October 1986.

Y. Fujitani and A.L. Schor, "Development of a Two Dimensional, Two-phase Flow Model for Power Plant Condensers," MITNE-275, March 1987.

3.2.6 Parity Simulation of Nuclear Plant Dynamics

This project is an attempt to develop electronic simulants of components of a nuclear plant system. In recent years faculty in the Electrical Engineering Department have developed integrated circuits that can be used to simulate the current-voltage characteristics of a large variety of electronic components. These integrated circuits are called "elements of a simulator". It is possible to combine elements to build a synthetic circuit that behaves as a "breadboard" model of a circuit design. Because the simulator preserves parity between circuit components and simulator elements the technique is called "parity simulation".

It is well-known that electric analogs to a variety of physical problems can be built. However, for most cases the electronic analog must have

nonlinear characteristic. With the parity simulator approach it is quite easy to design integrated circuits with nonlinear behavior.

What is done in this project is to develop integrated circuits that satisfy conservation laws appropriate to a given flow problem. For example, circuits are designed that represent conservation of mass, momentum, and energy in a pipe. Each component of the flow system has a single simulator element to represent the component. Flow systems can then be modeled by connecting together simulator elements.

In progress to date it has been possible to model compressible and incompressible fluid flow in complex networks. In addition models of reactor transients in the point kinetics model have been successfully achieved.

Investigators: Professors K.F. Hansen, A.F. Henry, J.E. Meyer, and M.W. Golay; Messrs. E. Depiante and P. Laughton.

Support: Department of Energy

Related Academic Subjects:

- 22.312 Engineering of Nuclear Reactors
- 22.211 Nuclear Reactor Physics I
- 22.212 Nuclear Reactor Physics II

Recent References:

K.F. Hansen and E. Depiante, "Parity Simulation for Nuclear Plant Analysis," Trans. Amer. Nuc. Soc., Vol. 53, November 1986.

K.F. Hansen, E.V. Depiante, P.J. Laughton, J.E. Meyer, A.F. Henry, and L.H. Mweene, "Parity Simulation: An Electronic Approach to Simple Flow Systems," Comp. In. Mech. Eng., Vol. 5, #4, January 1987.

E.V. Depiante and J.E. Meyer, "Parity Simulation of Two-Phase Thermal-Hydraulics in Plant Components," Trans. Amer. Nuc. Soc., Vol. 54, June 1987.

3.2.7 Thermal Phenomena in Severe LWR Accidents

As a result of a sequence of events at TMI, class 9 accidents, in which the events are of low probability, gained increased attention in LWR safety analysis. In one scenario, the loss of coolant may result in partial uncovering of the core and subsequent heat-up and damage of fuel elements. The initial two years of this research program is aimed at defining the cooling potential for a degraded LWR core. Subsequently, the focus has been on determining the containment thermal response to vessel melt-through, under severe accident conditions, and the fission product release potential during core-concrete interaction.

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.

Several processes, including melt freezing, liquid/liquid interfacial heat transfer, layer mixing, and droplet entrainment, involved in the analysis of the core/concrete interaction were investigated by scoping simulant experiments. Water and cyclohexane were used to form a multi-layer pool in a test unit designed with cooling capability and air injection through a porous plate. In the freezing tests with gas velocities in the range of 5 to 126 mm/s, a stable solidified layer was formed across the bubble agitated horizontal liquid/solid interface. The interfacial heat transfer between the water and cyclohexane layer was measured under different air injection rates. The experimental data showed good agreement with both the modified Szekely model and the Lee and Kazimi model. In the layer mixing tests, it was found that the water and cyclohexane with density ratio of 0.78 were entirely mixed under a modest superficial gas velocity of 50 mm/s. The amount of liquid droplet entrainment measured in the simulant experiments agreed qualitatively with the Kataoka and Ishii model.

The heat transfer from the corium to concrete will affect the cooling rate of the corium and the amount of gas generated by concrete decomposition, which will, in turn, affect the pressurization rate of the containment building and the degree to which fission products could be released from the melt. A semiempirical correlation was developed to describe the heat transfer at the horizontal core/concrete interface. The model assumes periodic contact between corium and concrete at low gas evolution rates, and separation by a stable gas film at high gas generation rates. The proposed model has been incorporated into an existing computer code, CORCON/MOD2, for integral analysis of the corium/concrete interactions. Good agreement was found when using this model to analyze the German BETA experiments involving several hundred kg oxidic and metallic melt with sustained internal heating by induction.

The impact of the downward heat transfer model on the calculations of concrete erosion, gas generation, and ex-vessel aerosol release was studied using CORCON/MIT (revised version of CORCON/MOD2) and VANESA. It was found that at high initial melt temperatures, the fission product release calculated by the periodic contact model was three to five times higher than the original gas film model used in the CORCON code. At low initial melt temperatures, with the formation of an initial bottom crust, the various heat transfer models did not lead to significant differences in the fission product release. Sensitivity studies involving variations in several parameters, such as initial melt temperature, concrete properties, amount of unoxidized zirconium, amount of melt, decay heat, and layering potential of melt constituents, were also performed. The initial debris temperature was found to be the most significant parameter in the calculation. The release fraction of the non-volatile fission products such as lanthanum was the most sensitive result of the parameter variations.

Investigators: Professors M. Kazimi, J. Meyer, Mr. L.S. Kao and Ms. Bhavia Lal.

Support: Electric Power Research Institute.

Related Academic Subjects:

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

Recent References:

B.R. Sehgal, M.S. Kazimi and M.L. Corradini, "Current Status of Molten Core-Concrete Interactions and Fission Product Release," Invited paper, Proc 2nd ANS Int. Top. Mtg. on Nuclear Power Plant Thermal Hydraulics, Tokyo, April 1986.

L.S. Kao, and M.S. Kazimi, "The Impact of Heat Transfer Models on Core/Concrete Interaction," Proc. CSNI Specialist Meeting on Core Debris - Concrete Interactions, EPRI NP-5054-SR, February 1987.

L.S. Kao and M.S. Kazimi, "Thermalhydraulics of Core/Concrete Interaction in Severe LWR Accidents," MITNE-276, June 1987.

L.S. Kao and M.S. Kazimi, "A Heat Transfer Model for Core/Concrete Interaction," presented at 24th National Heat Transfer Meeting, August 1987.

3.2.8 Accident Scenarios Analysis in Risk Assessment

This is a new project aimed at upgrading probabilistic risk assessment (PRA) tools and techniques for modeling accident scenarios. The approach used in current studies is essentially that developed in WASH-1400; scenarios are modeled as sequences of safety system successes and failures progressing from an initiating event to a final plant damage state. Event trees are used to organize and quantify the sequences.

The event tree is well-suited for treating scenarios where the dependencies between failure events are unidirectional (i.e., when there are no loops) and when the dependencies are binary in nature (e.g., when components are shared between systems). It is less well-suited for scenarios in which the physical behavior (e.g., pressurizer level response) of the system is a major factor in determining system success or failure, as was the case in the TMI-2 accident. To address this fault, we are developing both models which will supplant event trees for these types of scenarios and guidelines for determining when the new models should be applied. Candidate approaches include expanded event trees which explicitly include physical variables, digraphs, and simulation models.

Even for scenarios where the overall event tree methodology is adequate, recent PRAs indicate difficulties in the application of this methodology. These studies involve extremely large, detailed trees, whose sequences can number in the billions. To aid the analyst in splitting the single tree into smaller, more easily handled modules, and in relinking these modules we are developing an interactive computer program to construct and manipulate event tree modules. This program, written in PROLOG, will use user-supplied rules regarding dependencies between event tree top events to reduce the number of explicitly treated sequences to as small as possible. A major advantage of using

PROLOG over another more conventional language, is that the data and assumptions underlying the results can be directly queried without additional programming. Thus, this application will be useful for both performing and documenting a PRA analysis (the latter is of considerable concern to intended users); it also provides us with a case study for the use of Artificial Intelligence tools and techniques in PRA, a subject of growing interest in the PRA field.

Investigators: Professors N. Siu and N. Rasmussen; Messrs. K. Doremus and S. Nguyen.

Support: NRC (proposal pending).

Related Academic Subjects:

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

3.2.9 Application of Time-Dependent Unavailability Analysis to Nuclear Plant Life Extension

The FRANTIC computer code is being modified to deal with the long-term wearout of certain nuclear plant systems. In this work the code is being adapted to handle a variety of functions of time-dependent failure rates being observed in various types of system components. Using data for component failure from the older nuclear plants as input, the code will be developed to predict system failure rates. It is hoped that such predictions will be an aid to regulators in deciding the safe operational life of a system.

A second effort in this same general area is work on the propagation of uncertainties in the above calculations. Because, the actual data on time-dependent failure rates is limited, there will be considerable uncertainty in the predicted unavailability. Work is underway to develop analytical techniques to propagate these uncertainties in the data.

The goal of this work is to help regulators determine just how far into the future a given system can be qualified for safe operation based upon the uncertainty in the currently available data.

Investigators: Professors N.C. Rasmussen, N. Siu, Dr. W. Vesely, Ms. V. Dimitrijevic and Ms. S. Cooper.

Support: Brookhaven National Laboratory and EG & G, Idaho.

Related Academic Subjects:

- 22.40 Advanced Reliability Analysis and Risk Assessment.

3.3 Nuclear Materials and Radiation Effects

The nuclear materials program has four 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, 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 conservation, energy transmission, and environmental technology as related to power production.

3.3.1 Subjects of Instruction

In the area of nuclear materials and radiation effects, 22.070J, Materials for Nuclear Applications, and 22.071J, Physical Metallurgy Principles for Engineers, are available for undergraduates. Graduate students can select from other subjects described below.

22.070J: Material for Nuclear Applications, is an introductory subject for students who are not specializing in nuclear materials. 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.

22.071J: Physical Metallurgy Principles for Engineers, covers the following topics: crystallography and microstructure of engineering materials; thermodynamics of alloys; structural theory of metallic phases. Rate processes in metals; solidification, solid state diffusion, oxidation, and phase transformation. Defect properties; point defects, dislocations and radiation damage. Mechanical properties; plastic deformation, work hardening, strengthening mechanisms and fracture. Recovery and recrystallization. Emphasis on structure-properties relationships, their physical interpretation and quantification. The subject meets concurrently with 22.71J, but assignments differ.

22.70J: Materials for Nuclear Applications, is the introductory subject for graduate students who are not specializing in nuclear materials. This subject meets concurrently with 22.070J, but assignments differ.

22.71J: Physical Metallurgy Principles for Engineers, is the introductory course in this sequence of study and is intended for graduate students who did their undergraduate work in engineering and science fields which did not provide formal instruction in metallurgy or materials science. This subject meets concurrently with 22.071J, but assignments differ. This and subsequent courses are conducted jointly between the Department of Nuclear Engineering and the Department of Materials Science and Engineering.

22.72J: Nuclear Fuels, covers topics such as the behavior of nuclear fuels and fuel element cladding materials in reactor cores. Experimental observations; phenomenological and theoretical modeling of radiation; and thermal-induced effects such as fuel and cladding swelling, fission gas release, and radiation-induced creep. Fuel design, performance modeling, and reliability analysis using state-of-the-art computer codes. Recent developments in advanced nuclear and fusion related core materials are discussed.

22.73J: Radiation Effects in Crystalline Solids, is designed for graduate students of nuclear engineering, materials science and physics desiring a detailed background in the physics of radiation damage and the characteristics of crystal defects and defect interactions. Unified treatment based on governing principles in defect structures, thermodynamics and kinetics of equilibrium and nonequilibrium systems. Discusses phenomena of radiation effects in metals and nonmetals used in fission reactors, fusion reactors, nuclear waste encapsulation, and ion beam technology. Topics include defect generation, damage evolution, radiation enhanced and induced rate processes, radiation effects on mechanical and physical properties.

3.3.2 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.

Investigators: Professor R. Ballinger; Messrs. J. Prybylowski, I. Hwang, and Ms. C.K. Elliott.

Support: Electric Power Research Institute, Department of Energy.

Related Academic Subjects:

22.71J Physical Metallurgy Principles for Engineers
 3.54 Corrosion
 3.39 Mechanical Behavior of Materials

Recent References:

J.W. Prybylowski, R.G. Ballinger, "The Influence of Microstructure on Environmentally Assisted Cracking of Alloy 718," Corrosion, 43, No.2, 1987.

K. Hosoya, R. Ballinger, J. Prybylowski, I.S. Hwang, "The Role of Microstructure in Environmentally Assisted Cracking of Ni-Base Alloys," Corrosion 87, No. 101, 1987.

3.3.3 Modelling of Crack and Crevice Chemistry in High Temperature Aqueous Systems

A program is underway to develop predictive models for the evolution of the chemistry in cracks and crevices in high temperature aqueous systems. The program is part of a joint program with the General Electric Co. to relate environmental factors to stress corrosion cracking susceptibility, including the effects of radiation.

Investigators: Professor R.G. Ballinger; Mr. S. Simonson and Ms. M. Psaila.

Support: Electric Power Research Institute.

Related Academic Subjects:

22.71J Physical Metallurgy Principles for Engineers
 3.54 Corrosion

Recent References:

M. Psaila, "Crevice Modeling for High Temperature Aqueous Systems," S.M. Thesis, Nuclear Engineering Department, MIT, June 1986.

3.3.4 Alloy Development for Superconducting Magnet Sheathing Materials

A program is underway to develop optimized alloys for use as superconducting magnet sheathing. Structure/property relationships are being explored at temperatures as low as 4.2⁰K as a function of alloy chemistry and thermal processing history.

Investigators: Professor R.G. Ballinger; Messrs. M. Morra, J. Martin and F. Wong.

Support: Department of Energy.

Related Academic Subjects:

22.71J Physical Metallurgy Principles for Engineers
 3.39 Mechanical Behavior of Materials

Recent References:

J.L. Martin, R.G. Ballinger, M.M. Morra, M.O. Hoenig, M.M. Steeves, "Tensile Fatigue and Fracture Toughness: Properties of a New Low Coefficient of Expansion Cryogenic Structural Alloy, Incoloy 9XA," International Cryogenic Materials Conference and Cryogenic Engineering Conference, St. Charles IL, June 14-18, 1987.

M.M. Morra, R.G. Ballinger, J.L. Martin, M.O. Hoenig, M.M. Steeves, "Incoloy 9XA, a New Low Coefficient of Thermal Expansion Sheathing Alloy for Use MICCS Magnets," 1987 International Cryogenic Materials Conference and Cryogenic Engineering Conference, St. Charles, IL, June 14-18, 1987.

J. Martin, "Cryogenic Mechanical Testing of Superconducting Magnet Structural Materials," S.M. Thesis, Nuclear Engineering Department, MIT, June 1987

3.3.5 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 components. Recently a research proposal has been prepared for the research effort designed to develop a basic understanding of IASCC. This research program would include in-pile

testing using the MITR-II. The proposal was requested by the Tokyo Electric Power Co. (TEPCO).

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 is being sought from TEPCO.

Related Academic Subjects:

- 22.71J Physical Metallurgy Principles for Engineers
- 22.75J Radiation Effects in Reactor Structural Materials

3.3.6 Radiative 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 has initiated 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 PWR's and BWR's. These facilities are needed 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, D.D. Lanning and R.G. Ballinger; Drs. J.A. Bernard and G. Kohse.

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

Related Academic Subjects:

- 22.71J Physical Metallurgy Principles for Engineers
- 22.75J Radiation Effects in Reactor Structural Materials
- 22.39 Nuclear Reactor Operations and Safety
- 22.59 Principles of Radiation Measurement and Protection

Recent References:

M.R. Ames, M.J. Driscoll, O.K. Harling, G.E. Kohse, K.S. Kwok, D.D. Lanning and J.H. Wicks, "Safety Evaluation Report for the PWR Coolant Chemistry Loop (PCCL)," Report No. MITNRL-020, February 13, 1987.

K. Burkholder, "An In-Pile Loop for Corrosion Transport Studies in a PWR," S.M. Thesis, Nuclear Engineering Department, MIT, June 1985.

M.J. Driscoll, W. Luangdilok, I. Kato and C. Oliveira, "Preliminary Conceptual Design of a General Purpose In-Pile Loop for Simulation of BWR CoolChemistry," Report No. MITNRL-018, February 1987.

M.J. Driscoll, and A.M. Morillon, "Prospectus for PWR Coolant Chemistry Control Experiments to be Carried Out on the PCCL Facility at MIT," Report No. MITNRL-021, February 1987.

J.H. Wicks, Jr., "Design Construction and Testing of a In-Pile Loop for PWR Simulation," S.M. Thesis, Nuclear Engineering Department, MIT, June 1987.

3.3.7 The Development of Advanced Primary First Wall Alloys

The severe environment of future fusion reactors is expected to drastically limit the lifetime of the first wall structures is currently available materials are used in reactor construction. In this major research effort a broad ranging interdisciplinary approach is being applied to the development of improved structural alloys for the first walls of fusion reactors. The approach used in this project includes:

1. a determination of the structural alloys requirements based on an analysis of fusion reactors design,
2. production of carefully chosen test lots of alloy by rapid solidification from the melt, austenitic and ferritic alloys of Fe and Cu alloys are currently being employed,
3. microstructural characterization of pre- and post-irradiation,
4. mechanical property testing of unirradiated materials and irradiated material,
5. modeling of mechanical behavior, and microstructural irradiation response,
6. design of new improved alloys, production and testing and analysis of results,
7. development of miniaturized mechanical property tests, potentially applicable to in-service monitoring of reactor pressure vessels.

Investigators: Professors O.K. Harling, N.J. Grant (Department of Materials Science and Engineering), and L.W. Hobbs (Department of Materials Science and Engineering); Drs. J. Megusar and G. Kohse; Messrs. T. Lee, M. Ames and M. Capano.

Support: U.S. Department of Energy, EPRI.

Related Academic Subjects:

- 22.612 Introduction to Plasma Physics II
- 22.73J Radiation Effects in Crystalline Solids
- 22.75J Radiation Effects in Reactor Structural Materials

Recent References:

- O.K. Harling, N.J. Grant, G. Kohse, M. Ames, T.-S. Lee and L.W. Hobbs, "Neutron Irradiation Scoping Study of Twenty-five Copper-base Materials," submitted to J. Mater. Res., March 1986.
- M.P. Manahan, A.E. Browning, A.S. Argon, and O.K. Harling, "Miniaturized Disk Bend Test Technique Development and Application," ASTM STP 888, pp. 17-49, 1986.
- G. Kohse, M. Ames and O.K. Harling, "Progress in Developing DBTT Determinations from Miniature Disk Bend Tests," J. Nucl. Mater., 141-143 pp. 531-537, 1986.
- T.-S. Lee, L.W. Hobbs, G. Kohse, M. Ames, O.K. Harling and N.J. Grant, "Microstructural Evolution and Swelling of High Strength, High Conductivity RS-PM Copper Alloys Irradiated to 14 dpa with Neutrons," J. Nucl. Mater., 141-143 pp. 179-183, 1986.
- M.A. Capano, L.W. Hobbs, G. Kohse, N.J. Grant and O.K. Harling, "Microstructural Characterization of PCA-Type Splat-Quenched Foils of Austenitic Stainless Steels Irradiated in the HFIR to 14 dpa, 750 appm He," submitted to J. Nucl. Mater., 1986.
- M. Ames, G. Kohse, T.-S. Lee, N.J. Grant and O.K. Harling, "Mechanical Property and Conductivity Changes in Several Copper Alloys after 13.5 dpa Neutron Irradiation," J. Nucl. Mater., 141-143 pp. 174-178, 1986.
- N.J. Grant, O.K. Harling, G. Kohse, J. Megusar and T.-S. Lee, "The Potential for Iron and Copper Based Rapidly Solidified Alloys as Fusion Reactor Materials," J. Nucl. Mater., 141-143 pp. 427-433, 1986.
- O.K. Harling and G. Kohse, "Development of a Miniaturized Test for Estimation of Ductile-to-Brittle Transition Temperature," Final Report on EPRI Contract No. RP2180-12, February 1986.
- O.K. Harling and G. Kohse, "Miniaturization of Specimens for Mechanical Testing," Rad. Eff., 101 pp. 115-129, 1986.
- N.J. Grant, O.K. Harling, L.W. Hobbs, G. Kohse, J. Megusar, M. Ames, M. Capano and T. Lee, "ADIP Research at MIT, A Status Report," MITNRL-014, September 1985.
- D.-S. Sohn, G. Kohse, D.M. Parks and O.K. Harling, "Yield Stress Determination by the MIT Miniaturized Disk Bend Test," submitted to Nucl. Tech., August 1985.

D.-S. Sohn, G. Kohse, D.M. Parks and O.K. Harling, "Yield Stress Determination by the MIT Miniaturized Disk Bend Test," 29th DAFS Quarterly Progress Report No. DOE/ER-0046/21, pp.50-54, May 1985.

3.3.8 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 Principles for Engineers
- 22.73J Radiation Effects in Crystalline Solids
- 3.40J Physical Metallurgy

3.3.9 Accelerated Life Testing in Support of Waste Package Life Prediction

A program is being conducted to develop methodology for life prediction of High Level Radioactive Waste (HLW) disposal canisters. Methodology is being developed to allow extrapolation of corrosion data to long time with minimum error to allow optimization of experimental test programs.

Investigators: Professors N.C. Rasmussen and R.G. Ballinger; Mr. A. Wolford.

Support: Battelle Columbus Laboratories, Department of Energy.

Related Academic Subjects:

- 3.54 Corrosion
- 22.40J Advanced Reliability Analysis and Risk Assessment

Recent References:

A. Wolford, "Uncertainty-Optimized Predictive Testing for a Nuclear Waste Container," Ph.D. Thesis, Nuclear Engineering Department, MIT, January 1987.

3.4 Nuclear Chemical Technology

Major developments have taken place in this area over the past two years in the form of a substantial research project on LWR coolant chemistry employing in-pile loops at the MIT Research Reactor. Radiation dose and corrosion reduction are the primary goals of this research, which received substantial funding by the Electric Power Research Institute and the Empire

State Electric Energy Research Corporation for a four-year program beginning July 1986. A proposal which would significantly expand this effort has also been submitted to the Tokyo Electric Power Co., with a projected starting date of April 1988.

Work is underway in three interrelated areas: simulation of the PWR primary coolant system, BWR coolant chemistry studies, and irradiation-assisted stress corrosion cracking (IASCC).

In the PWR area, an in-pile loop which simulates a unit flow channel (steam generator tube/intra-fuel-rod channel) on a 1/3 scale basis, has been constructed and subjected to out-of-pile performance testing. Its first use will be to evaluate strategies for the reduction of corrosion product activation, transport and deposition by optimization of coolant pH (adjustment of LiOH/H₃BO₃ ratio).

The BWR loop will use many of the same components as the PWR. Thermal-hydraulic feasibility tests on an out-of-pile breadboard model are currently being carried out (summer, 1987). Initial applications of this loop will be to study the fundamental effects of hydrogen addition on N-16 carryover, local coolant chemistry, and radionuclide deposition.

Work on IASCC is in the conceptual design phase. An in-pile autoclave which will permit testing stressed specimens under well-characterized radiation-induced coolant chemistries is being designed. It will be used to obtain an understanding of the IASCC phenomenon on a fundamental level. This work fits in very well with earlier and ongoing ex-pile experimental and theoretical work on SCC carried out under department auspices (see Section 3.3., Nuclear Material and Radiation Effects).

Investigators: Professors O.K. Harling, M.J. Driscoll, R.G. Ballinger; Drs. G.F. Kohse and A. Kitamoto (visitor, 1987), W.T. Lindsay, Jr. (consultant); Messrs. M. Ames, J.H. Wicks, W. Luangdilok, I. Kato, C. Oliveira; Mlles. A.M. Morillon, B. Lal.

Support: Electric Power Research Institute (EPRI) and Empire State Electric Energy Research Corporation (ESEERCO); plus seed money from utilities in the Electric Utility Program of the MIT Energy Laboratory. Total funding is approximately \$400,000/year.

Related Academic Subjects:

- 22.58 Principles and Practices of Radiation Measurement and Protection
- 22.71J Physical Metallurgy Principles for Engineers
- 22.75J Radiation Effects in Reactor Structural Materials

Recent References:

J.H. Wicks, "Design, Construction, and Testing of an In-Pile Loop for PWR Simulation," S.M. Thesis, Nuclear and Ocean Engineering Departments, MIT, May 1987.

A.M. Morillon, "Modelling of Corrosion Product Radionuclide Transport in a Simulated PWR Environment," S.M. Thesis, Nuclear Engineering Department, MIT, August 1987.

3.5 Quantum Thermodynamics

Research activity in the area of quantum thermodynamics is continuing under the supervision of Professors Elias Gyftopoulos of the Nuclear Engineering Department and Gian Paolo Beretta of the Mechanical Engineering Department.

3.5.1 Subjects of Instruction

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

22.571J: General Thermodynamics I, presents the foundations of thermodynamics in a general way, followed by the application of thermodynamic principles to energy conversion systems and industrial processes. First part: the first and second laws are introduced together with the definitions of work, energy, stable equilibrium, available work, entropy, thermodynamic potentials, and interactions (work, non-work, heat, mass transfer). Second part: thermodynamic analysis of stable equilibrium properties of materials, bulk flow, energy conversion processes, chemical equilibria, combustion, and industrial manufacturing processes.

22.572J: Quantum Thermodynamics, presents a nonstatistical unified quantum theory of mechanics and thermodynamics for all systems, including a single particle, and all states, including nonequilibrium, and 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.

3.5.2 Foundations of Quantum Thermodynamics

Professors Gyftopoulos and Beretta continued their research on the foundations of quantum thermodynamics. The emphasis of this research has been on the general equation of motion of quantum thermodynamics and mathematical forms that distinguish between quantal and nonquantal uncertainties. Significant progress was made.

We are currently investigating the criteria that must be satisfied by the expression for entropy and by equation of motion of quantum thermodynamics.

Investigators: Professors E. Gyftopoulos and G. P. Beretta (Mechanical Engineering Department).

Support: None.

Related Academic Subjects:

22.571J General Thermodynamics I
22.572J Quantum Thermodynamics

Recent References:

G.P. Beretta, E.P. Gyftopoulos, J.L. Park, and G.N. Hatsopoulos, "Quantum Thermodynamics: A New Equation of Motion for a Single Constituent of Matter," *Il Nuovo Cimento*, 82 B, 2, pp. 169-191, 1984.

G.P. Beretta, E.P. Gyftopoulos, and J.L. Park, "Quantum Thermodynamics: A New Equation of Motion for a General Quantum System," *Il Nuovo Cimento*, 87 B, 1, pp. 77-97, 1985.

3.6 Nuclear Power Plant Innovation Project

During the present hiatus in electric utility ordering of new nuclear power plants in the U.S., the attention of the reactor design community has focused on the next generation of nuclear power plant systems, and on establishing new priorities for advanced nuclear reactor research and development more generally.

In 1983 the Department undertook a preliminary study with the objectives of (1) assessing the possible role of nuclear power plant design innovations in a broader effort to restore the competitiveness of the U.S. nuclear energy option, (2) identifying the most promising avenues for further technological development, and (3) defining a role for MIT in the context of such efforts. Based on the results of this study, a major multi-year research program was initiated. The program consists of four principal elements or areas of study: the light water reactor innovation project; the modular high temperature gas reactor project; liquid metal reactor studies; and institutional and policy analysis. Each of these program elements are described in more detail in the following sections.

3.6.1 The Light Water Reactor (LWR) Innovation Project

The Light Water Reactor (LWR) Innovation Project is summarized in Table 1 where the important areas of activity are those of

- o New plant performance requirements
- o Conceptual design innovation
- o Independent technological advances

In Table 1 the specific projects which are currently underway in each area are listed. Our intention in each case is to have at least one effort in each area of emphasis. This is done in order to provide examples of good work in order to illustrate the benefits which can be obtained from each area of work. The purpose of such illustrations is to stimulate other researchers and organizations to think and work in directions similar to our own.

Projects which comprise the overall LWR Innovation Project

The following projects comprise the overall LWR Innovation Project:

- o Leak-before-break project
- o Functionally-oriented nuclear safety regulation

- Design simplification
- Human error in maintenance
- Human error in operations
- Use of horizontal steam generators
- Design of a small (e.g., 600 MWe) BWR

TABLE 1

LWR INNOVATION PROJECT
(Current Activities)

- Conceptual Design
 - GE – Small BWR Project
- Utilities Requirements for New Plants
 - Simplification
 - . Condensate/Feedwater Systems
 - Human Error
 - . Condensate/Feedwater System Control
 - . Pump Seal Maintenance
- Technological Advances
 - Safety Rationalization
 - . Leak-Before-Break
 - . Functionally-Oriented Regulation
 - Horizontal Steam Generator
 - Automatic Steam Generator Controller

1) Implementation of the Leak-Before-Break Concept in New Nuclear Power Stations

The possibility of consequential damage to safety-related systems of components after postulated pipe breaks in light water reactors has led to the installation of pipe restraints capable of withstanding the loads in such an accident. These restraints are a significant part of initial capital cost, and, because of their size and location, impede plant maintenance. The Piping Review Committee of the NRC has concluded that, subject to fulfillment of certain criteria, the pipe restraints for pressurized water reactor main coolant piping are not necessary because the failure mode of this piping is such that it will leak before it will break, and the leakage of reactor coolant would be large enough to detect. There is no reason in principle why the proposed criteria might not be applied to piping systems other than the reactor coolant piping.

In this study we examine the piping systems of a 4-loop 1,150 MWe pressurized water reactor, determining the crack size that would be stable from a fracture mechanics point of view, and the range of conventional leak detection systems. We find that pipe sizes down to 20 inches in diameter would meet the leak-before-break criteria. Improvements in the sensitivity of conventional leak detectors could extend this range down to pipe sizes in the range of 15 to 5 inches in diameter. The development of local leak detection systems would make it possible to apply the criteria to sizes as small as 2 to 4 inches in diameter, which appear to be the limit of the net cost savings of eliminating pipe restraints and adding additional leak detection instrumentation.

Extending the leak-before-break concept into this smallest pipe range may require improved precision in crack definition, flow modeling, and leak detection. Better detection of leaks may also require use of new detection methods coupled to novel approaches to piping system design. The work of this project identifies several avenues by which such improvements may be advanced. This work was executed through a joint team at MIT and another performing complementary analysis at Stone and Webster Engineering Corporation.

Investigators: Professors E.S. Beckjord and M.W. Golay; Messrs. P.E. Roege and B. Day.

Support: None.

Recent References:

P.E. Roege, B. Day, E.S. Beckjord and M.W. Golay, "Application of Leak-Before-Break Criteria to Pressurized Water Reactors," Second International Topical Meeting on Nuclear Power Plant Thermal Hydraulics and Operation, Tokyo 1986.

P.E. Roege, "Potential Effects of Leak-Before-Break on Light Water Reactor Design," N.E. Thesis, Nuclear Engineering Department, MIT, September 1985.

B. Day, "Instrumentation for the Leak-Before-Break Concept," S.M. Thesis, Nuclear Engineering Department, MIT, June 1986.

E. Beckjord, B. Day, P.E. Roege, S. Shuman, F. Elia, Jr., E. Ewart, J. Rosen

and P. Sekerak, "Study of the Applicability of the Leak-Before-Break Criteria," Project Final Report, Nuclear Engineering Department, MIT and Stone and Webster Engineering Corp., Report No. MITNPI-TR-024, 1986.

2) Functionally-Oriented Nuclear Safety Regulation

In a project sponsored by the U.S. Nuclear Regulatory Commission the question of how a functionally-oriented nuclear safety regulatory system would perform in the United States is being investigated. In such systems, as are in use in many other countries, the mandate of the safety regulatory authorities is to specify the functional requirements which a nuclear power station must meet in order to protect public safety adequately. The authorities must also judge whether a particular plant design meets the stated requirements. However, the authorities do not become involved in specifying the plant systems needed to meet such functional requirements, or specifying performance requirements which such systems must meet. In such systems the regulatory literature is generally small and easily understood.

The regulatory structure of the United States is very different from those of such systems. It is plant systems-oriented and highly prescriptive. It has a large complicated literature. It has been a source of widespread dissatisfaction among those who must deal with it. The purpose of this project is to illustrate the feasibility and benefits of an alternative to this regulatory approach.

In doing this the example of accidents involving loss-of-offsite-power (LOOP) has been selected for study. The effort has three phases:

- o Formulation of a proposed regulation of LOOP events.
- o Illustration of the additional design benefits in terms of safety and economics – which could be captured under functionally-oriented regulation, in creating an improved plant design which satisfies the proposed regulation.
- o Execution of review by the NRC staff of the improved design to determine whether it satisfies the proposed regulation.

The proposed regulation is that the expected frequency of core damage, f_{cd} , for the plant shall satisfy two criteria:

- o $f_{cd} \leq 10^{-4} \text{yr}^{-1}$ for all accident sequences,
- o $f_{cd} \leq 2 \times 10^{-5} \text{yr}^{-1}$ for all LOOP accident sequences.

As an illustration we have examined a reference PWR plant in order to identify the most attractive design improvement which could be made. From sensitivity analysis involving the plant-specific PRA it was determined that the

marginally most important accident sequences involving LOOP are those of station blackout as follows:

- o Station blackout with loss of the steam turbine-driven auxiliary feedwater system due to exhaustion of the emergency battery DC power supply, and
- o Creation of an equivalent small break in the primary coolant system via overheating of the primary pump seals as a consequence of loss of pump seal injection flow.

From these insights, it was proposed that the plant could be brought into compliance with the proposed regulation through addition of a steam turbine-driven AC generator. This generator could be sized to supply all DC emergency power loads and to power the seal charging pumps. The resulting reduction in expected frequency of core damage would bring the plant into compliance with the proposed regulation with an attendant enhancement of the plant's investment protection.

In the remaining portion of the project, this modified plant design was reviewed by the NRC staff in the context of the proposed regulation. The purpose of this exercise was to identify problems of implementation of functionally-oriented regulation at the NRC. No fundamental problems were identified and the modified plant was found to be in compliance with the proposed regulation. However, reservations were expressed regarding the feasibility of use of probabilistically-formulated regulations. We are currently focusing our efforts upon extending the scope of functionally-oriented regulation and of defining data-base requirements for such regulation.

Investigators: Professors M.W. Golay and V.P. Manno; Messrs. C. Vlahoplus and E. Taylor.

Support: U.S. Nuclear Regulatory Commission.

Recent References:

M.W. Golay, et al., "Milestone Report No. 1, Safety Regulation of Advanced Reactors," Report No. MITNPI-TR-003, July 1985.

M.W. Golay, et al., "Milestone Report No. 2, Implementation of LWR Safety Improvement for Loss of Offsite Power Events in a Non-Prescriptive Regulatory Framework," Report No. MITNPI-TR-004, November 1985.

M.W. Golay, et al., "Final Report, Implementation of LWR Safety Improvement for Loss of Offsite Power Events in a Non-Prescriptive Regulatory Framework," Report No. MITNPI-TR-019, 1987.

M.W. Golay, V.P. Manno and C. Vlahoplus, "Non-Prescriptive Nuclear Safety Regulation — The Example of Loss of Offsite Power," Submitted to Nuclear Safety (May 1987).

3) Power Station Design Simplification

That current-generation LWRs are needlessly complex is well recognized. Such complexity has resulted in impaired operator performance and lost availability. In an effort to improve the next generation of LWRs a project focused upon the subject of design simplification has been undertaken. Ultimately, this project is intended to provide a methodology to guide design simplification and a means of testing whether the goals of simplification have been met by a design. These general aims are pursued by working on specific example problems. In doing this it is intended that contributions will be made concerning the specific examples and that the insights gained will aid development of a general understanding of how the problem would be approached.

In this work it has become evident that simplification is not a design goal in itself but is an attribute of a class of approaches to a particular goal. In that spirit the aim of this work is to improve the ability of a designer in trying to achieve such designs.

In attacking this problem it has been observed that the traditional approach to design tradeoff analysis is deficient in ways which help to account for the existence of needlessly complex features which are seen in current power station concepts. Specifically, the economic implications of plant availability currently are not factored into the design process. The result of this practice is that attributes such as high reliability and ease of operation are emphasized nowhere in the creation of a design except possibly through the personal preferences of the designers. From work performed to date it is seen that inclusion of availability-related decision factors in the design process can substantially reduce the creation of complex designs. The efforts of the Simplification project have been focused in the following areas:

- o Rationalization of the methodology for design in order to eliminate needless complexity
- o Refinement of the analytical approaches for the prediction of plant availability.

Availability-related design tradeoff factors have not been included in the economic evaluation process of a design in the past because the basis for their treatment has not been developed very thoroughly. A substantial portion of the work of the Simplification project has been concerned with such development. Plant availability can be reduced due to the following categories of failures by men and machines:

- o Machine-related failures, or failures of operating components to perform as intended
- o Human-related failures:
 - Failures in operations
 - Failures in diagnosis
 - Failures in repair
 - Failures in maintenance.

In all of these categories of failure data exist for their respective rates of occurrence. However, the available data are typically so incomplete and primitive that it has not been worthwhile for designers to attempt to take them into account in the creation of new concepts.

The area where this is most true concerns the ability to diagnose failures of systems, particularly when rapid diagnosis is required. It became recognized that this class of failure would be most sensitive to system complexity, which is to say that systems which are complex are also difficult to understand and diagnose. Stated differently, systems which are difficult to diagnose have a high uncertainty regarding the actual condition of the system. This is equivalent to having many possible alternative system configurations, or states, with the relative likelihoods of these different states being approximately uniform. Such uncertainty is measured by the informational entropy of the system which is defined as

$$H = -\sum_{i=1}^n p_i \ln(p_i),$$

where H = system entropy

i = i -th system state

n = the number of possible states of the system

p_i = the probability of the system being in the i -th state.

It has been shown in the work of the project that the number of interrogations necessary to diagnose the true state of a system increases in an approximately monotonic fashion with the system entropy.

From these efforts the way to create much simpler designs than those currently in-placed can be seen. However, much additional work must be done in quantifying the rates and causes of the various classes of failures which contribute to lost availability before this methodology will be easy and reliable to use.

Future work on simplification will also be concerned with design for easy construction and design for safe operation.

Investigators: Professors M.W. Golay, V.P. Manno and M.J. Driscoll; Messrs. P. Seong and G. Abu-Zaied.

Support: Electric Power Research Institute (EPRI).

Recent References:

V.P. Manno and M.W. Golay, "Nuclear Power Plant Design Innovation Through Simplification," Nuclear Engineering and Design, 85, pp. 315-325, 1985.

G. Abu-Zaied, "Control of PWRs Using Moderator Displacement and Fuel Assembly Reconstitution," Ph.D. Thesis, Nuclear Engineering Department, MIT, 1986.

P. Seong, "A Methodology for Simplification of Light Water Reactor System Design," Ph.D. Thesis, Nuclear Engineering Department, MIT, 1987.

S.R. Wickham and M.W. Golay, "The Economic Tradeoff Evaluation Program PC-Trade," MITNPI-TR-017, Nuclear Engineering Department, MIT, 1987.

4) Human Error in Plant Maintenance

Errors in maintenance have been indicated as comprising approximately half of human errors in nuclear power stations. In order to understand the causes of such errors better an investigation of the sources of maintenance errors in reactor coolant pump seal repair was performed. This work was focused upon a review of the relevant literature and a comparison of pump maintenance practices in two different utility companies. It was found that the pump seals in current use were not designed to be easy to repair. This is true in terms of every aspect of the maintenance operation: seal parts replacement, seal installation and pump access. Efforts have been undertaken by pump vendors to improve the designs of pump seals. However, most of the problems observed in this investigation would remain unaffected by such design work.

The seal maintenance practices of the two utilities which were studied in this work differ greatly. In one case a thorough parts quality verification program is used, and great effort has been devoted to assuring that the seal repair operation is one of high quality. In the other utility company seal maintenance is treated as a much more routine, but difficult, task. In the latter case the unsatisfactory experiences with pump seals which had been encountered by the former utility have not arisen. However, both utilities reported dissatisfaction with the inconvenience and difficulty of the pump seal operation. It appeared evident that significant improvements in controlled leakage reactor coolant pump seals would be difficult to achieve through redesign. Even with redesigned seals their radioactive contamination would continue to render the seal replacement task very cumbersome. However, large improvements in the designs of pump wells which would render the seal installation task easier are easily feasible. On balance it appears that use of a pump, such as the canned motor type, which does not require controlled leakage from the primary system would be a great improvement over current system configurations. Efforts to advance that goal are recommended.

Investigators: Professor M.W. Golay; Mr. E.F. Love.

Support: EPRI.

Recent References:

E.F. Love and M.W. Golay, "Human Error in Maintenance of Reactor Coolant Pump Seals," MITNPI-TR-022, 1987.

5) Design Approaches to Reduction of Opportunities for Human Error In Plant Operation

It has become evident that human error is a source of much of the disappointing experience which has been encountered with United States LWRs. The purpose of the effort of this project is to identify design means of reducing opportunities for commitment of errors during operations by humans. As with

simplification, human error reduction is not a design goal in itself. Rather, it is an attribute of a design formulated for fulfillment of a higher level goal.

The basic design approaches for reduction of opportunities for human error in accomplishing a particular function are the following:

- o Elimination of the need for the function
- o Replacement of human performance of the function by that of a machine (automation)
- o Reduction of human stress in performance of the function (means for accomplishing this include increasing the time over which actions are required, simplifying of systems, and providing supporting information and performance verification systems as operator aids).

In this project we are working on a set of examples in order to illustrate how elimination of human error can occur through design. In each phase of this work the example of control of the steam generator secondary liquid level at low power is chosen because of its importance in power station operation and because of the importance of human error in affecting this example. As with our other projects we are using specific examples to aid the evolution of our understanding of general approaches to reduction of human error.

Elimination of the need for performance of the function:

Elimination of the need for performance of the function is being pursued through the example of preheating of the feedwater being injected into the steam generator. Feedwater preheating at full power operation is employed routinely through use of the plant's feedwater heating system. However, such preheating is not employed routinely in the startup and low power ranges at most, but not all, power stations. Through numerical simulation of the dynamic behavior of a steam generator the value of such preheating has been investigated. It is found as the temperature of the feedwater approaches that of the saturation temperature of the steam generator that the amount of decrease of the liquid level due to an increase in the feedwater flowrate, and therefore the difficulty of controlling the level, diminishes to a null value. Such preheating can be accomplished in a variety of ways, for example by use of a fossil-fired auxiliary boiler or by use of steam fed-back from the steam line to the feedwater inlet. A design for the latter solution has been formulated for the Beaver Valley 2 Nuclear Power Station. Its estimated marginal cost for a newly-constructed plant is approximately \$100,000.

Reduction of the demands upon humans in operating a system: Reduction of the demands upon humans in operating a system has been investigated by means of numerical simulation of the dynamic behavior of a steam generator exploring the implications of increasing the liquid mass on the secondary side of the generator. Definitive results regarding this option have not yet been obtained.

Elimination of the human function through automation of the function:

Elimination of the human function through automation of the function has been investigated by attempting to create a control law for automatic control of a steam generator at all power levels, from startup to full power in order to demonstrate the feasibility of such automation. This has been done, and

numerical simulations of the resulting steam generator behavior indicate successful operation.

Investigators: Professors M.W. Golay, E. Gyftopoulos, J. Meyer, and D. Lanning; Messrs. J. Outwater and J.L. Choi.

Support: EPRI.

Recent References: None.

6) Horizontal Steam Generators for Pressurized Light Water Reactors

In the project the advantages and disadvantages of utilizing horizontal steam generators in pressurized light water reactors is assessed. The primary areas of investigation are the implications for thermal-hydraulic primary and secondary system behavior, the implications for plant configuration and operation, and the implications for component design and lifetime.

This project was undertaken to evaluate the potential for enhanced pressurized water reactor (PWR) performance by reintroduction of steam generators of horizontal orientation. This potential derives from the orientation of the tube sheet and the enhanced head available for natural circulation. The vertical orientation of the tube sheet allows for corrosion deposits to wash from the tube sheet and be collected on the bottom of the shell. The enhanced natural circulation head arises from the fact that the thermal center of the horizontal steam generator (HSG) will be considerably higher in containment than that of the vertical steam generator (VSG) if the tops of the two units are at the same elevation. While these two factors are apparent, their significance to overall PWR performance is not obvious.

With regard to the first factor, it must be recognized that over the last several years considerable remedial attention has been given to VSG component design and coolant chemistry control. Major steps taken in these areas to assure satisfactory performance of the VSG promise to yield satisfactory results. Hence, it is not obvious that a major plant redesign, such as that involving introduction of HSGs, is necessary to correct the unsatisfactory short VSG lifetimes which have been experienced in many PWR plants. Regarding the second factor, the specific benefits in startup, transient and accident sequences from enhanced natural circulation need to be quantified. While such benefits obviously exist, an assessment is necessary to establish if they are significant or simply marginal. Finally, even if important system operation benefits do exist, feasibility questions regarding containment arrangement and structural considerations must be answered. Specifically, the economic penalty of providing for the arrangement of an HSG in containment and the mechanical complexities involved in both supporting the HSG in this position and handling the seismic design of the generator and the associated main coolant pumping must be assessed.

This study, therefore, proceeds along two principle directions. The first was to determine the feasibility and the compromises necessary to accommodate an HSG in a PWR system. The second was the assessment of the potential benefit in overall system performance that might ensue from utilizing an HSG. Both evaluations were based on a typical 1200 MWe, four loop PWR system.

Additionally, a more limited assessment of the transient performance of a smaller 300 MWe plant employing HSGs was performed. Here, we evaluated the role of enhanced natural circulation from an HSG in promoting a slower flow coastdown in a complete loss of flow accident in a plant with canned motor pumps. This work reassesses a portion of the Westinghouse study of a small plant conducted as part of the EPRI small plant program.

CONCLUSIONS

1. Operating Experience – Experience with early U.S. and Canadian small PWR systems which utilized HSGs has been very good. Large Russian PWR systems utilize HSGs whereas large U.S. PWR systems utilize VSGs. The hypothesis that steam generator performance was dependent on operating pressure and temperature conditions as well as tube orientation was explored. Both the U.S. and Soviet designs have evolved toward increasing temperature, pressures and surface heat fluxes with the US having adopted higher values of each parameter well before the Soviets. However, clear correlation is not evident between steam generator performance and operating conditions independent of the tube orientation. For both HSGs and VSGs, it appears that individual plant chemistry control practice has been the most dominant factor in determination of SG performance.
2. Component design – A typical HSG of the LOVIISA type (once-through, pool boiling) was designed to obtain overall envelope dimensions. The resulting generator contained about 50% more tubes and had a steam/water evaporating region about 37% greater in volume and 90% more water by mass than a recirculating type VSG at the same power rating. The primary reason for these differences is that this HSG operates by pool boiling whereas the VSG operates with a flow boiling, heat transfer mechanism. These individual features cause the horizontal unit in total to be larger in envelope, larger in thermal inertia (because the larger metal mass of tubes) and larger in water inventory.
3. Containment Arrangement – The once-through, pool boiling horizontal unit was utilized to arrive at a containment arrangement. The arrangement was derived from a base case VSG arrangement devised by Stone & Webster Engineering Co (S&W). The key criteria in making the HSG arrangement was to retain the ability to remove every steam generator from containment and to provide comparable space for all other plant refueling and maintenance operations identified for the vertical arrangement. The resulting horizontal arrangement yielded a containment 8 feet larger in diameter and 10 feet shorter than the standard vertical arrangement. Further, the support of the HSG and the seismic design for both the generator and the primary piping were shown to be feasible. These results confirmed that from an arrangement viewpoint an HSG can be accommodated without feasibility question and without undue economic penalty.
4. Transient System Performance – A range of transients were considered and the following five were examined in detail using a lumped parameter PWR systems code – complete loss of forced reactor coolant flow, turbine trip with no reactivity feedback, loss of normal feedwater, loss of offsite power, and steam generator tube rupture. The HSG component parameters were found to dictate the system response in an anticipated way. The

enhanced thermal inertia of the HSG results in damped response of the primary and secondary systems to initiating upsets compared with the VSG. This causes less challenge to secondary and primary pressure relief valves in the HSG versus the VSG plant. Even when the set points are initially reached, the cycling sequence of relief pressure recovery-relief repeated less. Since the secondary side inventory of the HSG is greater, the time available before secondary-side dryout and to respond to a steam generator tube rupture is slightly increased. Included in the study was a calculation of the natural circulation transient. For the 18 ft. increase in system thermal length considered, natural circulation is increased from standard PWR conditions by only 1% for full flow. While the system thermal length as well as other HSG could have been varied further, it was judged that significant net benefits in HSG system performance would not have been forthcoming. Overall, while system performance differences exist for the HSG versus VSG cases studied, no dominant performance differences exist.

5. Small Plant Utilization of HSGs – The potential for the high natural circulation rates to allow a closed primary system by compensating for the loss of inertia resulting from the use of canned motor pump was explored. The Westinghouse small plant study conclusions regarding the steady state power that the natural circulation mode can dissipate and the need to provide a bypass around the pump for the complete loss of low accident (CLOFA) were validated.

The CLOFA flowrate at the critical MDNBR time of about three seconds was investigated more thoroughly than reported in the Westinghouse study. Here the transient flowrate was determined from a time-dependent momentum equation in which the buoyancy as well as the pump turbinizing effects were considered. The results of this analysis yield a more accurate and a higher flowrate than was obtained by neglecting the buoyancy effect until late (after 8–10 sec) in the transient. Typically, for an HSG plant configuration (50 foot elevation) and a nominally achievable internal canned motor pump inertia of 10% the resulting flowrate at the critical time of around three seconds after pump trip was only 11% lower than that which would be obtained from a VSG plant utilizing a shaft seal pump. This flow rate was used to assess MDNBR penalties using the Westinghouse selected EPRI–Columbia U correlation. Typically, the decrease in DNBR was found to be only 8% for these two cases. The DNBR correlation selection was closely examined and a number of alternate DNBR correlations were evaluated. It was found that the predictions of relevant correlations varied only by about 3% and that selection of the EPRI–Columbia U correlation is appropriate.

The computed penalty in MDNBR does not seem to be an insurmountable barrier. It appears warranted to pursue in detail the CLOFA behavior of a PWR system employing a canned motor pump in combination with an elevated HSG. The next investigation should focus on the achievable amount of internal inertia in a canned motor pump. Initial values of 10% or above yield significant benefit in delaying the reduction in transient system flowrates.

Investigators: Professor N.E. Todreas; Drs. S.-P. Kao, and M. Massoud; S. Baker

Support: EPRI

Related Academic Subjects:

- 22.32 Nuclear Power Reactors (A)
- 22.312 Engineering of Nuclear Reactors (A)
- 22.313 Advanced Engineering of Nuclear Reactors (A)
- 22.36J Two-Phase Flow and Boiling Heat Transfer (A)

Recent References:

M. Massoud, S.-P. Kao and N. Todreas, "Evaluation of Horizontal Steam Generators for PWR Application," MITNPI-TR-016, EPRI, Palo Alto, CA, August 1987.

7) Design of a Small BWR

In the area of design innovation the major activity in the project is concerned with design of a small BWR. This work is part of the EPRI and U.S. Department of Energy Advanced LWR program. In this project we are aiding a General Electric Co., Bechtel Power Corp. team in development of a conceptual design for a BWR of approximately 600 MWe capacity. This work is expected to continue over the next four years.

In this project a conceptual design for a new BWR is being evolved. It emphasizes use of highly reliable passive systems to the maximum extent feasible for both routine operation and safety functions. It also features extensive use of modular construction techniques. Work on this project has been concerned with the following topics:

- o Continuing review of the overall power station concept
- o Design of a system for passive space-conditioning of the emergency control center
- o The analysis, testing and design of the station steam injector for high pressure emergency coolant injection
- o Design of the station's advanced containment system.

Design of the space conditioning system for the plant's emergency control center utilized reliance upon natural convection for circulation of the center's air, passive absorbers of atmospheric poisons and cooling of the center's air using frozen coolant reservoirs.

Work on the emergency steam injector has been concerned with gaining a fundamental understanding of the physical behavior of a steam injector, in and assisting General Electric in deciding how the steam injector would be used and what tests would be performed as part of its development.

Work on the passive containment design has been concerned with conceptual designs, the rate of heat transfer from the containment vapor suppression pool and wetwell atmosphere to the environment and with the role of stratification in these systems in affecting such heat transfer.

Future work in these areas is expected to continue for at least two years more.

Investigators: Professors M.W. Golay, V.P. Manno, M. Driscoll, D. Lanning, M. Kazimi, and N.E. Todreas; Messrs. G. Baird, A. Dehbi, J. Keffer, and E. Sasson.

Support: EPRI, USDOE.

Recent References:

G. Baird and M.W. Golay, "Design of a Passive Space Conditioning System for the Small BWR Emergency Control Center," Nuclear Engineering Department, MIT, Report MITNPI-TR-023, 1987.

Related Academic Subjects:

Academic subjects of special relevance to the LWR Innovation Project include all of those concerned with Fission Engineering.

Future Efforts:

The organizational structure of the LWR Innovation Project is expected to remain unchanged in the initiation of future projects. In Table 2 are listed the intended directions of project growth. As is always the case, what will be possible will depend upon funding opportunities.

TABLE 2

POSSIBLE FUTURE LWR INNOVATION PROJECT EMPHASES

- Conceptual Design
 - Various LWR Design Alternatives
 - PWR Passive Containment Cooling
 - Source Term Minimization
- Utility Requirements for New Plants
 - Construction Methods/Quality Control
 - Maintenance Requirements
- Technological Advances
 - Safety Rationalization
 - Full Scope of Functionally-Oriented Regulation
 - Further Specific Topics for Conservatism Reduction
 - New Technology
 - Sensor Development
 - Optical Signal Transmission/Multiplexing
 - Automatic System Diagnosis (Identification of Information Needs)
 - Improved Designs
 - Improved Containment Systems
 - Containment Bypass Path Elimination
 - Troublesome Components
 - Valves

3.6.2 Modular Gas-Cooled Reactor (MGR) Project

In response to the conclusions reached in "Nuclear Power Plant Innovation in the 1990's: A Preliminary Assessment" (September 1983), we have initiated a comprehensive study of the Modular High Temperature Gas-Cooled Reactor, now designated as the MGR. This MGR has unique passive safety features, and our initial intent is to help determine whether a suitable design can be established for commercial deployment in longer range plan is to contribute to developing the ultimate potential of the MGR concept.

Because we cannot be equally active across the entire spectrum of issues involved in MGR research, we concentrated initial efforts on safety, investment, and licensing issues. Our recent projects involve issues of source term/core design interaction, applicability of safety goals, incentives for fuel quality improvement, and determination of design goals. We have also initiated studies to consider such questions as operational optimization and MGR designs combined with present-day direct cycle gas turbines. Recent projects include:

1) Reactor Core Design.

Development and use of simple models to determine characteristics of a range of possible modular gas-cooled reactors. The prime focus is the interaction of core design and fuel characteristics in determining the source term in heat-up events. We are attempting to develop useful working definitions for "fuel quality" and determine the incentives for fuel quality improvements.

2) Economies of Scale and Licensing.

Significant economic benefits are potentially available if advantage is taken of serial off-site fabrication, simplified plant construction, improved licensing via standardized modules, and possibly a reduced safety envelope. A dominant issue to be resolved is whether reduced specific plant costs available via serial production techniques offset the economy-of-scale dependence traditionally accepted by the nuclear electric industry. Impact of licensing regulations and consideration of advanced reactor licensing are being incorporated in our studies.

3) Source Term Effects.

The inherent safety features of some MGRs suggest substantial savings in balance-of-plant design may be made possible by rationalized licensing requirements and reduced security demands. Although new regulations may reasonably be advocated when the MGR is better developed and tested, reliance on new regulations at this time seems premature. We are studying the application of existing regulations to the MGR with particular attention given to issues of confinement. We will determine which existing requirements are limiting and determine whether these requirements are compatible with economic MGR deployment.

4) Probabilistic Risk Assessment.

A scoping level probabilistic risk assessment (PRA) of the modular high temperature gas-cooled reactor has been completed. This project, supported by G. A. Technologies, was designed to be an independent review of accident initiators and a search for accident sequences that might be major contributors to the safety risk. A more detailed study will be continued for sequences that are identified as major risk contributors.

5) Passive Safety Heat Transfer Sensitivity Studies.

One primary advantage of the MGR is the passive safety afforded by the ultimate heat removal capability of radiation from the walls of the vessel. Temperatures are predicted to always stay below the non-defective fuel damage conditions. We have been making an independent assessment of this heat removal path. The study is designed to evaluate the maximum temperatures after a loss of helium cooling flow and primary system depressurization. The objective is to determine the maximum fuel and vessel temperatures by an independent method and to assess their uncertainty by a study of the sensitivity of these temperatures to the various conduction and radiation heat transfer assumptions and parameters.

6) Direct Cycle Gas Turbine.

The MGR with passive safety is an ideal concept for development into a compact package of the module operating a direct cycle gas turbine. Initial investigations indicate that high efficiencies (approaching 45%) can be obtained with reactor outlet temperatures in the 800°C to 850°C range. If this can be demonstrated, then the technology available today can be utilized for near-term commercial development of this system. There is clearly a future potential for improved efficiency with higher temperature designs. We have initiated studies in this area and will be working with members of the Mechanical Engineering Department. Our studies include both design and assessments.

7) Water Ingress Effect.

If water enters the primary system from, for example, a steam generator tube rupture, there are potential neutronic effects. These include reactivity increases and peripheral control rod effectiveness reduction due to reductions in diffusion lengths. The reactivity increases can be controlled by limiting the amount of the fissile fuel loading. This in turn will give a fuel burnup lifetime limit, hence, increased fuel cycle costs. Methods to alleviate these problems, such as the use of burnable poisons and spectral shift neutron absorption changes, are going to be studied.

8) Fission Product Deposition and Lift-Off

Passive safety features of the MGR prevent the release of significant fission products over a wide spectrum of accidents. Hence, the major potential for fission product activity release becomes a lift-off during a depressurization blowdown, of any loosely deposited fission products that have been deposited

with time from low-level activity in the primary helium circulation system. This potential deposition and accidental lift-off is an important uncertainty in safety studies and could impact on the fuel quality requirements for future MGR designs. Planning and designs are being made to build a simple, experimental, pressurized helium circulation system for controlled experimental lift-off studies to be done at MIT by the Nuclear Engineering Department.

Investigators: Professors D.D. Lanning, L.M. Lidsky, R.K. Lester, N.C. Rasmussen, M.J. Driscoll, D. Wilson (Department of Mechanical Engineering); Messrs. R.L. Coxe, M.H. Fellows, M.G. Izenon, H. Kaburaki, R. Sanchez, A. Sich, J. Staudt, E. Tanker, E. Love, J. Martin; Mles. J.L. Maneke, M.C. Fordham.

Support: Energy Laboratory Utilities Program (primarily from Gas-Cooled Reactor Associates (GCRA)), G. A. Technologies, Oak Ridge National Laboratories.

Related Academic Subjects:

22.211	Nuclear Reactor Physics I
22.312	Engineering of Nuclear Reactors
22.32	Nuclear Power Reactors
22.33	Nuclear Engineering Design
22.341	Nuclear Energy Economics and Policy Analysis
22.35	Nuclear Fuel Management
22.39	Nuclear Reactor Operations and Safety

Recent References:

M.G. Izenon, D.D. Lanning, L.M. Lidsky, and J.L. Maneke, "Identification of the Safety Requirements of a New Reactor Concept: The MHTGR as an Example," MITNPI-TR-006, December 1985.

D.D. Lanning, M.G. Izenon, R.K. Lester, L.M. Lidsky, "Passively Safe Nuclear Reactors: Issues and Impact on Fuel Management," ANS Proceedings of the Topical Meeting on Advances in Fuel Management, Pinehurst, NC, March 1986.

J.L. Maneke, "Radiation Releases from MHTGR Confinement Buildings," MITNPI-TR-007, June 1986.

M.G. Izenon, "Effects of Fuel Particle and Reactor Core Design on Modular HTGR Source Terms," MITNPI-TR-012, October 1986.

M.H. Fellows, "A Scoping Level Probabilistic Risk Assessment of a Pebble Bed Modular High Temperature Gas-Cooled Reactor," MITNPI-TR-013, October 1986.

J.L. Maneke, D.D. Lanning, L.M. Lidsky (MIT); J.M. Oddo, J.S. Baron, A. Drozd (SWEC), "MHTGR Confinement Radiation Releases," Transactions of the American Nuclear Society, Vol. 53, pp.362-364, November 1986,.

R.G. Sanchez, D. D. Lanning, and L. M. Lidsky, "Passive After-Heat Removal: Sensitivity Study for Modular Pebble Bed Reactors," MITNPI-TR-015, January 1987.

J. E. Staudt, "Design Study of an MGR Direct Brayton Cycle Power Plant," MITNPI-TR-018, June 1987.

3.6.3 Liquid Metal Reactor Safety Studies

Two of the central requirements of the new generation of nuclear plant designs are that the proposed plants be both reliable and safe. Research activities in this area are aimed at modeling the risk of these new designs and using these models to identify potential improvements in the design. Two issues of interest are:

- Specification of emergency planning zone boundaries consistent with the improved understanding of LMR source terms and with the current implicit risk levels specified for LWRs.
- Analysis of the reliability of to-be-designed complex systems using partial evidence from subsystem tests.

Investigators: Professors N. Siu and N. Rasmussen; Mr. B. Day.

Support: Rockwell International/DOE, at approximately \$25,000/year.

Related Academic Subjects:

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

Recent Reference:

N. Siu and N. Rasmussen, "Evaluation of Emergency Planning Strategies for an LMR," MITNPI-TR-014, November 1986.

3.6.4 Advanced Instrumentation and Control Systems

It has been recognized for some time that improvements can be made in reactor instrumentation and control. An immediate need is in the area of signal validation with fault detection and identification (FDI). Some potential improvements in this area have been 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 technology that has been developed for aerospace control systems, to apply it to 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 for 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 non-linear 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 possibility of closed loop controls with specific applications to large nuclear power plants or plant components.

In addition to the members of the Nuclear Engineering Department, the MIT group involves contributors from the Mechanical Engineering Department and the Electrical Engineering and Computer Science Department. In particular, control display systems have been studied with the assistance of the Mechanical Engineering Department for human factor engineering considerations at the man-machine interface. Also, the Electrical Engineering and Computer Science Department is assisting in the studies of closed loop digital control systems. Funding from the National Science Foundation (NSF) has been provided for studies of the non-linear closed loop digital control methods. Funding is being 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 has been provided by CSDL. Recent approval from the NRC has allowed expanded studies 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 includes the development of a real-time supernodal code with transient reactor physics and coupled thermal hydraulics. The object is to incorporate fast running analytical information into the closed loop non-linear 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 is to extend the concept to the large, multi-dimensional core effects that occur in power reactors such as large pressurized water reactors (PWRs) and boiling water reactors (BWRs).

An additional Argonne Breeder Technology Award has given us the opportunity to extend and refine earlier research. The resulting composite package appears to be nearly ready for use on-line in the EBR-II plant. The package contains upgraded versions of three methods that we developed earlier to provide "analytic measurements" of core natural circulation flow. Each method provides a current flow value by using operating information only from thermocouple measurements and from a history of reactor neutron power. The methods have shown good performance when evaluated using input from tapes of EBR-II sensor signals during a total of about three hours of natural circulation operation during six Shutdown Heat Removal Tests (SHRTs). The relevant computer programs have been streamlined and the documentation improved in anticipation of shipment to EBR-II operations personnel.

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 among sensor uncertainty and calculational input parameters were studied.

Automation improvements of many types can contribute to the PWR upgrade portion of the Reactor Innovation 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). The resulting controller does not use steam flow and feedwater flow measurements at all and has exhibited good performance characteristics in all calculational tests to date. 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.

Investigators: Professors D.D. Lanning, J.E. Meyer, A.F. Henry, A.L. Schor, T.B. Sheridan (Department of Mechanical Engineering), L.A. Gould, and F.C. Schweppe (Department of Mechanical Engineering and Computer Science); Drs. J.A. Bernard (MIT), J.H. Hopps (Charles Stark Draper Laboratory); Messrs. J.A. Alfeo, B.N. Aviles, E.L. Cabral, J.I. Choi, P.W. Kao, M.H. Kim, J.M. Koonmen, E.S.H. Lau, K.S. Kwok, P.T. Menadier, K.L. Meyers, R.S. Ornedo, A.G. Parlos, G.S. Ueo, R.J. Witt, M. Yasuda, M.L. Zerkle.

Support: National Science Foundation, Department of Energy, Argonne Breeder Technology Program, Sandia National Laboratories, Charles Stark Draper Laboratory (computer support), self-supporting students with NED computer funding.

Related Academic Subjects:

- 22.32 Nuclear Power Reactors
- 22.36J Two-Phase Flow and Boiling Heat Transfer
- 22.42 Numerical Methods in Engineering Analysis
- 22.88 Human Factors in Design

Recent References:

R.J. Witt and J.E. Meyer, "Demonstration of Methods for Analytic Measurement of Natural Circulation Flow in EBR-II," Nuclear Engineering Department, MIT, Report MITNE-270, February 1986.

J.A. Bernard and D.D. Lanning, "Issues in the Closed-Loop Digital Control of Reactor Power: The MIT Experience," IEEE Transactions on Nuclear Science, Vol. NS-33, No. 1, pp.992-997, February 1986.

J.A. Bernard, K.S. Kwok, R.S. Ornedo, D.D. Lanning, and J. Hopps, "The Application of Digital Technology to the Control of Reactor Power: A Review of the MIT Reactor Experiments," Proceedings of the Sixth Power Plant Dynamics, Control, and Testing Symposium, Knoxville, TN, April 1986.

J.A. Bernard, "The Construction and Use of a Knowledge Base in the Real-Time Control of Research Reactor Power," Proceedings of the Sixth Power Plant Dynamics, Control, and Testing Symposium, Knoxville, TN, April 1986.

M.M. Blancaflor and J.E. Meyer, "Signal Validation for Millstone-3 SPDS; Special Problems and Solutions," SPDS Implementation and Emergency Response Facilities, EPRI Seminar, Boston, MA, May 1986.

G.S. Ueo, "Uncertainty Estimation and Signal Validation for Performance Monitoring of Power Plant Components," Ph.D. Thesis, Nuclear Engineering Department, MIT, May 1986.

R.S. Ornedo, "Concept and Demonstration: A Reconfigurable Control System for Nuclear Power Plants," Ph.D. Thesis, Nuclear Engineering Department, MIT, (CSDL-T-903), May 1986.

J.A. Bernard, "The Behavior of Component Terms in the Dynamic Period Equation," Transactions of the American Nuclear Society, Vol. 52, pp. 490-492, June 1986.

H.F. Polenta, A. Ray, P.T. Menadier, D.D. Lanning, and J.A. Bernard, "Implementation of a Fault Detection Procedure," American Control Conference, Seattle, WA, June 1986.

A.G. Parlos, "Non-Linear Multivariable Control of Power Plants Based on the Unknown-but-Bounded Modeling Methodology," S.D. Thesis, Nuclear Engineering Department, MIT, June 1986.

E.J. Ashburner, "Real Time Solutions to Point Kinetic Equations," S.M. Thesis, Nuclear Engineering Department, MIT, September 1986.

M. Yasuda, "Signal Validation for the Performance Monitoring of Feedwater Heaters," S.M. Thesis, Nuclear Engineering Department, MIT, June 1986.

J.A. Bernard, A.F. Henry, and D.D. Lanning, "The Design and Experimental Evaluation of a Closed-Loop Digital Controller Based on an Alternate Formulation of the Dynamic Period Equation," Proceedings of the American Nuclear Society Topical Meeting on Reactor Physics and Safety, Saratoga Springs, NY, pp. 610-621, September 1986.

J.A. Bernard, "Human Approach to Process Control and the Provision of Predictive Information," Transactions of the American Nuclear Society, Vol. 53, pp. 139-140, November 1986.

J.A. Bernard, K.S. Kwok, D.D. Lanning, A.F. Henry, and J.E. Meyer, "Applications of the Reactivity Constraint Approach to the Transient Control of Spacecraft Reactors," Proceedings of the Fourth Symposium on Space Nuclear Power Systems, Albuquerque, NM, January 1987.

B.N. Aviles, "State Variable Feedback Techniques for Predictive Control of Nuclear Reactors," S.M. Thesis, Nuclear Engineering Department, MIT, February 1987.

J.A. Bernard, "An Experimental Comparison of Reactor Power Controllers Based on the Standard and Alternate Formulations of the Dynamic Period Equation," IEEE Transactions on Nuclear Science, Vol. NS-34, No. 1, pp. 548-552, February 1987.

3.6.5 Automated Reasoning: Applications of PROLOG

The potential of computers in simplifying and optimizing the control and operation of complex systems is apparent. Although the more explicitly algorithmic control and display applications have been mastered, attempts to computerize more complex areas such as malfunction diagnosis or Technical Specifications compliance have been disappointing, largely because these problem areas generate highly complex, brittle codes when conventional programming techniques are used. The resulting programs are hard to validate, verify, and maintain. The "expert system" paradigm, that has been so successful in some areas, is not well-matched to the complexity of the problem domain and suffers from many of the same difficulties, including lack of formal proof of correctness and inability to respond easily to incremental change. We have applied a relatively new, but very powerful, symbolic processing language, PROLOG, to this problem area. Because of PROLOG's roots in logical analysis, it is particularly well-suited to representing, and to drawing logical inferences in, systems with complex relationships between multiple objects.

We have demonstrated that typical power reactor Technical Specifications can be usefully and reliably expressed in the PROLOG programming language and that useful logical implications can be drawn from that data base. We have also developed a domain-relevant shell that allows utility staff to efficiently interact with the computerized Technical Specifications. The applying logic programming to this problem is that the formal structure of the Technical Specifications is reproduced as transparently as possible. The internal structure of the language allows hierarchical levels to be arbitrarily assigned and facilitate the use of operability trees in explicit form to ensure uniform interpretation of subsystem functionality. We have also applied these techniques to the generation of a surveillance scheduling system, SRM, which is capable of scheduling the surveillance and maintenance functions mandated by the Technical Specifications. This project has been enthusiastically reviewed by industry observers and a commercial version has already been installed at one utility.

Investigators: Professors L.M. Lidsky and D.D. Lanning; Messrs. A. Dobrzeniecki, K. Meyers, T. Reese, Y.-F. Wu.

Support: U. S. Department of Energy.

Recent References:

A.B. Dobrzeniecki, "Automated Reasoning Methods for Managing Power Plant Equipment Test and Maintenance Requirements," S.M. Thesis, Nuclear Engineering Department, MIT, MITNPI-TR-020, June 1987.

Y.-F. Wu and L.M. Lidsky, "Nuclear Power Plant Technical Specifications Computerization: Application of PROLOG," MITNPI-TR-007, May 1986.

3.6.6 Cross-National Analysis of Nuclear Industrial Performance

This research is intended to provide insights into the factors that have contributed to international variations in industrial performance in nuclear power plant design, construction and operation. The industries in France, West Germany, Japan, and the United States are being studied. During the last year, the work has focused on the relationships between economic organization and performance in nuclear power plant construction and the influence of industrial structure on learning in nuclear power plant operations. We have developed a statistical technique that can be used to quantify the contribution of 'learning by using' to the improvement of nuclear power plant operating performance. Using plant availability as the indicator of operating performance, the model has revealed significant differences in rates and patterns of learning in the United States, France and Japan. The results indicate that in the United States a substantial operating performance penalty has been paid as a consequence of nuclear utility fragmentation and dispersed siting, both of which have inhibited information exchange. In Japan, by contrast, neither the physical separation of reactors nor differences of ownership appear to create major barriers to the transfer of operating information. The structure of information flows in the French nuclear industry differs from that in both Japan and the United States. In France, local exchanges of information seem to be less important than industry-wide learning effects. This result is probably a consequence of the high level of design standardization and the centralized industrial structure in that country.

The statistical results also suggest that while "embodied" learning by nuclear plant suppliers has apparently played an important role in improving operating performance in Japan, neither NSSS vendors nor architect engineers in the U.S. have exploited the results of prior experience in order to develop more reliable designs.

In a separate study, we have developed a theoretical framework for analyzing the economic consequences of variations in the organization of nuclear power plant construction projects. Our approach focuses on three aspects of project organization: the extent of utility involvement in design and construction; the extent to which the externally contracted functions are integrated horizontally; and the nature of the contracts linking the utilities and their suppliers. The analytical framework, which is based on the theory of transaction costs, is used to show how organizational differences in each of these dimensions result in variations in the relative contributions of production scale economics, transaction cost economics and the efficiency gains of market competition among the four countries studied.

Investigators: Professor R.K. Lester; Ms. M.B. Crocker; Messrs. M.J. McCabe, C. Schmidt.

Support: Andrew W. Mellon Foundation; MIT Center for Energy Policy Research

Related Academic Subjects:

- 22.341 Nuclear Energy Economics and Policy Analysis
- 22.81 Energy Assessment

Recent References:

J.M. Kindinger, "An Analysis of Nuclear Power Plant Construction Times," S.M. Thesis, Management of Technology Program, Sloan School of Management, MIT, 1985.

G. Stairs, "An Analysis of Nuclear Power Plant Construction Costs," S.M. Thesis, Sloan School of Management, MIT, 1985.

M.J. McCabe, "An Empirical Analysis of Measurement Errors: Power Plant Construction Costs," S.M. Thesis, Technology and Policy Program, MIT, 1985.

R.K. Lester and M.J. McCabe, "The Effects of Industrial Organization on Learning By Using in Nuclear Power Plant Operation," Nuclear Engineering Department Working Paper, December 1986.

R.K. Lester and M.B. Crocker, "On the Economic Organization of Nuclear Power Plant Construction," MIT Center for Energy Policy Research Working Paper, August 1987.

3.6.7 International Comparison of LWR Performance

This project is an effort to quantify the performance of light water reactors (LWR's) in several countries, and to develop an understanding of the causes of discrepancies. The nations involved include the United States, France, the Federal Republic of Germany, Japan, Sweden, and Switzerland. Data on all causes of capacity loss of each plant over 300 MWe in each country have been obtained for the years 1975-1984.

Results indicate very large discrepancy in performance between countries. For example, the Swiss plants have the highest average performance for both PWR's and BWR's, averaging better than 85% for the 10-year study interval. The United States has the lowest 10-year average in capacity factor. Causes of capacity loss are recorded in terms of plant system, e.g. NSSS, balance of plant, etc. In addition the losses are categorized as to forced, scheduled or regulatory imposed losses.

It is recognized that plant performance may be affected by the context in which the plants operate. Part of the study has been given to understanding the character of the nuclear industry in the countries involved. Factors which have been incorporated include: utility industry structure, supply industry structure, utility internal capability, economics of nuclear power, safety regulation, and the role of the public opinion.

One understanding difference between the US data and the other countries is the relatively large safety regulatory capacity loss in the U.S. Further investigations have compared the mode and impact of safety regulation in the United States with those of France, Germany, Sweden, and Switzerland.

Investigators: Professors K.F. Hansen, M.W. Golay, E.P. Gyftopoulos, R.K. Lester, N.C. Rasmussen; Messrs. C.T. Wilson, S.D. Hulkower, S.C. Anderson.

Support: U.S. Department of Energy, MIT Center For Energy Policy Research, Electric Power Research Institute, and Westinghouse Electric Corporation

Recent References:

C.T. Wilson, "A Numerical Comparison of International Light Water Reactor Performance 1975 to 1984," S.M. Thesis, Nuclear Engineering Department, MIT, May 1986.

S.D. Hulkower, "The Effects of Regulation on the Performance of Nuclear Power in the United States and The Federal Republic of Germany," S.M. Thesis, Technology and Policy Program, MIT, June, 1986.

S.C. Anderson, "An International Comparison of the Impact of Safety Regulation on LWR Performance," S.M. Thesis, Technology and Policy Program, MIT, June, 1987.

3.7 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 nonlinear turbulence theory, MHD equilibrium and stability theory, transport theory both classical and anomalous, and alpha particle effects.

It is also worth noting that over the past several years a new effort has been initiated, which makes use of our theoretical expertise in plasma physics. The area of research concerns space plasma physics with emphasis on whistler waves and associated phenomena in the earth's magnetic field.

3.7.1 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, mirrors, alternate concepts; systems analysis and design of power reactors, ignition experiments, hybrid reactors; neutronics, blanket design, magnet design, first wall, materials and activation, heating technology, tritium handling, safety and environment.

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: MHD Theory of Magnetic Fusion Systems I deals with the theory and applications of ideal MHD theory 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: MHD Theory of Magnetic Fusion Systems 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.

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.

22.65J: Advanced Topics in Plasma Kinetic Theory, varying content including topics of current interest. Typical subjects: theories of collective phenomena such as linear instability and non-linear saturation mechanisms in plasma, particularly in regimes described by the Vlasov-Maxwell equations. Effects of wave-particle resonance: trapping and scattering of particles by waves. Linear theory of instabilities in inhomogeneous plasma. Reflection and eigenmode problems in bounded systems. Diffusion phenomena and anomalous resistivity associated with wave-particle interaction. Discussion of experiments.

22.66 Plasma Transport Phenomena, transport theory analyzes the processes by which particle energy, momentum, and mass diffuse across the magnetic field. Develops the collisional classical and neoclassical transport theory of tokamaks (and stellarator) including the theory of MHD equilibrium, particle orbits and Fokker-Planck operators, for the hydrogenic and impurity ions, as well as injected and alpha particles. Emphasizes connection to experimental confinement and achievement of high beta.

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, ion sources and beam optics, cryogenics, magnetic field generation, and other topics of current interest; brief lectures and literature references to elucidate the physical basis of the laboratory work.

3.7.2 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:

1. Tokamak Group. This group provides state of the art expertise and new contributions to MHD equilibrium and stability theory, neoclassical and anomalous transport, and α -particle physics. Theoretical investigations of MHD equilibrium and ideal and resistive stability limits show that such calculations play a vital role, not only in present and near term experiments, but in the extrapolation of any given configuration to an ignition experiment and reactor.

There are two objectives of the MHD calculations. The first consists of developing an analytic description of MHD equilibria in multi-dimensional configurations such as the tokamak. The goal is to provide qualitative and semi-quantitative scaling information for future experiments and for reactor systems studies (i.e., such information as scaling of toroidal shift with beta, vertical field, location of the separatrix, dependence of β limits on magnetic well, etc.).

The second objective is to determine the most dangerous MHD modes (ideal and resistive) and the corresponding values of critical beta, critical current, etc. An important feature of these calculations is that the equilibrium must be allowed the maximum possible degrees of freedom so that optimization can be carried out to maximize the critical beta.

The transport theory has focused on neoclassical and 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 CIT 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.

2. Mirror and Advanced Toroidal Concepts. The Mirror and Advanced Toroidal concepts group explores theoretical questions related to stability of mirror devices and evaluates the critical theoretical issues in promising advanced toroidal configurations. This group interacts strongly with the Tara experimental program and the focus of the effort will be determined to a significant degree by the direction of that research effort. In this interaction we both focus on theoretical issues that arise from these experiments and lay the groundwork for future research directions. Advanced toroidal concepts of interest include stellarator-like DRAKON devices and advanced TOKAMAK concepts.

Investigators: Professors J.P. Freidberg, D.J. Sigmar; Drs. M. Gerver, C.T. Hsu, J. Kesner, B. Lane, J. Ramos; Messrs. E. Chaniotakis, S.P. Hakkarainen, S. Haney, Y. Lau, G. Svolos, G. Tinios.

Support: U.S. 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 MHD Theory of Magnetic Fusion Systems I
- 22.616 MHD Theory of Magnetic Fusion Systems II
- 22.64J Plasma Kinetic Theory
- 22.65J Advanced Topics in Plasma Kinetic Theory
- 22.66 Plasma Transport Phenomena

3.7.3 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.

1. Whistler Emission Research

Theoretical work is continuing on the explanation of triggered magnetospheric emissions. The progress to date includes a theoretical explanation of the triggering process, complete with a demonstration of the threshold behavior (sometimes known as the dot-dash anomaly) and the generation of specific falling frequency emissions that compare favorably to typical observations made in the controlled experiment based in Siple Station, Antarctic. Most of the features of the emission process can be determined analytically and properties, such as the rate of change of the frequency, related to magnetospheric parameters. For more quantitative predictions such as pulse-shaped evolution and frequency time curves, we have developed a numerical code which integrates the nonlinear wave equations. An interesting feature of the emissions is that the triggering process does not depend on the number of high energy electrons (provided they exist in sufficient quantity to offset convection), but only on bulk magnetospheric parameters such as magnetic field, gradient scale length, and the plasma density in the plasmopause. Also the marginal signals generated just above the threshold are always fuller as is observed. None of these features have been explained by existing theories. Unresolved issues include the mechanism of termination, the generation of risers and hooks for more intense emission situations, and the detailed synchronization of the frequency time and amplitude wave forms. These are all points that should be explainable within the present theory but have not been to date.

2. Boolean Models for Physics

This project is concerned with the computing potential, the programmability, and the learning capabilities of large ensembles of very simple processing elements. It focuses on the applications of fully discrete dynamical systems, mainly cellular automata, for problems generally expressed in term of differential equations. This work relies on and will contribute to the growing cross-fertilization between physics, computer science and discrete mathematics.

It involves a vast experimental use of existing and planned massively parallel computers such as CAM-6, CAM-7, and the Connection Machine.

Previous work has shown the fruitfulness of fully discrete dynamical systems for the qualitative representation of physical phenomena. This program extends this work to develop quantitative predictive power for this branch of applied mathematics, considering specific problems in hydrodynamics and plasma physics, as well as in critical phenomena, growth and pattern formation. The previous work will be enhanced and made quantitative by using tools recently developed for the physics of scaling and complexity. These new tools will also allow the extension of results obtained on cellular automata to two other types of automata networks: neural networks and random Boolean nets, with expected applications to pattern recognition and to the understanding of self-organization.

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 its place one has to develop a new kind of kinetic theory for discrete systems that links them to the continuum descriptions currently used in physics.

Investigators: Professor K. Molvig; Dr. G. Vichniac; Messrs. R. Miller, J. Myczkowski, J. Braunstein, P. Donis.

Support: Office of Naval Research.

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 MHD Theory of Magnetic Fusion Systems I
- 22.616 MHD Theory of Magnetic Fusion Systems II
- 22.64J Plasma Kinetic Theory
- 22.65J Advanced Topics in Plasma Kinetic Theory
- 22.66 Plasma Transport Phenomena

3.8 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, and also including mirror and alternative confinement schemes. 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.

3.8.1 Subjects of Instruction

Subjects of Instruction are the same as those listed in Section 3.7.1.

3.8.2 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 half scale model for the proposed national ignition experiment, CIT, and will provide the opportunity to study the many very important questions concerning CIT's operation and performance.

An important area where the Nuclear Engineering Department faculty and students are involved is the design and implementation of the poloidal field system for Alcator C-MOD. This involves the calculation of MHD equilibria and optimization of the control and programming of the machine. This activity will naturally develop still further, once the machine is constructed and begins operation, and will be crucial to the success of the experiment.

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, and probe and edge diagnostics.

The other main confinement scheme which has been studied in the U.S. in the past few years has been the tandem mirror. Recent decisions concerning the national program have de-emphasized this research, but nevertheless MIT maintains an active program in this area including the operation of the TARA tandem mirror and the Constance machine. Nuclear Engineering students are actively involved in both of these areas and also in the smaller Tokamak program of the RF heating and current drive on MIT's Versator II Tokamak.

Investigators: Professor I.H. Hutchinson, Dr. D.B. Montgomery, Dr. R.F. Post; Messrs. K. Chung, T. Hsu, R. Kirkwood, C. Petty, C. Tsui, K. Wenzel.

Support: U.S. 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:

I.H. Hutchinson, K. Kato and S.C. Texter, "Measurements of Mildly Relativistic Electron Distribution Functions During Lower Hybrid Heating and Current Drive," Rev. Sci. Instr. 57, 1959 (1986).

D.A. Humphreys and I.H. Hutchinson, "Analysis of Vertical Stability in Alcator C-MOD," Bull. APS, 31, 1959 (1986).

I.H. Hutchinson, "Requirements for Ohmic Ignition," MIT Report PFC-JA-86-30 to be published in J. Fusion Energy (1987).

3.8.3 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) Cost-Benefit Assessment of D-D vs. D-T Fuel Cycles

The DT DD and DHe fusion fuel cycles have been compared on the basis of safety and economics. The designs for the comparison employ HT-9 structure and helium coolant: liquid lithium was used as the tritium breeder for the DT fuel cycle. The reactors are pulsed superconducting tokamaks, producing 4000 MW thermal power, and assuming first stability scaling laws. Modest extrapolations of current day technology were employed.

The cost of electricity (COE) produced by the DT fuel cycle was projected to be 57 mills/kWh in 1986 dollars. This cost decreases with increasing plasma beta up to a value of 10%, beyond which no further improvement is seen. The lowest COE for the DD fuel cycle is 85 mills/kWh, at 20% Beta. The COE of the DHe fuel cycle is 79 mills/kWh, assuming a helium-3 cost of 40 k\$/kg. The COE is shown to increase by 10% as the helium-3 fuel cost increases tenfold. Some cost reduction is seen for the tritium handling components of the plasma exhaust and purification system due to the reduced tritium throughput in DD and DHe cycles. However, this is overshadowed by the much higher costs associated with the larger components of the advanced fuel fusion islands. Parametric studies performed for the DT fuel cycle indicate a strong dependence of the COE on the mass utilization factor, or fusion island mass per unit of thermal power produced. A strong influence on the neutron fluence limit on the COE is evident up to 15 (MW.yr)/m²; above this value, the decrease in COE is not large.

The total vulnerable inventory is reduced by a factor of 20 for the DD and DHe fuel cycles compared to DT. The total onsite inventory, including both vulnerable and non-vulnerable forms, is reduced by nearly two orders of

magnitude for the advanced fuels. The average tritium source term at the DD and DHe plants is roughly one one-hundredth that at the DT plants.

There appears to be no great advantage in terms of blanket activation with the advanced fuel for the materials considered in this study. These conclusions are a reflection of the material used and cannot be regarded as a generalization. Because of the large volume of structure used, activity and afterheat levels in the DD blankets exceed that in the DT blankets. The levels found in the DHe blanket are lower than both DT and DD, but are still of significance. Since equal volume fractions of structural material are found in the first walls, activity and afterheat levels are greater for DT. This reflects the high neutron energy and greater flux intensity associated with the DT designs. Higher levels of activity are seen at higher values of beta for a given fuel cycle. None of the wastes produced at the fusion plants qualifies for shallow land burial, although material modifications may allow the criteria to be met.

2) Lithium Fire Kinetics

A series of experiments have been run with the aim of measuring the reaction rate of lithium with nitrogen and oxygen mixture over a wide spectrum of lithium pool temperatures. In these experiments, gas was blown at the controlled flow rate over a preheated lithium pool. The pool had a surface area of approximately 4 cm^2 and a total volume of approximately 6 cm^3 . The system pressure varied from 0 to 4 psig.

Three mixed gas compositions were used: 80% N_2 and 20% O_2 , 90% N_2 and 10% O_2 , and 95% N_2 and 5% O_2 . The reaction rate was obtained as a function of lithium temperature and the oxygen fraction. Liquid lithium temperature varied from 400 to 1100°C . By varying the composition, the degree of inhibition of the lithium-nitrogen reaction rate due to the presence of oxygen was observed. The results indicate that the lithium-nitrogen reaction rate depended on both the fraction of oxygen present and lithium temperature. The lithium nitrite layer formed from the reaction also had a significant inhibition effect on the lithium-nitrogen reaction rate while the lithium-oxygen reaction rate was not as greatly hindered.

LITFIRE, a computer code which simulates temperature and pressure history in a containment building following lithium spills, was modified by including 1) an improved model for the lithium-nitrogen reaction rate and 2) a model for the lithium- CO_2 reaction. LITFIRE was used to simulate HEDL's LC-2 and LA-5 experiments, and the predicted temperatures and pressures were in a reasonable agreement. Furthermore, LITFIRE was applied to a prototypical fusion reactor containment in order to simulate the consequences of a lithium spill accident. The result indicated that if nitrogen was used as containment building gas during the accident, the consequences of the accident would be less severe than those with air. The pressure rise in the building was found to be reduced by 50% and the maximum temperature of the combustion zone was limited to 900°C instead of 1200°C in the case of air.

3) Thermal Margin In Blankets

The ability of liquid metal cooled fusion reactors to remove decay heat during a loss of flow accident (LOFA) has been investigated. Particularly, the temperature rise of coolant through the blanket during a LOFA has been determined for various cases. The STARFIRE and MARS studies were used as references for reactor parameters, and the Blanket Comparison and Selection Study (BCSS) provided blanket designs. For each reactor type a primary loop was defined. Pure lithium, and lithium-lead (Li17-Pb83) coolants were considered; decay heat was not determined precisely, but was assumed to be a small fraction ($\cong 1\%$) of full power.

To calculate the temperature rise of the coolant through the blanket, one-dimensional flow loop equations and energy balances were used. The magnetic field was assumed to remain at the normal conditions. The flow loop equations were then solved for the steady state that emerges some time after a LOFA. The synopsis of the steady state results is that the LiPb coolant can remove decay heat with a temperature rise that is at or below normal operational temperature rise, but a pure lithium coolant cannot remove decay heat without excessive temperature rise. Also, it is seen that the simplicity of the MARS type blanket results in lower temperature rises for tandem mirror reactors than for tokamaks. Finally, a transient analysis which gives temperature rise after a LOFA is initiated was performed. For the lithium cooled tokamak, these studies indicate that it takes about 30 minutes for temperature rise to become excessive for both scenarios. For a lithium cooled TMR it takes about four hours for temperature rise to become excessive.

Investigators: Professors M.S. Kazimi, J. Meyer; Ms. S. Brereton and Ms. D. Hanchar; Messrs. J. Massidda, S. Barnett, T.K. Gil, J. Snyder.

Support: U.S. Department of Energy and EG&G, Idaho.

Related Academic Subjects:

22.38	Reliability Analysis Methods
22.602	Thermonuclear Reactor Design
22.63	Engineering Principals for Fusion Reactors

Recent References:

S.J. Brereton and M.S. Kazimi, "A Methodology for Cost/Benefit Safety Analysis of Fusion Reactors," *Fusion Technology* 10 (2), pp. 275-289 September, 1986.

T.K. Gil and M.S. Kazimi, "The Kinetics of Liquid Lithium Reactors with Oxygen-Nitrogen Mixtures," PFL/RR-86-1, January 1986.

B. Malinovic and M.S. Kazimi, "Passive Decay Heat Removal for Fusion," *Nuclear Technology* 10 (3), pp. 12205-12110 November 1986.

M.S. Kazimi and S.J. Brereton, "A Cost/Benefit Approach to Fusion Safety," Paper presented at IAEA Washington Fusion Safety, Culham November 1986.

3.8.4 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) Compact Ignition Tokamak (CIT) Design: There is active participation in a number of aspects of the design of the CIT, the next major tokamak experiment planned in the U.S. 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. The national CIT project draws heavily on the ignition experiments concepts and engineering approaches originated by the plasma engineering group, particularly the Long Pulse Ignition Test Experiment (LITE) concept. Members of the group are currently working on the CIT project in the areas of magnet design, heating, burn control and diagnostic development.

2) Systems Studies and Superconductor Technology: Concepts have been developed for engineering test reactors using high-field, state-of-the-art Nb₃Sn 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. In addition, new design concepts for demonstration reactors using new high temperature oxide superconductors have been developed, with emphasis on the potential impacts of the combination of very high fields and high temperature operation. Very significant advantages may result if practical magnets can be developed. An experimental research program to study fusion applications of high temperature superconductor materials for magnets and other technologies, as well as system studies activities, is being initiated.

3) Diagnostic Development: Millimeter-wave scattering from plasma fluctuations using a state-of-the-art gyrotron (electron cyclotron resonance master) has been carried out in the TARA tandem mirror. The gyrotron uses a superconducting magnet to provide electron cyclotron resonance. A large variety of phenomena was observed. A concept has been developed for application of gyrotron scattering to measure alpha-particle velocity distribution, the ion temperature, and microinstabilities in the CIT device and funding has been approved for experimental research.

Investigators: Professor J. Freidberg; Drs. D. Cohn, L. Bromberg, P. Woskoboinikow; Mr. J. Williams; Messrs. E. Chaniotakis, J. Machuzak, D. Rhee, J. Schwartz, and J. Wei.

Support: U.S. Department of Energy

3.9 Condensed Matter Sciences

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 measurements, radiation interactions, and computational methods, while the research part involves neutron and laser scattering spectroscopy, and atomistic simulations of materials properties and behavior. The program is part of the Radiation Science and Technology Group which is also composed of the Radiological Sciences program (Section 3.10), the Radiation Health Physics program (Section 3.11), and the physical metallurgy part of the Nuclear Materials program (Section 3.3).

3.9.1 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 (A). Principles and applications of quantum theory of nuclear and charged particle collision sections. Detailed study of partial wave and phase shift analysis, time-dependent perturbation theory, and Born approximation. Optical model description of nuclear reactions. Atomic stopping power. Thermal neutron inelastic scattering in condensed matter.

22.51: Radiation Interactions and Applications, 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.

22.53: 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 Condensed Matter Sciences will take 22.113, 22.51, 22.53, and 22.59.

3.9.2 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 inhomogenities 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 wavelengths 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. M.A. Ricci, Dr. K. Toukan, Dr. G. Briganti

Support: National Science Foundation

Related Academic Subjects:

22.51 Radiation Interactions and Applications

Recent References:

S.H. Chen, K. Toukan, C.K. Loong, D.L. Price and J. Teixeira, "Hydrogen-bond Spectroscopy of Water by Neutron Scattering," Phys. Rev. Lett. 53, 1360, 1984.

J. Teixeira, M.C. Bellissent, S.H. Chen and A.J. Dianoux, "Experimental Determination of the Nature of Diffusive Motions of Water Molecules at Low Temperature," Phys. Rev. A31, 1913, 1985.

J. Teixeira, M.C. Bellissent, S.H. Chen and B. Dormer, "Observation of New Short Wavelength Collective Excitations in Heavy Water by Coherent Inelastic Neutron Scattering," Phys. Rev. Lett. 54, 2681, 1985.

M.A. Ricci and S.H. Chen, "Chemical Bond Spectroscopy with Neutrons," Phys. Rev. A34, 1714, 1986.

3.9.3 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 $\langle I(t)I(t+E) \rangle_t$ 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 μ sec 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, Dr. G. Briganti, Messrs. Y.S. Chao, E.Y. Sheu, C.F. Wu and B. Carvalho.

Support: National Science Foundation

Related Academic Subjects:

- 22.51 Radiation Interactions and Applications
- 8.442 Statistical Optics and Spectroscopy

Recent References:

P.C. Wang and S.H. Chen, "Quasielastic Light Scattering from Migrating Chemotactic Bands of *E. Coli* III," *Biophys. J.*, 1986.

Y.S. Chao, "Studies of Interactions and Critical Behavior of Ionic Micellar Systems by Light and Neutron Scattering," Ph.D. Thesis, Nuclear Engineering Department, MIT, January 1985.

S.H. Chen and J.S. Huang, "Dynamic Slowing-down and Non-exponential Decay of the Density Correlations Function in Dense Microemulsions," *Phys. Rev. Lett.*, 55, 1888, 1985.

3.9.4 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 γ 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; Messrs. T.L. Lin, E.Y. Sheu, and C.F. Wu

Support: National Science Foundation

Related Academic Subjects:

- 22.51 Radiation Interactions and Applications
- 8.442 Statistical Optics and Spectroscopy

Recent References:

- E.Y. Sheu, C.F. Wu and S.H. Chen, "Effects of Ion Sizes on the Aggregation and Surface Charge of Ionic Micelles in 1-1 Electrolyte Solutions," J. Phys. Chem. 90, 4179, 1986.
- R. Nossal, C.J. Glinka and S.H. Chen, "Small Angle Neutron Scattering Studies of Concentrated Protein Solutions: I. Bovine Serum Albumin," Biopolymers 25, 1157, 1986.
- S.H. Chen, "Interactions and Phase Transitions in Micellar and Micro-emulsion Systems Studied by Small Angle Neutron Scattering," Physics 137B, pp. 183-93, 1986.
- D. Bratko, H.L. Friedman, S.H. Chen and L. Blum, "Interpretations of the Intermicellar Structure Factors in the HNC-PY Approximation," Phys. Rev. A23, 2215, 1986.
- T.L. Lin, S.H. Chen, N.E. Gabriel, and M.F. Roberts, "Use of Small Angle Neutron Scattering to Determine the Structure and Interaction of Dihexaolylphosphatidylcholine Micelles," J. Am. Chem. Soc. 108, 3499 1986.
- S.H. Chen and J. Teixeira, "The Structure and the Fractal Dimension of Protein-Detergent Complexes," Phys. Rev. Lett. 57, 2583, 1986.
- E.Y. Sheu, K.E. Goklen, T.A. Hatton and S.H. Chen, "SANS Studies of Protein/Reversed Micelle Complexes," Biotechnology Progress, 2, 175 1986.
- T.L. Lin, S.H. Chen, N.E. Gabriel and M.F. Roberts, "SANS Techniques Applied to the Study of Polydispersed Rodlike Diheptanoylphosphatidylcholine Micelles," J. Phys. Chem. 91, 1535, 1987.

E.Y. Sheu, S.H. Chen and J.S. Huang, "The Structure, Interaction and Growth of Sodium Dodecyl Orthoxylene Sulfonate Micelles in Aqueous Solutions," J. Phys. Chem. 91, 1535, 1987.

M. Kotlarchyk, J.S. Huang, M.W. Kim and S.H. Chen, "Analysis of SANS Data from Dense Microemulsions," Surfactants in Solutions, to be published in 1987.

E. Bratko, E.Y. Sheu and S.H. Chen, "Analysis of Intermicellar Structure Factors with the Mean Spherical and Hypernetted Chain Approximations," Phys. Rev. A, May 1987.

E.Y. Sheu, S.H. Chen and J.S. Huang, "The Structure and Growth of AOT Micelles in Aqueous Solutions," J. Phys. Chem., May 1987.

T.L. Lin, S.H. Chen and M.F. Roberts, "Thermodynamic Analysis of the Structure and Growth of Asymmetric Linear Short-Chain Lecithin Micelles Based on Small Angle Neutron Scattering Data," J. Am. Chem. Soc., May 1987.

C.F. Wu, E.Y. Sheu, D. Bendedouch and S.H. Chen, "Studies of Double Layer Interaction in Micelle and Protein Solutions by SANS," an invited lecture delivered by S.H. Chen in XVI Reunion de Fisica Estadistica, Oaxtepec, Mexico, Jan. 12-15, 1987.

S.H. Chen, T.L. Lin and C.F. Wu, "SANS Study of the Structure, Growth, and Polydispersity of Short-chain Lecithin Micellar Systems -- A Ladder Model Analysis," an invited paper presented at the conference on "Physics of Amphiphilic Layers," Feb 9-19, 1987, Les Houches, France.

S.H. Chen, "Small Angle Neutron Scattering Studies of the Structure and Interaction in Micellar and Microemulsion Systems," Annu. Rev. Phys. Chem. 37, 351, 1986.

3.9.5 Atomistic Simulation Studies of Materials Properties and Behavior

The purpose of this group of projects is to develop techniques of discrete-particle simulation and apply them to fundamental problems in materials science. In the case of molecular dynamics simulation, one integrates numerically Newton's equations of motion for a system composed of typically several hundred atoms and obtains the system properties by appropriate analysis of the resulting atomic positions and velocities. In the case of Monte Carlo simulation, the properties are obtained as ensemble averages over system configurations generated by allowing the atoms to move according to a prescribed transition probability. There are two important advantages of these modeling techniques. First, they enable the macroscopic properties to be directly calculated in terms of atomic structure and interatomic forces. Secondly, they provide detailed microscopic information about structure and dynamics that often cannot be obtained by other means, either theoretical or experimental.

Atomistic simulation has no difficulty in dealing with processes that are highly nonlinear, inhomogeneous, nonequilibrium, or strongly coupled. They are

therefore particularly effective for treating problems that are not amenable to analytical studies. Recent and current studies are diffusion kinetics of point defects, high-temperature properties of grain boundary solids, migration energies and structure of vacancy clusters, and molecular vibrations in hydrocarbon liquids. Each project generally involves an external collaborator who is a scientist at an industrial research laboratory or a national laboratory, and the student gains additional experience by spending some time at the laboratory of the collaborator.

Investigators: Professor S. Yip; Ms. C. Nitta, and Messrs. J. Anderson, K. Cheung, T. Nguyen, and M. Sabochick.

Support: Argonne National Laboratory, IBM Watson Research Center, Schlumberger-Doll Fellowship (1982-86), IBM Graduate Fellowship (1983-86), DOE NSEHPWM Fellowship (1984-), NSF Fellowship (1985-).

Related Academic Subjects:

- 22.53 Statistical Processes and Atomistic Simulation (new)
- 22.71J Physical Metallurgy Principles for Engineers

Recent References:

M.J. Sabochick, "Atomistic Simulation Study of Vacancy Clusters in Copper," Ph.D. Thesis, Nuclear Engineering Department, MIT, December 1985.

C.K. Nitta, "Computer Simulation Study of Grain Boundary Diffusion in Aluminum and Aluminum-Copper Systems," Sc.D. Thesis, Nuclear Engineering Department, MIT, May 1986.

J.J. Anderson, "Atomistic Simulation of Vibrational and Dielectric Properties of Molecular Liquids," Ph.D. Thesis, Nuclear Engineering Department, MIT, May 1986.

P.S. Ho, T. Kwok, T. Nguyen, C. Nitta, and S. Yip, "Observation of Local Melting in an Aluminum Bicrystal by Molecular Dynamics Simulation," Scripta Metallurgica, 1, 993, 1985.

S. Yip, "Atomistic Simulations in Materials Science," Lecture at International Summer School of Physics 'Enrico Fermi,' Varenna, Italy, 1985, in Molecular Dynamics Simulation of Statistical Mechanical Systems, G. Ciccotti and W. G. Hoover, eds (North Holland, Amsterdam, 1986), p. 523.

J. Anderson, J.J. Ullo, and S. Yip, "Inelastic Neutron Scattering by Benzene: Direct Spectral Analysis Using Molecular Dynamics Simulation," Physica 136B, 4056, 1986.

T. Nguyen, P.S. Ho, T. Kwok, C. Nitta, and S. Yip, "Grain-Boundary Melting Transition in an Atomistic Simulation Model," Physical Review Letters 57, 1919, 1986.

J.J. Ullo and S. Yip, "Molecular Dynamics Simulation of Hydrocarbon Molecules in Condensed Phases: II. Liquid in n-Butane," Journal of Chemical Physics 85, 4056, 1986.

M.J. Sabochick, S. Yip, and N.Q. Lamé, "Calculation of Properties of Vacancy Clusters in Copper Using a New, Efficient Energy Minimization Scheme," in Proceedings of International Conference on Vacancies and Interstitials in Metals and Alloys, Berlin, 1986.

J. Anderson, J.J. Ullo, and S. Yip, "Molecular Dynamics Simulation of Hydrocarbon Molecules in Condensed Phases: II. Benzene," Journal of Chemical Physics 86, 4078, 1987.

J. Anderson, J.J. Ullo, and S. Yip, "Molecular Dynamics Simulation of Dielectric Properties of Water," Journal of Chemical Physics, August 1987.

T. Nguyen, T. Kwok, C. Nitta, P.S. Ho, and S. Yip, "High Temperature Properties of an Aluminum Bicrystal Model: I. Melting Transition," Physical Review B, to appear.

3.9.6 Dynamics of Dense Fluids, the Glass Transition, and Defect-Induced Amorphization

This project is mainly concerned with the study of transport and fluctuation phenomena in simple fluid systems which undergo a liquid-glass transition and the study of defect migration and clustering in irradiated crystals which undergo a transition to amorphous structure. Molecular dynamics simulation is used to investigate the atomic-scale behavior of density and current correlations in fluids up to the freezing density and beyond, and the results analyzed using self-consistent mode coupling theory. Simulation is also used to follow the structural relaxation of crystals into which point defects have been introduced and to determine the mechanism of amorphization process.

Investigators: Professor S. Yip; Mr. H. Hsieh.

Support: National Science Foundation, Argonne National Laboratory.

Related Academic Subjects:

- 22.51 Radiation Interactions and Applications
- 22.53 Statistical Processes and Atomistic Simulations (new)
- 22.71J Physical Metallurgy Principles for Engineers

Recent References:

T. Lackner and S. Yip, "Boltzmann-Enskog Equation Analysis of Tagged Particle Motions with Inverse Power Law Interactions," Physical Review, A31, 451, 1985.

J.J. Ullo and S. Yip, "Dynamical Transition in a Dense Fluid Approaching Structural Arrest," Physical Review Letters, 54, 1509, 1985.

L. Letamendia, G. Nouchi, S. Yip, "Kinetic Model of the Generalized Enskog Equation for Binary Mixtures," Physical Review, A32, 1082, 1985.

S. Yip, "Molecular Dynamics," a chapter in Encyclopedia of Physical Science and Technology, Vol. 8, p. 482 (Academic Press, New York) 1987.

S. Yip, "Molecular Dynamics Studies of Glass Transitions: Vitrification and Amorphization," in *Condensed Matter Theories*, R. Kalia and P. Vashishta, eds. (Plenum Press, New York), in press.

Y. Limoge, A. Rahman, H. Hsieh and, S. Yip, "Computer Simulation of Studies of Radiation Induced Amorphization," *Journal of Noncrystalline Solids*, to appear.

3.9.7 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 Principal Investigator and other Co-Investigators consisting of Professors R. E. Cohen and U. W. Suter (Chemical Engineering), D. M. Parks (Mechanical Engineering). The objective of this particular part is to study, using the method of molecular dynamics and Monte Carlo simulations, the atomic motions in melting, quenching through a glass transition, and structural and shear in the glassy state.

Investigators: Professor S. Yip; Messrs. M. Moghimi, M. Sylvester, and M.-J. Wang.

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

Related Academic Subjects:

- 22.53 Statistical Processes and Atomistic Simulations (new)
- 22.71J Physical Metallurgy Principles for Engineers

3.9.8 Interfacial Properties of Semiconductor Materials

This project is part of an MIT-IBM Joint Studies Program. The primary purpose of the project is to apply the techniques of molecular dynamics and Monte Carlo simulation to the study of epitaxial growth of thin films with emphasis on atom aggregation, cluster nucleation, and structural stability of monolayers. Recent developments in the construction of interatomic potentials for semiconductor materials such as silicon have led to expectations that atomistic simulation of interfacial phenomena can provide considerable physical insight. Research involves collaboration with Drs. Paul S. Ho (IBM Yorktown) and F. F. Abraham (IBM San Jose).

Investigators: Professor S. Yip; Mr. T.W. Poon.

Support: IBM Watson Research Center.

Related Academic Subjects:

- 22.53 Statistical Processes and Atomistic Simulation (new)
- 22.71J Physical Metallurgy Principles for Engineers.

3.10 Radiological Sciences

Radiological science covers the general field of radiation and radioisotope applications in biology and medicine. The field includes radiation biophysics, diagnostic techniques including medical imaging, radiation therapy and some aspects of radiopharmaceutical chemistry. Research in this field is rapidly expanding and interfaces with a growing and important area of health care. Research opportunities exist at MIT and at the teaching hospitals.

3.10.1 Subjects of Instruction

The basis subjects of instruction in the radiological sciences field include the undergraduate subject 22.04, Radiation Effects and Uses, and the three graduate subjects, 22.55J, Biological and Medical Applications of Radiation and Radioisotopes, 22.56J, Principles of Medical Imaging, and 22.57J, Radiation Biophysics.

22.04: Radiation Effects and Uses, this course covers a wide range of material concerning ionizing radiation, its origins, uses and hazards. Tours through facilities such as the MIT nuclear reactor, fusion center, positron camera lab, electron microscope lab and Harvard cyclotron lab are integral to the course. Lectures include discussions on the history of radiation research, cosmic rays, nuclear power and weapons, detection methods 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. Principles of nuclear medicine. Requires a comprehensive term paper and presentation.

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 and physics of NMR. Quantitation of images and reconstruction algorithms. Medical applications, biological hazards, and cost-benefit analysis of imaging modalities. A comprehensive term paper required.

22.57J: Radiation Biophysics, covers radiobiology, in vivo models for radiation effects on tumors, mathematical models of cell survival, radiation chemistry, diagnostic radiology and radiation therapy. The contents of this course evolve as new information becomes available for analysis.

3.10.2 Boron Neutron Capture Therapy for Brain Cancer

A highly malignant type of brain cancer, glioblastoma, is fatal for 5000-6000 US residents each year. Conventional modalities of treatment are not effective in treating this cancer. Recently a major project leading to

clinical trials has been funded. The approach is to use neutron capture therapy at the MIT Research Reactor to selectively destroy the malignant cells in high grade astrocytomas. Initially ten patients will be treated. If results are positive, expanded clinical trials will be initiated.

Investigators: Professor O. K. Harling; Dr. J. 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 Radiation Interaction and Applications
- 22.55J Biological and Medical Application of Radiation and Radioisotopes
- 22.56J Principles of Medical Imaging
- 22.561J Magnetic Resonance – Analytic, Biochemical, and Imaging Techniques
- 22.57J Radiation Biophysics

3.10.3 Track ETCH Techniques for Application to Boron Neutron Capture Therapy

A program of preclinical study of BNCT continues. Studies are aimed at the development of track ETCH techniques for determining the distribution of boron compounds in 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; Dr. A.-L. Kariato (Division of Comparative Medicine, MIT).

Support: National Institutes of Health

Related Academic Subject:

- 22.55J Biological and Medical Applications of Radiation and Radioisotopes

Recent References:

G.L. Brownell, J.E. Kirsh and J. Kehayias, "Accelerator Production of Epithermal Neutrons for Neutron Capture Therapy," Second International BNCT Conference, Tokyo Japan, October 1985.

G.L. Brownell, J.E. Kirsh and J. Kehayias, "Accelerator Production of Epithermal Neutrons for Neutron Capture Therapy," Proceedings of the Second International Symposium on Neutron Capture Therapy, October 1985.

J.E. Kirsch and G.L. Brownell, "Improved Methods of Neutron-Induced Track ETCH Autoradiography," Proceedings on the 1st International Symposium on Neutron Capture Therapy, pp. 164-173, October 1983

M. Ashtari, G.L. Brownell and M. Forrest, "Preliminary Dosimetry Studies of the MIT Reactor (MITR-II) Medical Facility," Proceedings of the First International Symposium on Neutron Capture Therapy, pp. 88-98, October 1983.

G.L. Brownell, J.E. Kirsch, J.C. Murphy, M. Ashtari, W.C. Schoene, C. Rumbaugh and G.R. Wellum, "Pre-Clinical Neutron Capture Therapy Trials at MIT Using Na B H SH," Proceedings of the First International Symposium on Neutron Capture Therapy, pp. 304-314, October 1983.

3.10.4 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

Support: National Institutes of Health; U.S. Department of Energy

Related Academic Subject:

22.56J Principles of Medical Imaging

Recent References:

K. McKluskey, G.L. Brownell, C.A. Burnham, D.A. Chesler, D. Kaufman, R.C. McKinstry, C.W. Stearns, D. Wolfson and B.J. Fox, "Video Presentation of PCR-I Studies," Massachusetts General Hospital, J. Nucl. Med. 28, p.1759, April 1987.

C.W. Stearns, D.A. Chesler and G.L. Brownell, "Three Dimensional Image Reconstruction in the Fourier Domain," Massachusetts General Hospital, N.S 34, No. 1, pp. 374-378, February 1987.

E. Livni, J.P. Spellman, J.A. Correia, N.M. Alpert, G.L. Brownell, H.W. Strauss and D.R. Elmaleh, "[C-11]MPTP: A Potential Tracer for Parkinson's Disease Research in Laboratory Animals," J. Nucl. Med. (in press).
H. Kuzuka, D.R. Elmaleh, G.J. Boudreaux, H.W. Strauss, R.H. Ackerman and G.L. Brownell, "N-[11C-methyl]Chlorophentermine and N,

N-[11C-dimethyl]Chlorophentertamine as Brain Blood-flow Agents for Positron Emissions Tomography," J. Nucl. Med. 27 pp. 532-537, 1986.

C.W. Stearns, D.A. Chesler, J.E. Kirsch and G.L. Brownell, "Quantitative Imaging with the MGH Analog Ring Positron Tomograph," IEEE, NS-32(1), pp. 898-890, February, 1985.

A.-L. Kairento, G.L. Brownell, D.R. Elmaleh and M.R. Swartz, "Comparative Measurement of Regional Blood Flow, Oxygen and Glucose Utilization in Soft Tissue Tumor of Rabbit with Positron Imaging," The British Journal of Radiology, 58, pp. 637-643, 1985.

G.L. Brownell, A.-L. Kairento, M. Swartz and D.R. Elmaleh, "Positron Emission Tomography in Oncology - the Massachusetts General Hospital Experience," Seminars in Nuclear Medicine, Grune and Stratton (eds.), 1985.

G.L. Brownell, C.A. Burnham and D.A. Chesler, "High Resolution Tomograph Using Analog Coding," Chapter 2 in The Metabolism of the Human Brain Studies with Positron Emission Tomography, T. Greitz, et al. (eds.) Raven Press, New York, 1984.

G.L. Brownell, T.F. Budinger, P.C. Lauterbur and P.L. McGeer, "Positron Tomography and Nuclear Magnetic Resonance Imaging," Science, 215, pp. 619-626, 1982.

3.11 Radiation Health Physics

The Radiation Health Physics Program is designed to provide students with a strong foundation in the scientific and engineering disciplines needed for the management and control of irradiation exposures. It emphasizes principles of radiobiology, radiation measurement and dosimetry, risk assessment, and management of radiation exposure.

3.11.1 Subjects of Instruction

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

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.

22.37: Environmental Impacts of Electricity, 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.

22.39: 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.

22.51: Radiation Interactions and Applications, 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.

22.55J: 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. Principles of nuclear medicine. Requires a comprehensive term paper and presentation.

22.57J: Radiation Biophysics, covers radiobiology, in vivo models for radiation effects on tumors, mathematical models of cell survival, radiation chemistry, diagnostic radiology and radiation therapy. The contents of this course evolve as new information becomes available for analysis.

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. Assignments for graduate and undergraduate students will differ. Students will have choices in the experiments they perform.

3.12 Energy: Policy and Environmental Issues

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.

3.12.1 Subjects of Instruction

The basic subjects of instruction in the energy field include the undergraduate subject 22.08, Energy, and the two graduate subjects 22.341, 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.

22.085: Introduction to Technology and Law, introduces the basic principles and functions of law, using legal cases and materials arising from scientific and technical issues. Provides an understanding of the law and legal processes as they impact upon the work of engineers and scientists. Study of judicial law making focuses on elementary civil procedure and how change in legal doctrine takes place. Examination of statutory law making shows how federal and state power to govern grows as technology grows. Administrative law making focuses on the regulatory agencies' role in controlling and supporting technology as well as the extent and curbs on their power. Study of law cases, using so-called "Socratic method," and of legal processes and doctrines provides insight into the lawyer's working methods. Law's task of resolving conflicts found in scientific and engineering alternatives sensitizes students to choice of values questions.

22.341: 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.

22.37: Environmental Impacts of Electricity, 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.

22.38: 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.

22.821: 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.

22.82: 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.

22.913: Graduate Seminar in Energy Assessment, is primarily designed as a communication medium among students conducting research in energy related areas, and as a means for obtaining critical evaluation of their ongoing research work. Covers topics ranging from technological comparisons to environmental, social, resource, and political impacts, depending on current student and faculty interest.

3.12.2 International Nuclear Relations

International trade in nuclear equipment, materials and technology is essential for the preservation and expansion of nuclear power's contribution to world energy supplies. The conduct of this trade is complicated by the need to ensure that the goods and services involved are being used exclusively for civilian purposes. The goal of creating a trading regime which maximizes the separation of peaceful and military nuclear activities has been assigned a high priority by the U.S. and other governments since the outset of the nuclear era. Political and diplomatic developments in this field have had an important

impact on the direction taken by nuclear power programs during these years. Conversely, technical and economic developments in nuclear power generation have strongly influenced the nonproliferation policy agenda.

Recent work in this area has focused on the following areas: (1) development of an international regime for spent fuel storage featuring fuel supplier takeback schemes; (2) assessments of the proliferation implications of new processes for uranium enrichment; (3) international safeguards for reprocessing plant in non-NPT states; and (4) physical protection measures for plutonium used as recycle fuel in light water reactors.

Investigators: Professor R.K. Lester, Dr. M. Miller

Related Academic Subjects:

- 22.81 Energy Assessment
- 22.341 Nuclear Energy Economics and Policy Analysis
- 22.841 Nuclear Weapons and Arms Control: Technology and Policy Issues

Recent References:

M.M. Miller, "Stemming the Spread of Nuclear Weapons," *Technology Review*, August/September 1987.

C.A. Eberhard and M.M. Miller, "Reprocessing Plant Safeguards in Non-NPT States," July 1987.

R.K. Lester, "Backing Off the Back End," in A.M. Weinberg (ed.), *The Nuclear Connection*, (Paragon House, New York), 1985.

3.12.3 Nuclear Waste Management Technology

The outlook for civil nuclear power in the United States and several other countries throughout the world is closely linked to the resolution of problems at the back-end of the nuclear fuel cycle, including, especially, the management and disposal of nuclear wastes. The successful performance of mined geologic repositories for final disposal of reprocessed high level wastes or spent fuel is of central importance to the overall effectiveness of the national nuclear waste management program. Analysis of the thermomechanical and thermo-hydrological behavior of the host rock medium is a key element of waste repository design. Past efforts in this area have included the development of models to predict the near-field temperature distribution and far-field temperature, stress and displacement profiles in waste repository host rock and to assess the regulation governing the geologic disposal of high-level waste recently promulgated by the Nuclear Regulatory Commission and the Environmental Protection Agency. During the last year work in this area has focused on the development of methods for evaluating alternative strategies for interim storage, packaging and transportation of spent power reactor fuel.

Investigators: Professors M.J. Driscoll and R.K. Lester; Ms. K. Yuracko, and Mr. V. Pareto.

Related Academic Subjects:

- 22.77 Nuclear Waste Management
- 22.341 Nuclear Energy Economics and Policy Analysis

Recent References:

C.M. Malbrain and R.K. Lester, "An Improved Environmental Pathway Model for Assessing High-level Waste Repository Risks," Health Physics, (forthcoming).

V. Pareto, "Reprocessing As An Alternative To Storage of Spent Fuel," Ph.D. Thesis, Nuclear Engineering Department, MIT, 1986.

K. Yuracko, "Monitored Retrievable Storage of Spent Nuclear Fuel: A Policy Assessment," N.E. Thesis, Nuclear Engineering Department, MIT, 1987.

3.13 MIT Reactor

The MIT Reactor has operated since 1958, most recently at the thermal power of 5,000 kw. 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 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 produce 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, start up and checkout

operation of the modified reactor. Recent studies are in the area of experimental-facility design, fuel management, advanced control systems and in the use of waste heat from the reactor for heating a significant part of the MIT building complex.

While the MITR-II is no longer in the NED, there is a close relationship between the Nuclear Reactor Laboratory and NED. The director of the Nuclear Research Laboratory is Otto K. Harling, Professor of Nuclear Engineering, and he is strongly interested in developing NED projects and uses of the MITR-II. The use of the reactor for nuclear materials research and for teaching of NED subjects is an example.

Investigators: Professors A.S. Argon, R.G. Ballinger, T. Begley, G.L. Brownell, S.-H. Chen, B. Costa, M.J. Driscoll, B. Dyer, B.J. Evans, A. Foster, F.A. Frey, N.J. Grant, O.K. Harling, R. Hon, A. Kaczmarzyk, A. Kitamoto, D.D. Lanning, H. Lechtman, H. Madoc-Jones, V.P. Manno, P.M. Newberne, C. Officer, M. Posner, I.L. Preiss, D.A. Reckhow, R.L. Reuss, A.F. Sarofim, C.G. Shull, P. Sokol, J. Spengler, B. Styr, N.E. Todreas, J.B. Vander Sande, J. Wei, R.A. Wobus, B.J. Wuensch, S. Yip, V.R. Young, R. Zamenhof, A. Zeilinger; Drs. J.A. Bernard, Jr., E.L. Fireman, O. Gebizlioglu, R.I. Henkin, B. Hoop, G. Kohse, I. Olmez, A. Ray, W.E. Robinson, C. Sledge, P. Venkatesaan, J. Zuckerman; Messrs. M. Ames, L. Clark, Jr., J. Cross, W. Fecych, K. Finkelstein, M. Horne, S. Kerekes, K.S. Kwok, C. Lee, C. Lobo, W. Luangdilok, J. O'Connor, C. Oliveira, P. Redmond, C. Tang; Mses. A. Giblin, M. Hayes, B. Lal, N. Memon, A.M. Morillon, K. Yuracko

Support: DOE, EPRI, NSF, NIH and MIT

Related Academic Subjects:

- 22.32 Nuclear Power Reactors
- 22.33 Nuclear Engineering Design
- 22.313 Advanced Engineering of Nuclear Reactors
- 22.314J Structural Mechanics in Nuclear Power Technology

Recent References:

M. Ames, "An Improved Miniaturized Disk Bend Test System," M.S. Thesis, Nuclear Engineering Department, MIT, February 1986.

M. Ames, G. Kohse, T.-S. Lee, N.J. Grant and O.K. Harling, "Mechanical Property and Conductivity Changes in Several Copper Alloys after 13.5 dpa Neutron Irradiation," J. Nucl. Mater., Vol. 141-143, pp. 174-178, 1986.

M. Ames, M.J. Driscoll, O.K. Harling, G.E. Kohse, K.S. Kwok, D.D. Lanning and J.H. Wicks, "Safety Evaluation Report for the PWR Coolant Chemistry Loop (PCCL)," Report No. MITNRL-020, February 1987.

B. Aviles, "State Variable Feedback Techniques for Predictive Control of Nuclear Reactors," S.M. Thesis, Nuclear Engineering Department, MIT, February 1987.

E.J. Ashburner, "Real Time Solutions to Point Kinetics Equations," S.M. Thesis, Nuclear Engineering Department, MIT, September 1986.

J.A. Bernard, and D.D. Lanning, "Issues in the Closed-Loop Digital Control of Reactor Power: The MIT Experience," IEEE Trans. on Nucl. Sci., Vol. NS-33, No. 1, pp. 992-997, February 1986.

J.A. Bernard, K.S. Kwok, R.S. Ornedo, D.D. Lanning and J. Hopps, "The Application of Digital Technology to the Control of Reactor Power: A Review of the MIT Reactor Experiments," Proceedings of the Sixth Power Plant Dynamics, Control and Testing Symposium, Knoxville, TN, April 1986.

J.A. Bernard, "The Construction of Knowledge Base for Use in the Real-Time Control of Research Reactor Power," Proceedings of the Sixth Power Plant Dynamics, Control and Testing Symposium, Knoxville, TN, April 1986.

J.A. Bernard, A.F. Henry and D.D. Lanning, "The Design and Experimental Evaluation of a Closed-Loop Digital Controller Based on the Standard and Alternate Formulations of the Dynamic Period Equation," to be published in IEEE Transactions on Nuclear Science, Vol. NS-34, No. 1, February 1987 (in press).

L. Clark, "Reactor Sharing Program Report for the Period September 1, 1985 to August 31, 1986," Report No. DOE/ER-10770-6, February 1986.

M.J. Driscoll, and A. Morillon, "Prospectus for PWR Coolant Chemistry Control Experiments to be Carried Out on the PCCL Facility at the MIT Research Reactor," Report No. MITNRL-021, February 1987.

M.J. Driscoll, W. Luangdilok, I. Kato and C. Oliveira, "Preliminary Conceptual Design of a General Purpose In-Pile Loop for Simulation of BWR Coolant Chemistry," Report No. MITNRL-018, February 1987.

M.J. Driscoll, O.K. Harling and W. Luangdilok, "Development of a Dose Reduction Research Facility and Test Program," Quarterly Progress Report for January-March 1986, April 1986.

N.J. Grant, O.K. Harling, G. Kohse, J. Megusar and T.-S. Lee, "The Potential for Iron and Copper Based Rapidly Solidified Alloys as Fusion Reactor Materials," invited paper, J. Nucl. Mater. Vol 141-143, pp. 427-433, 1986.

O.K. Harling, and G. Kohse, "Miniaturization of Specimens for Mechanical Testing," an invited paper presented at Workshop on the Relation Between Mechanical Properties and Microstructure Under Fusion Irradiation Conditions held in Ebeltoft, Denmark, June 27-July 2, 1985, Rad. Effects, Vol. 101, pp. 115-129, 1986.

O.K. Harling and G. Kohse, "Development of a Miniaturized Test for Estimation of Ductile-to-Brittle Transition Temperature," Final Report on EPRI Contract No. R2180-12, February 1986.

O.K. Harling and G. Kohse, "Miniaturization of Specimens for Mechanical Testing," an invited paper presented at Workshop on the Relation Between Mechanical Properties and Microstructure.

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, 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 S.B. thesis project. In this manner, the student is prepared for immediate employment at the S.B. 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.

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 advance 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
- 6) Radiological Science
- 7) Nuclear Materials Engineering
- 8) Nuclear and Alternate Energy Systems and Policy
- 9) Radiation Health Physics (SM only)

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.

Fields 1-8 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 eight 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 Principles for Engineers; 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 |
| 22.003 | Nuclear War: Threat and Avoidance |
| 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, Technology, and Medicine |
| 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
22.05	Introduction to Engineering Economics
22.061	Fusion Energy I
22.062	Fusion Energy II
22.069	Undergraduate Plasma Laboratory
22.070J	Materials for Nuclear Applications
22.071J	Physical Metallurgy Principles for Engineers
22.08	Energy
22.084	Inventions and Patents
22.085	Introduction to Technology and Law
22.088J	Human Factors in Design
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
22.341	Nuclear Energy Economics and Policy Analysis
22.35	Nuclear Fuel Management
22.36J	Two-Phase Flow and Boiling Heat Transfer
22.37	Environmental Impact of Electricity
22.38	Reliability Analysis Methods
22.39	Nuclear Reactor Operations and Safety
22.40J	Advanced Reliability Analysis and Risk Assessment
22.571J	General Thermodynamics I
22.572J	Quantum Thermodynamics

Numerical and Mathematical Methods

22.41	Numerical Methods of Radiation Transport
22.42	Numerical Methods in Engineering Analysis
22.43	Advanced Numerical Methods in Engineering Analysis

Radiation Interactions and Applications

22.51	Radiation Interactions and Applications
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- 22.53 Statistical Processes and Atomistic Simulations
- 22.55J Biological and Medical Applications of Radiation and Radioisotopes
- 22.56J Principles of Medical Imaging
- 22.57J Radiation Biophysics
- 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 MHD Theory of Magnetic Fusion Systems I
- 22.616 MHD Theory of Magnetic Fusion Systems II
- 22.63 Engineering Principles for Fusion Reactors
- 22.64J Plasma Kinetic Theory
- 22.65J Advanced Topics in Plasma Kinetic Theory
- 22.66 Plasma Transport Phenomena
- 22.67 Principles of Plasma Diagnostics
- 22.69 Plasma Laboratory

Nuclear Materials

- 22.70J Materials for Nuclear Applications
- 22.71J Physical Metallurgy Principles for Engineers
- 22.72J Nuclear Fuels
- 22.73J Radiation Effects in Crystalline Solids
- 22.74J Mechanical Behavior of Materials
- 22.77 Nuclear Waste Management

General

- 22.81 Energy Assessment
- 22.82 Engineering Risk-Benefit Analysis
- 22.821 Engineering Systems Analysis
- 22.841 Nuclear Weapons and Arms Control: Technology and Policy Issues
- 22.86 Entrepreneurship
- 22.87J Cases and Issues in Engineering Management
- 22.901-4 Special Problems in Nuclear Engineering
- 22.911 Seminar in Nuclear Engineering (Fall)
- 22.912 Seminar in Nuclear Engineering (Spring)
- 22.913 Graduate Seminar in Energy Assessment (Fall)
- 22.914 Graduate Seminar in Energy Assessment (Spring)
- 22.92 Advanced Engineering Internship
- 22.93 Teaching Experience in Nuclear Engineering

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

Civil Engineering

- 1.143J Mathematical Optimization Techniques
- 1.146 Engineering Systems Analysis
- 1.52 Structural Analysis and Design
- 1.581 Structural Reliability
- 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	Thermodynamics of Power Systems
2.55	Advanced Heat Transfer
2.56	Conduction Heat Transfer

Materials Science and Engineering

3.14	Physical Metallurgy
3.25J	Physics of Inelastic Deformation of Solids
3.26J	Micro Mechanisms of Fracture
3.38	Behavior of Metals at Elevated Temperatures
3.39J	Mechanical Behavior of Materials
3.54	Corrosion – The Environmental Degradation of Materials

Electrical Engineering and Computer Science

6.013	Electromagnetic Fields and Energy
6.271	Introduction to Operations Research
6.683	Operation and Planning of Electric Power Systems

Physics

8.312	Electromagnetic Theory
8.321	Quantum Theory I
8.322	Quantum Theory II
8.511J	Theory of Solids I
8.512J	Theory of Solids II
8.641	Physics of High Temperature Plasmas I
8.642	Physics of High Temperature Plasmas II

Chemical Engineering

10.38	Analysis and Simulation of Chemical Processing Systems
10.39	Energy Technology
10.50	Heat and Mass Transfer
10.52	Mechanics of Fluids
10.70	Principles of Combustion
10.86	School of Chemical Engineering Practice—Bethlehem Station
10.87	School of Chemical Engineering Practice—Bethlehem Station
10.88	School of Chemical Engineering Practice—Brookhaven Station

Ocean Engineering

13.21	Ship Power and Propulsion
13.26J	Thermal Power Systems

Economics

14.272	Government Regulation of Industry
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Management

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

Aeronautics and Astronautics

- 16.551 Plasmadynamics and Magnetohydrodynamics

Mathematics

- 18.085 Mathematical Methods for Engineers
- 18.175 Theory of Probability

4.4 Independent Activities Period

The January Independent Activities Period continued to be a very popular event. Professor Michael Driscoll described miniature in-pile loops in his seminar "The World's Smallest (Simulated) Nuclear Reactors." In the area of applied radiation physics, Professor Sow-Hsin Chen conducted an activity entitled "Use of Neutrons as a Microanalytical Tool in Biotechnology." A well attended workshop, sponsored by Professor David Lanning, on "Human Factors in Automatic Digital Control of Nuclear Power-Plants," deals with various man-machine interface aspects introduced by computerized control. Professor Norman Rasmussen presented his now traditional seminar on "Engineering WAGS (Wise Astute Guesses)," designed to teach the use of rough approximations to get answers quickly.

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 December 1985, the department has introduced seven 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

- 22.011 Seminar in Nuclear Engineering
- 22.012 Seminar in Fusion and Plasma Physics
- 22.013 Applications of Radiation in Science, Technology, and Medicine
- 22.113 Nuclear and Atomic Collision Phenomena
- 22.53 Statistical Processes and Atomistic Simulations
- 22.59 Principles of Nuclear Radiation Measurement and Protection
- 22.74J Mechanical Behavior of Materials

B. Subjects Retitled

The following subjects have been renamed:

22.09	Principles of Nuclear Radiation Measurement and Protection
22.841	Nuclear Weapons and Arms Control: Technology and Policy Issues
22.87J	Cases and Issues in Engineering Management

C. Subjects No Longer Offered

Since our last Activities Report, the following subjects are no longer offered by the Department:

22.112	Nuclear Physics for Engineers II
22.29	Nuclear Measurements Laboratory
22.44J	Computational Methods in Materials Science and Engineering
22.58	Principles and Practice of Radiation Measurement and Protection
22.75J	Radiation Effects in Reactor Structural Materials

4.7 Undergraduate Program

The Undergraduate Program in nuclear engineering is

- founded on engineering fundamentals;
- illustrated by applications to practical nuclear engineering examples; and
- adjusted to individual preferences for areas of study.

The program incorporates many subjects from other MIT departments which enables the program to be given in an efficient way using existing resources.

4.7.1 Description of the Undergraduate Program

Most students are expected to choose an area of study in one of three tracks:

a) Fission Track

The fission option includes design, analysis, and operations topics associated with light water reactor plants and with other fission reactor plant concepts. This education is preparation for direct career placement or for entry to graduate school.

b) Fusion Track

The fusion option is intended for students planning careers in areas of research or engineering development for fusion power reactors. This will, in most cases, require an advanced degree. Generally, more knowledge of mathematical physics and electromagnetism is needed in this area than in the other options in nuclear engineering.

c) Radiological Sciences Track

The radiological sciences option is intended for students planning careers in medicine or biomedical engineering with particular emphasis on the

applications of radiation in diagnostics and therapy.

There are other combinations of subjects that make educational sense and fit all MIT and Department requirements. Student and advisor conferences are used to determine a suitable combination for each individual.

In each of these options, the content of the curriculum can be divided into several categories. The first category contains requirements that apply to all MIT undergraduates and are therefore not considered part of the departmental program. These requirements include: five entry level subjects in chemistry, physics, and mathematics; eight subjects in humanities, arts, and social studies (with rules on selection of "distribution" and "concentration" subjects); a science distribution subject outside of the departmental program; and a demonstration of writing proficiency.

The second category is the background portion of the departmental requirements. A seminar is specified to provide familiarity with departmental academic and research activities. The requirements also include one differential equations subject, one that supplements the entry level physics, and one that supplies an introduction to applied nuclear physics.

The third category is engineering principles. It is a major component in the departmental program and covers the foundations of engineering practice. The required topics of study are strength of materials, fluid flow, thermodynamics, heat transfer and computer modeling.

The remaining categories in the departmental program are nuclear engineering specialties and a bachelor's thesis. Requirements include a laboratory subject, a subject dealing with physics as applied to nuclear reactors, and three subjects dealing with design and systems.

This program has remained small since its inception in 1975 (6 to 10 degrees granted per year). However, it has produced many quality graduates who continue to contribute in engineering graduate schools, in medical schools, and in industry/research.

4.7.2 Subjects of Instruction

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

22.006: Computer Models of Physical and Engineering Systems, reduction of physical and engineering systems to idealized computer models; selection of numerical algorithms to explore model behavior. Linear and nonlinear equations, curve fitting, integration, finite differences, finite elements, initial-value problems. Examples drawn from fields primarily of interest to engineers. Extensive "hands-on" computing experience. Working knowledge of FORTRAN, PASCAL, or C expected.

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 Plasma Fusion Center experimental facilities.

22.013: Applications of Radiation in Science, Technology, and Medicine, seminar explores a wide range of topics in radiation effects and uses. Some involve state of the art experimental techniques, others make use of unique laboratory facilities or novel computer simulation programs. Each is a current area of teaching or research for one or more faculty members. Most lectures are accompanied by laboratory demonstrations.

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; engineering and heat-transfer principles. Description of various reactor types (LWR, LMFBR, etc.). Emphasizes reliability and reactor safety methods for improving design and operation of future reactors.

22.031: Engineering of Nuclear Reactors, engineering principles of nuclear reactors, emphasizing power reactors. 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. Meets with 22.312, but examinations differ.

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 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. Meets with 22.33, 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.

22.061: 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.

22.062: Fusion Energy II, basic engineering and technology of controlled thermonuclear reactors. Current confinement devices: tokamaks, mirrors, alternative concepts. Thermonuclear reactors: systems analysis and design of power reactors, ignition experiments, hybrid reactors. Reactor technologies: neutronics, blanket design, magnet design, first wall, materials and activation, heating technology, tritium handling. Present reactor designs; detailed critical review of prototype reference reactor designs. Safety and environment. Meets with 22.602, 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. Application 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.

22.071J: Physical Metallurgy Principles for Engineers, thermodynamics and stability of alloy phases. Diffusion-controlled rate processes. Defect properties and mechanical properties. Emphasizes structural evolution, structure-property relations, and the common features among various materials. Introduces quantitative analysis in physical metallurgy for engineering materials. Meets with 22.71J, 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.

22.088J: Human Factors in Design, analyzes human and computer roles, interfacing and reliability in nuclear and chemical plants, air traffic control, industrial robots, office automation, and other systems. Introduces methods for measurement of and statistical inference about human behavior in such interactions. Reviews human sensory and motor performance characteristics and the derivation of human engineering design criteria for displays and controls. Readings from the human factors engineering literature. Case studies and design projects.

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 , and 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.

A total of six—three graduate, one senior and two juniors are now in the program. Companies which have placed students from the Nuclear Engineering Department are Brookhaven National Laboratory, Commonwealth Edison, EG & G, Idaho, Stone and Webster Engineering Corporation, and Los Alamos National Laboratory.

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: Plasma Physics and Controlled Fusion (K. Molvig); Innovative Nuclear Reactor Designs (M. Driscoll); Nuclear Science and Engineering: A Sampling (D. Lanning); Systems Simulation with DNSP (A. Schor).

5. RESEARCH FACILITIES

5.1 M.I.T. Reactor

As of July 1976, the M.I.T. Reactor became an Institute facility. 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.

Since its shutdown in May 1974, the Reactor has been redesigned and restarted. On July 1, 1976, it was designated an Institute laboratory under the responsibility of the Vice President for Research. Professor Otto Harling was appointed Director of the Nuclear Reactor Laboratory. In this new mode of operation it is hoped that the facility will be more broadly used by the MIT research community.

The Nuclear Engineering Department will continue to be a major user of this facility. Programs in neutron scattering, fast reactor blanket studies, nuclear materials, coolant corrosion, computer control for reactors, and medical applications described earlier in this report will still depend heavily upon the reactor.

5.2 Computing Facilities

The Nuclear Engineering Department has continued to upgrade and expand its computer facilities in order to give its students an even greater variety of equipment and computational power.

New peripherals, including a Laserprinter and plotter, have been added to the computer room at Building NW12-234. At our second location, the addition of 2 MicroVAX/VMS systems and the recent addition of 5 MicroVAX/UNIX systems, which are networked into the university-wide Project ATHENA workstation system, necessitated the move to a larger space. This new facility in Building 24-023A has been designed with special attention to lighting, temperature control, wiring and restricted access devices.

A number of students continue to use the MIT IBM 4381 for work which requires the strengths of a mainframe system. Communication with computers at other universities and national laboratories is provided by BITNET, TELENET and others, while undergraduates and those involved in curriculum development enjoy the campus-wide networking enabled within the Project ATHENA system.

A departmental code library is supported within which a collection of widely used reactor design and analysis codes is maintained. In addition students are given advice, assistance and instruction in the use of these codes and the available computer tools.

5.3 Nuclear Engineering Department Teaching Laboratories

The Nuclear Engineering Department teaching laboratories are specially equipped rooms located in Buildings NW12-133 and NW13-133. The

NW12-133 (22.09/59 Principles of Nuclear Radiation Measurement and Protection) laboratory combines lectures, demonstrations, and experiments. The course 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. Demonstrations and experiments using the MIT research reactor, accelerators, and power reactors are also included.

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

Neil E. Todreas

Professor of Nuclear Engineering, Head of the Department; B. and M.Mech.E. '58, Cornell; Sc.D. '66 (nuclear engineering) MIT; Reactor engineering; reactor thermal analysis; heat transfer and fluid flow.

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 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.

Thomas J. Dupree

Professor of Nuclear Engineering and Physics; B.S. '55, Ph.D. '60 (physics) MIT; Mathematical physics; particle transport theory; plasma kinetic theory.

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; Associate Director, Energy Laboratory; 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 Hutchinson

Associate Professor of Nuclear Engineering; B.A. '72 Cambridge University; Ph.D. '76 (plasma physics) Australian National University; Experimental plasma physics; controlled fusion.

Irving Kaplan

Professor of Nuclear Engineering, Emeritus; A.B. '33, A.M. '34, Ph.D. '37 (chemistry) Columbia; Nuclear physics; reactor analysis; reactor physics measurements; history of science and technology.

Mujid S. Kazimi

Professor of Nuclear Engineering; B.S. '69 University of Alexandria, Egypt; M.S. '71, Ph.D. '73 (nuclear engineering) MIT; Fusion and fission reactor safety; reactor engineering.

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

Arco Associate Professor in Energy Studies; 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

Professor of Nuclear Engineering; 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 Nuclear Engineering and Metallurgy; Met.E. '59 Colorado; Ph.D. '64 (nuclear engineering) Carnegie Institute of Technology; Radiation effects on materials.

Nathan O. Siu

Assistant Professor of Nuclear Engineering; B.S. '77, S.M. '80, Ph.D. '84 (nuclear engineering) UCLA; Risk and reliability analysis, systems modeling.

Dieter J. Sigmar

Adjunct Professor of Nuclear Engineering; M.S. '60, Ph.D. '65 Technical University of Vienna; Plasma theory and controlled thermonuclear fusion research.

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 Personnel (as of August, 1987)Professor

M. Benedict (Institute Emeritus)
 G.L. Brownell
 S.H. Chen
 M.J. Driscoll
 T.H. Dupree (joint w/Physics)
 J.P. Freidberg
 M.W. Golay
 E.P. Gyftopoulos (joint w/Mechanical)
 K.F. Hansen (Assoc. Dir., Energy Lab)
 O.K. Harling (Dir., NRL)
 A.F. Henry
 I. Kaplan (Emeritus)
 M.S. Kazimi
 D.D. Lanning
 L.M. Lidsky
 J.E. Meyer
 N.C. Rasmussen
 K.C. Russell (joint w/MS&E)
 N.E. Todreas (Department Head)
 S. Yip

Associate Professor

R.G. Ballinger (joint w/MS&E)
 I.H. Hutchinson
 R.K. Lester
 K. Molvig

Assistant Professor

N.O. Siu

Adjunct Professor

D.J. Sigmar (Research Staff/PFC)

Senior Lecturer

F.X. Masse (RPO/Medical)

Lecturer

J.A. Bernard (Research Staff/NRL)

Senior Research Engineer

D.B. Montgomery (joint w/PFC)
 J.E.C. Williams (joint w/FBNML)

Senior Research Scientists

D.R. Cohn (joint w/PFC)
 M.M. Miller (joint w/CIS)

Research Staff

R.M. Morton

Research Affiliate

D.C. Aldrich
 R. Christensen
 J.H. Hopps, Jr.
 A. Schor
 K. Smith
 W.E. Vesely
 L. Wolf

Administrative Officer

J.B. deVries Gwinn

Administrative Staff

C.M. Egan

Support Staff

L. Arduino
 P. Cornelio
 A. Hudson
 E. Kehoe
 M. Levine
 C. Lydon
 E. Parmelee
 G. Rook
 L. Sparks
 L. Suter

Visiting Professor

S. Bacharach (joint
 w/Whitaker) NIH

Visiting Assistant Professor

V. Manno (Tufts U.)

Visiting Engineer

M. Mori (I-H Heavy
 Industries Co., Ltd.,
 Japan)

Visiting Scientist

G. Briganti (U. of Rome,
 Italy)

6.3 Complete List of Graduate Student Staff (as of Spring 1987)Teaching Assistants

Christopher, Edward
 Chu, Tak Sum
 Dehbi, Abdelouahab
 Eland, Bernice
 Free, Scott
 Houts, Michael
 Hsu, Thomas
 Hwang, Il Soon
 Jurgensen, Teese
 Kwapong, Oheneaku
 Lapp, Christopher
 Love, Edward
 McInall, Steven
 Neuder, Michelle
 Plomgren, Susan
 Sich, Alex
 Siegel, Matthew
 Vance, Scott

Research Assistants

Alfeo, Joseph
 Aviles, Brian
 Barakat, Abdel
 Barnett, David
 Bieri, Robert
 Bushko, Dariusz
 Chaniotakis, Emmanouil
 Chien, Daisy
 Chung, Kyu-Sun
 Cooper, Susan
 Coxe, Raymond
 Depiante, Eduardo
 Dias, Antonio
 Dimitrijevic, Vesna
 Farish, Thomas
 Fu, Gang
 Hakkarianen, Pekka

Research Assistants

Hsieh, Horngming
 Izatt, Joseph
 Kao, Lain-Su
 Kupfer, Kenneth
 Laughton, Peter
 Luangdilok, Wison
 Machuzak, John
 Meyers, Kenneth
 Miller, Ronald
 Moghimi, Mohammadali
 Mogstad, Torkil
 Morillon, Anne
 Myczkowski, Jacek
 Outwater, John
 Palmer, Matthew
 Pendergast, Ken
 Peng, Scott
 Poon, Tze
 Psaila, Maureen
 Reese, Timothy
 Rempe, Ken
 Rhee, David
 Sands, Mark
 Sasson, Eric
 Seong, Poong
 Spira, Susan
 Stewart, William
 Tanker, Ediz
 Tinios, Gerasimos
 Tsui, Chi-Wa
 Wang, Dan
 Wang, Ling
 Wang, Pei-Wen
 Wei, Jiann
 Witt, Robert
 Wong, Dilys
 Wong, Frank
 Wu, Chuan Fu
 Yoon, Peter
 Zerkle, Michael

7. DEPARTMENTAL STATISTICS (Summary)

Academic Year Sept- June	September Registration				Degrees Granted					No. of Professors	No. of Subjects
	Under-graduate	Graduate	Special	Total	B.S.	S.M.	Nucl. E.	Sc.D., Ph.D.	Total		
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	58
86 - 87	20	150	1	171	6	32	3	20	61	25	66
TOTALS					95	1016	151	471	1733		

Note: AY 1973/74 - 1985/86 statistics updated to agree with Bruce Report, July 1987.

8. STUDENTS

Chapter 8 presents statistical information about the 141 full-time graduate students registered in the Department during the spring term 1987. Table 8.1 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 and electrical engineering majors.

The distribution of schools from which our domestic students are drawn is very widespread. Approximately 13% of our domestic graduates entered the Department with degrees from MIT. Our international student population represents 40% of our total graduate enrollment for the spring term 1987. This number reflects an increase in our international representation since the last report.

Table 8.2 summarizes the various sources of financial support available for the spring term 1987. 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 8.3. 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 8.1 summarizes the distribution of types of first employment of our graduate students through June 1987.

Table 8.1 (continued)

By Country (141)

Algeria	(1)
Argentina	(1)
Bangladesh	(1)
Brazil	(4)
Canada	(3)
Chile	(2)
Finland	(1)
France	(1)
Ghana	(1)
Greece	(2)
Guatemala	(1)
India	(1)
Iran	(1)
Japan	(2)
Korea	(8)
Morocco	(1)
Nigeria	(1)
Pakistan	(1)
People's Republic of China	(3)
Poland	(2)
Republic of China	(13)
Saudia Arabia	(1)
Thailand	(1)
Turkey	(2)
United Kingdom	(1)
United States of America	(84)
Yugoslavia	(1)

Table 8.2

Sources of Financial Support
(as of Spring Term 1987)

Research Assistantship	(57)
Teaching Assistantship	(18)
DOE Radioactive Waste Management Fellowship	(6)
DOE Magnetic Fusion Energy Science Fellowship	(1)
DOE Nuclear Energy/ Health Physics Fellowship	(2)
DOE Magnetic Fusion Energy Technology Fellowship	(4)
Pickard, Lowe & Garrick (PLG) Fellowship	(1)
Rotary Foundation	(1)
Mellon Foundation	(1)
LASPAU	(1)
Abbott, Brewer & Zoepfl (ABZ) Fellowship	(1)
NIH Trainee	(5)
Sherman Knapp Fellowship	(1)
NSF Fellowship	(3)
NASA Fellowship	(1)
Thompson Fellowship	(1)
Benedict Fellowship	(1)
Rockwell Fellowship	(1)
TRW Fellowship	(1)
Graduate Professional Opportunity Program	(1)
U.S. Army	(4)
U.S. Navy	(1)
Government of Nigeria	(1)
Government of Canada	(1)
Government of Chile	(1)
Government of Korea	(4)
Government of Brazil	(3)
Government of Republic of China	(2)
Government of Japan	(1)
Government of Saudi Arabia	(1)
Government of Pakistan	(1)
Government of Turkey	(1)
Self-supported	(10)
Outside support	(2)

Table 8.3

Activities of Nuclear Engineering Department Graduate Students

(Place of first employment — information current as of June 1987)

U. S. Industry and Research (425) (28.4%)

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 (10)
 Bechtel (5)
 Bendix
 Berkeley Research Associates
 Bettis (4)
 Booz, Allen & Hamilton
 Boston Edison
 Burns & Roe (3)

 California Oil
 Colonial Management Associates
 Combustion Eng. (21)
 Commonwealth Edison (15)
 Computer Processing
 Conn. Mutual Life Ins.
 Consolidated Edison (3)
 Consultant
 Consumers Power
 Cornell Univ. (research)
 Creare Research & Development

Detroit Power Co.
 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)
 EPM, Inc. (4)
 EPRI
 Exxon Research & Eng.

 Fauske & Associates, Inc.

 GA Technologies
 Georgia Power Co.
 General Atomic (5)
 General Dyn., Elec. Boat (7)
 General Electric (30)
 Gulf General Atomic (18)

 Hercules
 Hewlett-Packard
 Hughes (5)
 Hybrid Systems
 Hanford Eng. Dev. Lab.

 IBM (3)
 Industrial Tech. Services Inc.
 Inst. for Defense Analysis
 Internuclear Co.
 Isotopes, Inc.

Table 8.3 (continued)

Jackson & Moreland	Perkin-Elmer Co.
Jet Propulsion Lab	Philco
Lane Wells	Pickard, Lowe & Garrick (2)
A.D. Little (4)	Planning Research Corp.
Lockheed	Princeton (research) (5)
Long Island Lighting Co.	Public Service Elec. & Gas
	Purdue (research)
Management & Tech. Cons.	Radiation Tech.
Martin-Marietta (3)	Rand Corp.
Mass. General Hospital (5)	RCA Research Lab
Maxson Electric	Resources for the Future
McKinsey & Co. (2)	Sanders Corp.
MIT (research) (26)	Science Applications (7)
Mobil Oil	Scientific Data Systems
Monsanto	Siemens Medical Systems
MPR Associates (3)	Sloan Kettering Mem. Hospital
National Nuclear Corp. (2)	Smithsonian Astrophys. Obs.
National Academy of Eng.	Southern Calif. Edison (4)
New England Nuclear Corp.	Spire Corp.
New England Power Service Co.	Stanford Research Institute
New York Law Firm	S.M. Stoller Assoc.
North American Rockwell (2)	Stone & Webster (14)
Northeast Utilities Serv. (4)	Systems Sci. & Eng.
Northern Research & Eng. (3)	Systems Control
Nortronics	
Nuclear Fuel Service (2)	Texaco
Nuclear Mater. & Equipment	Texas Instruments
Nuclear Products	Thermo Electron (2)
Nuclear Utility Services (4)	TWR Systems (2)
NUS Corporation (2)	
NUTECH Engineers	Union Carbide
	United Aircraft (3)
	United Eng. & Constr. (2)
	United Nuclear (5)

Table 8.3 (continued)

U. of Calif. (research) (3)	Army Nuc. Def. Lab.
U. of Maryland (research)	Army Research Lab. (2)
U. of Texas (research)	Ballistic Research Lab
U. of Wisc. (research) (2)	CIA
Vacuum Industries	Coast Guard
Wastechem	Dept. of Commerce
Watkins-Johnson	Dept. of Energy
Westinghouse (32)	Energy Res. & Dev. Admin. (5)
Wisconsin Electric	Environmental Prot. Agency (2)
Yale (research) (2)	NASA
Yankee Atomic (18)	Nat. Bureau of Standards
<u>National Laboratories (100) (6.7%)</u>	Naval Research Lab
Argonne (18)	Navy (63)
Brookhaven (7)	Nuclear Regulatory Comm. (4)
Knolls Atomic Power (18)	Peace Corps
Lawrence Livermore (6)	Picatinny Arsenal
Lawrence Radiation (5)	Dept. of Public Health
Los Alamos (15)	<u>Teaching (66) (4.4%)</u>
Oak Ridge (17)	American Univ. (Wash., D.C.)
Sandia (9)	Brooklyn College (CCNY)
Savannah River (5)	Calif. State (Long Beach)
<u>Further Study (257) (17.1%)</u>	Carnegie Mellon Univ.
MIT (218)	Case Institute
Other (39)	Catholic Univ. of America
<u>U.S. Government (212) (14.1%)</u>	Cornell
Atomic Energy Commission (22)	El Rancho High School
Air Force (17)	Georgia Inst. of Tech.
Army (85)	Howard University
	Iowa State
	Kansas State
	Lehigh
	Lowell Tech (4)
	Loyola University

Table 8.3 (continued)

Mass. Maritime Academy
 Michigan State University
 MIT (13)
 Northeastern University
 Northwest Nazarene
 Pennsylvania State
 Princeton
 Purdue
 Radford College
 Rensselaer Polytech.
 Swarthmore
 Texas A & M (2)
 U.S. Military Academy
 Univ. of British Columbia
 Univ. of California (9)
 Univ. of Florida
 Univ. of So. Florida
 Univ. of Illinois (2)
 Univ. of Kentucky
 Univ. of Missouri (2)
 Univ. of New Hampshire
 Univ. of Texas
 Univ. of Washington
 Univ. of Wisconsin (2)

Foreign (249) (16.6%)

Algeria (4)
 Argentina (8)
 Belgium (10)
 Brazil (27)
 Canada (14)
 Chile (11)
 Columbia, S.A. (2)
 England (2)

France (26)
 Germany (3)
 Greece (6)
 India (13)
 Indonesia
 Iran (26)
 Israel (4)
 Italy (5)
 Japan (17)
 Jordan
 Korea (10)
 Libya (1)
 Malaysia (2)
 Mexico
 Nigeria
 Norway
 Pakistan (4)
 People's Republic of China
 Philippines
 Poland
 Republic of China (15)
 Saudi Arabia
 Spain (14)
 Switzerland (7)
 Turkey (4)
 Venezuela (5)

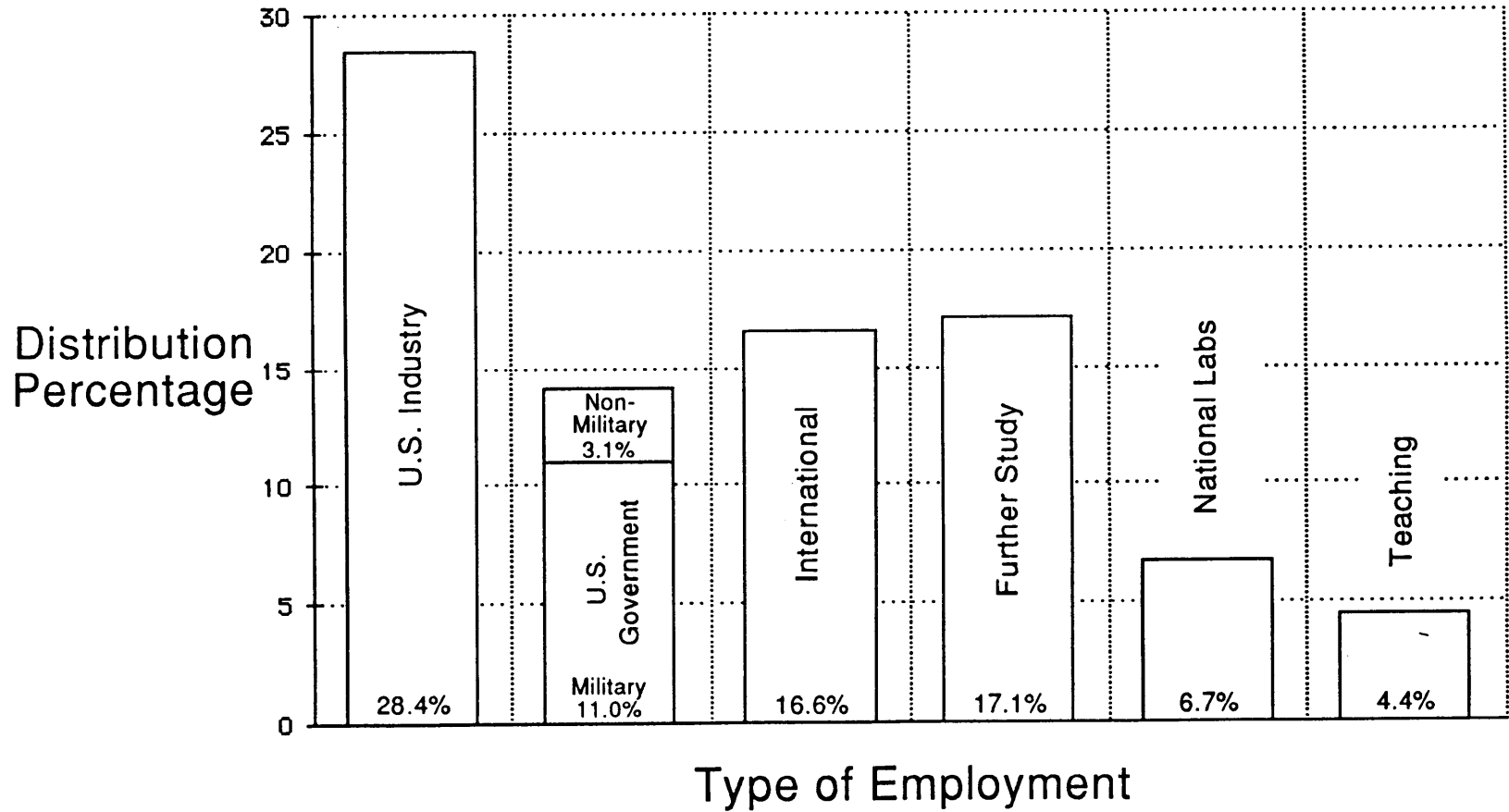
Not Reported (191) (12.7%)

TOTAL 1500*

*Records from early years are incomplete

Figure 8.1

Distribution of First Place of Employment of Nuclear Engineering Graduates* (as of June 1987)



* Excludes 191 (12.7%) Students Not Reporting

9. LIST OF THESES
(FEBRUARY 1986 - JUNE 1987)

The following theses were submitted to the Department of Nuclear Engineering in February 1986:

G. Abu-Zaied, "Control of PWRs Using Moderator Displacement and Fuel Assembly Reconstitution," Sc.D. Thesis.

M.R. Ames, "A Characterization of the Post-Irradiation Properties of Copper Alloys for Fusion Applications," S.M. Thesis.

E.H. Esarey, "Stabilization of the Tearing Mode by Turbulent Diffusion and Runaway Electrons," Ph.D. Thesis.

V.P. George, "Human Machine Interface System for MITR-II," N.E./S.M. Thesis.

T.K. Gil, "Lithium-Mixed Gas Reaction Kinetics," S.M. Thesis.

D.A. Petti, "Ag-In-Cd Control Rod Behavior and Aerosol Formation in Severe Reactor Accidents," Sc.D. Thesis.

C.C. Petty, "A High-Power Radio-Frequency Plasma Source," S.M. Thesis.

T.S. Ro, "Porous Body Analysis of Vertical Rod Bundles Under Mixed Convection Conditions," Ph.D. Thesis.

M.J. Sabochick, "Atomistic Simulation Study of Vacancy Clusters in Copper," Ph.D. Thesis.

R.G. Sanchez, "Passive After Heat Removal: Sensitivity Study for Modular Pebble Bed Reactors," S.M. Thesis.

M.J. Schor, "Control of Multi-module Nuclear Reactor Stations," S.M. Thesis.

E. Tanker, "Matching the Solution of the Transport Equation With Diffusion Theory Using Average Discontinuity Factors," S.M. Thesis.

S.C. Texter, "Plasma X-ray Spectroscopy During Lower Hybrid Current Drive on Alcator," Ph.D. Thesis.

C. Vlahoplus, Jr., "Safety Regulation of Advanced Reactors: Evolution of a Nonprescriptive Safety Regulatory Approach as Applied to Station Blackout," S.M. Thesis

The following theses were submitted to the Department of Nuclear Engineering in June 1986:

J.J. Anderson, "Atomistic Simulation of Vibrational and Dielectric Properties of Molecular Liquids," Ph.D. Thesis.

- A.V. D'Amico, "Analysis of Mammalian Tumor Vascularization in the Development of a Therapy to Prevent Metastasis," Ph.D. Thesis.
- B.C. Day, "Instrumentation for the Leak-Before-Break Concept," S.M. Thesis.
- R.M. Erickson, "Far-Infrared Polarimetry/Interferometry for Poloidal Magnetic Field Measurement on ZT-40M," Sc.D. Thesis.
- M.H. Fellows, "A Scoping Level Probabilistic Risk Assessment of a Pebble Bed Modular High Temperature Gas Cooled Reactor," Ph.D. Thesis.
- R.W. Fieldhack, "The Fuel Cycle Economics of PWR Extended Burnup," S.M./S.B. Thesis.
- W.H.G. Francis, "A Systematic Treatment of Earlier Nodal Methods Using the Analytic Nodal Method," Sc.D. Thesis.
- R.G. Gamino, "The Development and Application of Supernodal Methods to PWR Analysis," Ph.D. Thesis.
- P.J. Goodrich, "Neutral Particle Transport in the Tara Tandem Mirror Equipment," S.M. Thesis.
- G.M.J.K. Hilfer, "A Theory of Magnetospheric VLF Emissions," Ph.D. Thesis.
- V. Iannello, "Mixed Convection in Vertical Parallel Channels Connected at Upper and Lower Plena," Sc.D. Thesis.
- D.N. Kennedy, "A System for Three-Dimensional Analysis of Magnetic Resonance Images," S.M. Thesis.
- B.L. Labombard, "Poloidal Asymmetries in the Limiter Shadow Plasma of the Alcator C Tokamak," Sc.D. Thesis.
- R.J. LeClaire, Jr., "Conceptual Design of a Commercial Tokamak Reactor using Resistive Magnets," Sc.D. Thesis.
- T.-L. Lin, "Study of the Structure and Growth of Lecithin Micelles and Microemulsions," Ph.D. Thesis.
- J.L. Maneke, "Radiation Releases from MHTGR Confinement Buildings," Ph.D. Thesis.
- M.A. Marks, "An Auxiliary Large Field Electron Beam Flattening Filter," S.M. Thesis.
- R.A. Morchio, "An Instrumentation and Control Strategy for a Nuclear Program - The Case of Argentina," S.M. Thesis.
- T. Nguyen, "Current Density and Temperature Distribution in VLSI Multilevel Interconnects," S.M. Thesis.
- C.K. Nitta, "Computer Simulation Study of Grain Boundary Diffusion in Aluminum and Aluminum-Copper Systems," Sc.D. Thesis.

R.S. Ornedo, "Concept and Demonstration: A Reconfigurable Control System for Nuclear Power Plants," Ph.D. Thesis.

V.E. Pareto, "Reprocessing as an Alternative to Storage of Spent Nuclear Fuel," Ph.D. Thesis.

A.G. Parlos, "Non-Linear Multivariable Control of Power Plants Based on the Unknown-but-Bounded Modeling Methodology," Sc.D. Thesis.

C.B. Paschal, "Positron Emission Tomography (PET) Analysis of the Effects of Auditory Stimulation on the Distribution of C-N-Methylchlorphentermine in the Brain," S.M./S.B. Thesis.

J.J. Petillo, "Equilibrium and Stability Properties of an Intense Relativistic Electron Ring in a Modified Betatron Accelerator," Ph.D. Thesis.

M.J. Psaila, "Analytic Crevice and Crack Tip Modeling in Aqueous Environments," S.M. Thesis.

K.R. Rempe, "Analysis of Zion-2's First Cycle of Operation with Nodal Methods," S.M. Thesis.

P.E. Reyes-Morel, "An Experimental Study of Constitutive Relations of Transformation Plasticity in Zirconia Based-Ceramics," Ph.D. Thesis.

K.-C. Tran, "Technology Acquisition Success Factors," S.M.(JMT) Thesis.

G.-S. Ueo, "Uncertainty Estimation and Signal Validation for Performance Monitoring of Power Plant Components," Ph.D. Thesis.

A.S.-H. Wan, "Ion and Electron Parameters in the Alcator C Tokamak Scrape-off Region," Sc.D. Thesis.

C.H. Wang, "Decision Analysis of Nuclear Power Plant Size Effects on Capacity Expansion Planning," Sc.D. Thesis.

G.L. Warren III, "Gated Blood Flow Measurement in the Canine Myocardium Using Positron Computed Tomography," S.M. Thesis.

C.T.B. Wilson, "A Numerical Comparison of International Light Water Reactor Performance 1975-1984," S.M. Thesis.

Y.-F. Wu, "Nuclear Power Plant Technical Specifications Computerization: Application of Prolog," S.M. Thesis.

M. Yasuda, "Signal Validation for Performance Monitoring of Feedwater Heaters," S.M. Thesis.

The following theses were submitted to the Department of Nuclear Engineering in September 1986:

E.J. Ashburner, "Real Time Solutions to Point Kinetics Equations," S.M. Thesis.

J.-L. deFanti, "Interactive Graphics Display of 3-Dimensional Medical Images," S.M. Thesis.

D.L. Dorrell, "An Assessment of the Dose Rate at the Surface of Transuranic Waste Containers," S.M. Thesis.

J.S. Elson, "Numerical Modeling of Lithium Thaw in a Space Reactor Core," S.M./S.B. Thesis.

R.A. Heft, "A Polymorphic DNA Locus Linked to the Huntington's Disease," Ph.D. Thesis.

K. Kato, "Diagnosis of Mildly Relativistic Electron Velocity Distributions by Electron Cyclotron Emission in the Alcator C Tokamak," Sc.D. Thesis.

B. Malinovic, "Natural Convection Characteristics of Liquid Metal Cooled Fusion Reactors," S.M. Thesis.

R.C. McKinstry III, "Data Collection and Processing: High Resolution Positron Tomography," S.M. Thesis.

D.J. Michael, "Automatic Processing of Digitized Hand Radiographs: An Application of Computer Vision," S.M. Thesis.

J.A. Mohamad, "Transient and Steady State Dryout Zone Modeling for Pressurized Water Reactors," S.M. Thesis.

A. Pachtman, "Extraordinary Mode Absorption at the Electron Cyclotron Harmonic Frequencies as a Tokamak Plasma Diagnostic," Ph.D. Thesis.

B.R. Parnas, "Design and Implementation of An Advanced Nuclear Magnetic Resonance System Controller," S.M. Thesis.

R.E. Scott, "Theoretical Determination of the Energy Dependence of Charged-Particle Cross Sections," S.M. Thesis.

G.M. Shedd, Jr., "Focused Ion Beam Assisted Deposition of Gold," S.M. Thesis.
S.F. Shedd, "Water Proton Relaxation Studies of Paramagnetic Metal Ion Chelates Covalently Attached to Poly-L-Lysine and Bovine Serum Albumin," S.M. Thesis.

The following theses were submitted to the Department of Nuclear Engineering in February 1987:

B.N. Aviles, "State Variable Feedback Techniques for Predictive Control of Nuclear Reactors," S.M. Thesis.

M.S. Boehle, "An Improved Method for the Computation of Passive Heat Removal for LMRs," S.M. Thesis.

G.S. Case, "Safety Relief Valve Modeling: Multi-Dimensional Calculations, A Mass Flow Analysis, and the RELAP5/MOD2 Model," S.M./S.B. Thesis.

M.E. Foord, "Visible Continuum Measurements on the Alcator C Tokamak: Changes in Particle Transport During Pellet Fuelled Discharges," Ph.D. Thesis.

T.-T. Huang, "Flow Recirculation in Liquid Metal Reactor Rod Bundles," Sc.D. Thesis.

M.G. Izenson, "Effects of Fuel Particle and Reactor Core Design on Modular HTGR Source Terms," Ph.D. Thesis.

M.D. Kim, "Electricity Tariff Setting and Its Role on the Demand-Side Management," N.E./S.M. Thesis.

G. Russo, "A New Methodology of Computer-Aided Thermodynamics," Ph.D. Thesis.

E.Y.-L. Sheu, "Theoretical Development and Experimental Verification of a Primitive Model for the Inter-Micellar Interactions," Sc.D. Thesis.

K.Y. Suh, "Mixed Convective Low Flow in Vertical Rod Assemblies," Ph.D. Thesis.

A.Z. Tanker, "BWR Depletion and Flux Reconstruction Using Nodal Methods," S.M. Thesis.

X.-Y. Wang, "A Fiber Optics Delivery System for Recanalizing Thrombus of Occluded Arteries," S.M. Thesis.

X.-B. Wei, "The Effect of the 5790 A Line From Copper Vapor Laser on Thrombus and Occluded Arteries," S.M. Thesis.

A.J. Wolford, "Uncertainty Optimized Predictive Testing for a Nuclear Waste Container," Sc.D. Thesis.

The following theses were submitted to the Department of Nuclear Engineering in June 1987:

G.R. Baird, Jr., "Monte Carlo Simulation of Radiation Effects in Gallium Arsenide Semiconductor Devices," S.M. Thesis.

S.J. Brereton, "Safety and Economic Comparison of Fusion Fuel Cycles," Ph.D. Thesis.

D.A. Bucko, "A Computational Model of Natural Convection Air Cooling for Nuclear Reactors," S.M. Thesis.

P.E. Cavoulacos, "The Impact of Fiscal Risk on the Value of Petroleum Investments," Ph.D. Thesis.

G.J. Dau, "An Evaluation of Technology Transfer in the Electric Utility Industry," S.M. (JMT) Thesis.

C.M. Denault, "The Effects of the Radiosensitizing Agent Misonidazole on X-ray Induced Mutations Under Oxic and Hypoxic Conditions in Human Lymphoblast Cells," S.M. Thesis.

- A.F.V. Dias, "Systematic Derivation, from 3-D Nodal Equations, of Simpler Models for Describing Reactor Transients," Ph.D. Thesis.
- A. Dobrzeniecki, "Automated Reasoning Methods for Managing Power Plant Equipment Test and Maintenance Requirements," S.M. Thesis.
- E.S. Gordon, "New Problems in Queues: Social Injustice and Server Production Management," Ph.D. Thesis.
- I.S. Hwang, "Embrittlement Mechanisms of Nickel-base Alloys in Water," Ph.D. Thesis.
- L.S. Kao, "Thermal Hydraulics of Core/Concrete Interaction and Its Impact on Severe LWR Accidents," Ph.D. Thesis.
- E.F. Love, Jr., "Human Error in Maintenance of Reactor Coolant Pump Seals," S.M./S.B. Thesis.
- J.L. Martin, "Cryogenic Mechanical Testing of Superconducting Magnet Structural Materials," S.M./S.B. Thesis.
- K.L. Meyers, "Characteristics of a Natural Language Interface to the Technical Specifications of a Nuclear Power Plant," S.M. Thesis.
- D.J. Merzke, "Net Energy and Environmental Impact Analyses for the Recovery of Uranium from Seawater," S.M. Thesis.
- T. Nguyen, "An Autoradiographic Investigation of Cell Kinetics in Tumor Growth," S.M. Thesis.
- M.R. Sands, "Structure of Jupiter's Dayside Middle Magnetosphere," Ph.D. Thesis.
- P.H. Seong, "A Methodology for Simplification of Light Water Reactor System Design," Ph.D. Thesis.
- E.L. Taylor, "A Comparative Analysis of LMR and LWR Fuel Cycle Economics," N.E./S.M. Thesis.
- J.H. Wicks, Jr., "Design, Construction and Testing of an In-pile Loop for PWR Simulation," S.M. Thesis.
- R.J. Witt, "Structural Failure Modes of Toroidal Field Coils for Long-Pulse Ignition Experiments," Ph.D. Thesis.
- P.H. Yoon, "Electromagnetic Waves and Instabilities in Relativistic Plasma," Ph.D. Thesis.
- K.L. Yuracko, "Monitored Retrievable Storage of Spent Nuclear Fuel: A Policy Assessment," N.E./S.M. Thesis.