MITNE-272

ACTIVITIES IN NUCLEAR ENGINEERING AT MIT

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Prepared by the Staff of the

Nuclear Engineering Department

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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 for students interested in developing the peaceful applications of nuclear reactions, plasma physics, and radiation. Every attempt is made to provide the student with the necessary courses and research opportunities that will prepare him or her to make the key scientific and engineering advances in this evolving industry.

Departmental teaching and research activities are centered around the following four areas: 1) fission reactors; 2) controlled fusion; 3) radiation science and technology; and 4) energy systems and policy analysis. 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 and risk analysis. Fusion students would consider topics in fusion reactor technology and applied plasma physics. Technical specialties within the area of radiation science and technology include radiological sciences, radiation health physics, condensed matter sciences, and the physical metallurgy portion of nuclear materials. In the area of energy systems and policy analysis, 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 current academic year 1985-86, the Department's graduate program enrolled 153 domestic and international students. Of this number, approximately 47% expressed interest in the area of fission reactors, 29% were involved in controlled fusion, 19% registered in the radiation science and technology program, and 5% in energy technology and resources. In September 1985, our undergraduate enrollment totaled 25 students. At that time, six undergraduates entered the Department as sophomores to major in the field of nuclear engineering.

The Department awarded 48 advanced degrees during the academic year 1984-85. This included 18 doctorates, 2 nuclear engineers, and 28 master of science degrees. Ten bachelor degrees were awarded, seven of which were joint SM/SB degrees.

Table 1

Enrollment in M.I.T. Nuclear Engineering Department

Fall Semester*	
1973	127
1974	138
1975	202
1976	221
1977	217
1978	213
1979	209
1980	189
1981	191
1982	197
1983	194
1984	182
1985	178

*Source: Bruce Report, March 1985 (for AY 1973/74 to 1983/84)

Table 2

Applications for Graduate Admission
to M.I.T. Nuclear Engineering Department

Fall 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

1.2 Financial

As mentioned previously, departmental research is conducted in the areas of 1) fission reactors, 2) controlled fusion, 3) radiation science and technology, and 4) energy systems and policy analysis. During the fiscal year ending June 30, 1985, Departmental faculty supervised a research volume of $3,066,710, including research funded through the Department, the Department of Materials Science & Engineering, the MIT Energy Laboratory, the Whitaker College of Health Sciences, Technology and Management, the Nuclear Reactor Laboratory, the Plasma Fusion Center, and the Research Laboratory of Electronics.

During the academic year 1984-85, approximately 65 percent 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. Other departmental financial aid available to graduate students in Nuclear Engineering include two MIT-endowed tuitionships, three departmental administered fellowships -- the Sherman R. Knapp Fellowship sponsored by Northeast Utilities, the Theos J. Thompson Memorial Fellowship, and the Manson Benedict Fellowship -- and graduate school allocations to the Nuclear Engineering Department from the College Work Study Program.

Additional scholarship support was provided during the past year through the generosity of the United States Department of Energy, the National Science Foundation, Schlumberger Doll Research Center, International Business Machines Corporation, the General Electric Foundation, Rockwell International, the National Aeronautics and Space Administration, the Institute of Nuclear Power Operations, the National Institutes of Health, the Jerry McAfee Chair, and the MIT Graduate and Professional Opportunities Program.

1.3 Organization of Activities Report

Section 2 of this report contains a summary of developments within the Department since September 1984. 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 September 1984 through September 1985.

2. SUMMARY OF DEVELOPMENTS SINCE SEPTEMBER 1984

Section 2 summarizes developments within the Department during the past year. 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.

The Nuclear Power Plant Design Innovation Project continues to be a major research effort. Faculty involved in this work include Professors Eric Beckjord, Michael Driscoll, Michael Golay, Elias Gyftopoulos, David Lanning, Richard Lester, Lawrence Lidsky, Norman Rasmussen and Neil Todreas. More detailed information about the various aspects of this project can be found in Section 3.11.

During the past year the Department has held considerable discussion among faculty and graduate students regarding review of its curriculum and the associated structure of the doctoral qualifying examination. A major focus has been the role of experimental experience in the graduate curriculum and the means to insure our students receive such experience. As a result of these meetings, the faculty has voted to issue a revised list of graduate courses and qualifying examination requirements as well as institute a major requirement (36 credits) in addition to the existing minor requirement (24 credits) for Ph.D./Sc.D. candidates. The effective date of these changes will be September 1986.

The Engineering Internship Program continues to be very successful as it enters its eighth year of operation. Seven students -- three graduates, three seniors, and one junior -- are currently receiving significant on-the-job experience as part of this educational program. Companies which have placed students from our Department include Brookhaven National Laboratory, Commonwealth Edison, EG&G Idaho, Stone & Webster, and Los Alamos National Laboratory.

The MIT Student Branch of the American Nuclear Society (ANS) has completed another productive year. They have organized departmental seminars, student/faculty meetings, departmental steak fries, social hours, and a holiday party. They have also been responsible for the distribution of course evaluation forms. During the year, they have also arranged for student escorts for visiting prospective graduate students.

In November 1985, former Secretary of Energy James R. Schlesinger was the invited speaker at the inaugural lecture of the David J. Rose Lectureship in Nuclear Technology. This lectureship, sponsored by the Nuclear Engineering Department and the Alpha Nu Sigma Honor Society, was established in 1984 to honor Professor Rose on the occasion of his retirement, and in recognition of his work in fusion technology, energy, nuclear waste disposal, and most recently with ethical problems arising from advances in science and technology.

Faculty participation in various workshops/seminars continued over the past year. In September 1984, Professor Mujid Kazimi was invited to be a guest lecturer at the University of Stuttgart. Professor Lester directed a major conference on national advanced reactor research and development strategies. This conference was held in January 1985 in Cambridge and involved U.S. and international participants from government, industry, and research organizations.

In February 1985, Professor Sow-Hsin Chen, along with colleagues from UCLA and Cornell, organized an NSF workshop of the Physics and Chemistry of Surfactants in Solutions. He was also invited by the American Chemical Society to organize a symposium on Statistical Thermodynamics of Micellar and Microemulsion Systems for its national meeting which was held in Miami Beach.

Professor Golay led the Energy Laboratory's Electric Utility Program workshop. This workshop focussed upon materials problems of nuclear power stations reflecting the increasing importance of such problems as the current generation of plants grows older.

A special seminar for high school science teachers was organized and conducted by Professor Driscoll at the annual meeting of the American Nuclear Society which was held in Boston last June. Also at this same ANS meeting, Professor Andrei Schor was responsible for chairing a special session. He also served as session chairman at the Eleventh Liquid Metal Boiling Working Group in Grenoble, France.

A special two-week summer course entitled "Nuclear Power Reactor Safety," was presented once again during 1985. Under the direction of Professors Rasmussen and Todreas, this offering was attended by members of the U.S. nuclear industry as well as members of the international community. Professor Allan Henry offered a new program during the summer of 1985. His session was entitled, "Modern Nodal Methods for Analyzing Light-Water Reactors," and was also very well attended.

Nuclear Engineering faculty members have actively participated in both Institute and national professional activities throughout the year. Professor Rasmussen continues to serve as Chairman of the MIT Committee on Reactor Safeguard, as well as Chairman of the MIT School of Engineering Committee on Energy Systems. He also chairs both the Scientific Review Committee and the Fusion Safety Committee at the EG&G Idaho National Engineering Laboratory. He holds an appointment to the National Science Board and also serves on the Scientific Advisory Board for the Cleanup of TMI-2. He was a member of the Ad Hoc Committee on Technology, Policy and Society Studies at MIT.

Professor Gyftopoulos continued his services as Faculty Chairman of the MIT Sustaining Fellows Program, and as Chairman of the Committee on Discipline. He was also appointed a member of the Committee on Energy Conservation Research of the National Academy of Sciences and the National Academy of Engineering. He served on the Working Group appointed by the Deans of the Schools of Engineering and Humanities to study the history of the humanities requirements for engineering students at MIT and other institutions.

Other faculty selected to hold Institute appointments include Professors Henry, Driscoll, Lester, and Russell. Professor Henry is a member of the MIT Advisory Committee on Shareholder Responsibility. He is also the Committee on Graduate School Policy (CGSP) representative to the Committee on Educational Policy (CEP). Professsor Driscoll continues to serve on the Institute Committee on the Writing Requirement. Professor Lester was appointed to the MIT Committee on International Institutional Commitments. The School of Engineering Committee on Minorities and Women is chaired by Professor Russell.

Professor Otto Harling continues to direct the interdepartmental Nuclear Reactor Laboratory. In addition to Professor Rasmussen, other faculty members serving on the MIT Committee on Reactor Safeguard include Professors Lanning, Kazimi, and Ballinger.

Professor Lanning holds membership 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 and Webster Engineering Corporation. The Nuclear Heat Transfer Committee of the American Institute of Chemical Engineering is chaired by Professor Kazimi. He is also the chairman of the Advisory Committee of the DOE Fellowship for Magnetic Fusion Energy Technology.

Professor Driscoll is a member of the Executive Committee of the Fuel Cycle and Waste Management Division of the ANS. Professor Todreas serves on the Executive Committee of the ANS. He also chairs the EG&G TMI-2 Accident Analysis Industry Review Group.

Professor Lester serves as chairman of the Systems Review Committee of the Office of Crystalline Repository Development at Battelle Memorial Institute. Professor John Meyer is a member of the Review Committee for the Applied Physics Division at Argonne National Laboratory.

Three faculty members are represented on editorial review boards. They are Professor Todreas on the thermal design section of the Journal of Nuclear Engineering and Design, Professor Henry on the Nuclear Science and Engineering Review Board, and Professor Jeffrey Freidberg on the Physics of Fluids Editorial Board.

Department administrative responsibilities were handled by several faculty members during the past year. Graduate admissions were reviewed by Professor Lanning, and Professor Sidney Yip continued as financial aid officer. Professor Driscoll served as graduate recruiting officer. Professor Henry represented the Department to the CGSP. The Committee on Undergraduate Students was chaired by Professor Meyer. During Professor Meyer's sabbatical, Professor Ballinger served in this capacity. Professor Meyer continued as faculty advisor for both the honorary Alpha Nu Sigma Society and the ANS Student Branch. UROP activities were coordinated by Professor Ballinger. He also directs our Engineering Internship Program. Our Department's IAP activities were handled by Professor Schor.

Over the past year there have been a few changes in our faculty. Professor Eric Beckjord joined the Department as a Visiting Professor.

Professor Kent Hansen was named Associate Director of the MIT Energy Laboratory. His responsibilities include the Electric Utility Program, the Northeast Residential Experiment Station, Nuclear Energy, and Energy Engineering.

Professor Lester was selected as the second holder of the Atlantic Richfield Career Development Professorship in Energy Studies at MIT. This is a two-year appointment.

Several of our faculty were bestowed with honors since our last report. Professor Rasmussen was named a 1985 recipient of the Enrico Fermi Award given by the U.S. Department of Energy. Professor Henry was elected to the National Academy of Engineering. Professor S.-H. Chen was named a fellow of the American Association for the Advancement of Science. Professor Alan Nelson received an endowed chair entitled, the W.M. Keck Foundation Associate Professor of Biomedical Engineering. The Outstanding Teacher Award for the academic year 1984-85 was presented to Professor Ballinger by the MIT Student Branch of the ANS.

Finally, it is with great sadness that we report the recent passing of Professor David Rose. Internationally known and respected, he enriched the lives of all those who came in contact with him. He will be missed by his colleagues and friends.

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: Introductory Nuclear Measurements Laboratory, deals with the basic principles of interaction of nuclear radiation with matter. Statistical methods of data analysis; introduction to electronics in nuclear instrumentation; counting experiments using Geiger-Muller counter, gas-filled proportional counter, scintillation counter and semiconductor detectors. A term project emphasizes applications to experimental neutron physics, radiation physics, health physics, and reactor technology.

22.29: Nuclear Measurements Laboratory, covers basic principles of interaction of nuclear radiations with matter. Principles underlying instrumental methods for detection and energy determination of gamma-rays, neutrons and charged particles are discussed. Other topics include applications to applied radiation physics, health physics, and reactor technology; laboratory experiments on gas-filled, scintillation, and semiconductor detectors; nuclear electronics such as pulse amplifiers, multi-channel analysers and coincidence techniques; applications to neutron activation analysis, X-ray fluorescence analysis, thermal neutron cross sections, and radiation dosimetry.

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 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.

22.41: 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 problem 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 (with EPRI support).

If global flux distributions are to be computed by a nodal scheme, it is necessary to develop procedures for obtaining the homogenized cross sections that characterize the nuclear properties of the nodes. In addition, if local fuel-pin powers are desired, it is necessary to develop a "dehomogenization" procedure so that detailed, heterogeneous flux shapes can be recaptured from node-averaged values. The resolution of these problems is discussed in the next two sections.

(2) Homogenization Methods

The derivation of the QUANDRY nodal equations starts from a group diffusion theory model of a reactor composed of nuclearly homogeneous nodes. Hence before QUANDRY can be used it is necessary to find homogenized group diffusion theory parameters that reproduce correctly the average reaction rates and neutron leakage rates of the actual heterogeneous nodal zones making up the reactor.

To find such parameters we have developed a variant of a method suggested by Koebke in which the flux for the homogenized model is permitted to be discontinuous across nodal interfaces. If the proper discontinuity factors are known, the scheme will reproduce exactly the average leakage and reaction rates for each node in the reactor.

To find exact discontinuity factors is self-defeating since, to do so, it is necessary to know in advance the average leakage and reaction rates of the heterogeneous core. However, it has been found that the discontinuity factors are not very sensitive to the current boundary conditions on the nodal surfaces, and this fact suggests that it may be possible to estimate them, along with the homogenized group cross sections, by performing local calculations for the heterogeneous node alone or for that node and its nearest neighbors.

The simplest procedure for carrying out such calculations is to impose arbitrary boundary conditions on two-dimensional assembly-sized subregions of the reactor. In earlier work we showed that, for interior PWR and BWR assemblies containing no control rods or burnable poison pins, discontinuity factors and homogenized cross sections found by applying zero-current boundary conditions to the assemblies themselves reproduce reference nodal powers with maximum errors of ~ 1%. However, for assemblies containing control rods, or burnable poison pins, or next to the reflector, color set calculations are necessary to find the homogenized parameters and discontinuity factors. (A color set is an assembly-sized node composed of four different quarter-assembly regions.)

During the past year we have evaluated the color set method against a fine-mesh quarter-core depletion calculation for Cycle-1 of the ZION-2 reactor. Unfortunately, since both the fine-mesh color set and quarter-core calculations were run before comparison with the nodal approach was contemplated, edits needed to carry out the nodal calculation in an optimal fashion had not been requested. Thus, it is not possible to establish the exact cause of discrepancies between the nodal and reference quarter-core calculations. There is, however, considerable evidence that it is due to inaccuracy of the color-set homogenized cross sections. Whatever the cause, the maximum error in nodal power through the cycle was ~ 4% and the error in k_{eff} grew from -0.1% to +0.4%. These errors are larger than those encountered in earlier tests. They correlate very well with differences between homogenized cross sections edited from the quarter-core reference calculation and those edited from the color sets.

During the past year we have applied the discontinuity factor procedure to the systematic determination of adjustable parameters and for the standard nodal codes FLARE and PRESTO and to the editing, from assembly transport codes, of fine-mesh, two-group cross sections for finite-difference diffusion theory calculations. Usually such parameters are found by a trial and error procedure. The discontinuity factor approach is a one-step, automatic method. The key to carrying it out is to replace the face-dependent discontinuity factors for each node by their average value. Special adjustments must be made for nodes next to a reflector or adjacent to nodes containing control rods or burnable poison pins. However, these can be made automatic, and, by renormalizing cross sections and fluxes, the discontinuity factors can then be made to disappear from the final equations. Numerical testing indicates that the accuracy of the more systematic methods is comparable to that of the standard trial and error schemes.

We have also been applying the discontinuity factor approach to the development of "supernodal" methods (nodes of size ~ 40x40x60 cm^3). The idea is to determine supernodal homogenized cross sections and discontinuity factors from "fine-node" (10x10x15 cm^3) results. Initial application will be to fuel depletion and load-follow problems. The initial supernodal discontinuity factors are used for the entire problem. However, at the end of each time-step an updated fine-node shape and set of supernodal homogenized cross sections are reconstructed from the initial shape, modulated (in two dimensions) by bi-quadratic functions for each node. Coefficients for the bi-quadratic functions are inferred from the supernodal solution. The hope is to analyze fuel-depletion and load-follow transients by a very efficient, fully three-dimensional scheme.

(3) Dehomogenization

Several methods have been developed for reconstructing detailed heterogeneous flux shapes from node-averaged values. These are all based on the fact that node-face-averaged fluxes and currents for the heterogeneous reactor can be backed out of a QUANDRY solution, and this information can be used by interpolation to infer node-corner-point flux values. The reconstructed flux for a given group is then expressed as the product of a detailed two-dimensional "assembly shape" (obtained from a heterogeneous, finite-difference assembly or color set calculation) multiplied by a triquadratic "form function" (a 27-term expression having terms of the form $a_{ijk}\, x^i\, y^j\, z^k$, i, j, k + 0, 1, 2). The a_{ijk} are found by fitting to the QUANDRY output.

This procedure has been shown to work well for PWRs (maximum errors of ~ 1% in hot pin power). However, much more elaborate schemes appear necessary for BWRs. We are currently attempting to circumvent this difficulty for BWRs by obtaining the detailed assembly flux shapes from a full-core, fine-mesh beginning-of-cycle calculation. The initial triquadratic form function will then be flat, but will change as depletion takes place to match the face- and volume-averaged fluxes inferred from the nodal solution.

(4) Kinetics Development

The fact that QUANDRY can solve the three-dimensional, time-dependent nodal equation simultaneously with a simple heat transfer model makes it an excellent tool with which to examine standard point kinetics and one-dimensional methods for analyzing transients.

In this vein we have tested some standard point kinetics methods for analyzing rod withdrawal and inlet coolant temperature drop transients. To be as consistent as possible, the point kinetics equations -- and hence input parameter -- were derived directly from the time-dependent nodal equations. (In the course of doing this, a method for solving the adjoint QUANDRY equations was finally found.)

For a small three dimensional reactor composed of realistic PWR fuel elements, it was found that even though the reactivity worth of ejected control rods was determined from a precomputed table (rather than by perturbation theory), the use of perturbation theory to determine reactivity feedback coefficients in the standard manner led to an overprediction of the reactor power peak by a factor of over 12. In addition, for the inlet temperature drop transient (with control rods fixed in position), it was found that use of a core-average temperature coefficient as opposed to position-dependent, local temperature coefficients over-estimated peak power by a factor of 2.5.

We also tested the quasi-static kinetics method and found it fairly accurate. Unfortunately, however, it was more expensive than the full three-dimensional transient solution.

These results suggest that some of the standard point kinetics methods now in use by utilities and vendors should be reevaluated now that three-dimensional transient nodal codes are available.

With the possibility of the point kinetics model being unacceptable but recognizing that the full three-dimensional nodal model is moderately expensive, we have begun to look at a transient supernodal model and, in addition, have derived and programmed a transient one-dimensional model derived systematically from the three-dimensional nodal equations. These schemes may prove to be a better mixture of accuracy and economy for transient analysis.

Finally, with an eye towards carrying out reactor transient calculations in real time or better, we have begun to investigate the use of a parity analog simulator for solving kinetics problems.

Investigators: Professor A.F. Henry; students A. F. V. Dias, R. G. Gamino, W. H. Francis, P. J. Laughton, K. R. Rempe, A. G. Parlos, T. A. Taiwo, A. Z. Tanker, E. Tanker.

Support: Electric Power Research Institute, MIT Energy Laboratory Utility Program, 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

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Ray G. Gamino, "Group Collapsing in Fast Reactor Physics Calculations Using Discontinuity Factors," S.M. Thesis, Department of Nuclear Engineering, MIT, May 1984.

A. F. Henry, "The Definition and Computation of Average Neutron Lifetimes," Advances in Nuclear Science and Technology, Vol. 15, p. 55 (Plenum Press) 1983.

A. F. Henry, P. Finck, H.-S. Joo, H. Khalil, K. Parsons, J. Perez, "Continued Development of the QUANDRY Code," Energy Laboratory Report No. MIT-EL-84-001, (January 1984).

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J. F. Perez, "Reconstruction of Three-Dimensional Flux Shapes from Nodal Solutions," N.E. Thesis, Department of Nuclear Engineering, MIT, June 1984.

D. K. Parsons, "Replacement of Reflector Baffles in Nodal Calculations by Albedo Boundary Conditions," PhD Thesis, Department of Nuclear Engineering, MIT, February 1984.

T. A. Taiwo and A. F. Henry, "Perturbation Theory Based on a Nodal Model," Proceedings of the International Meeting on Advances in Nuclear Engineering Computational Methods, Knoxville, TN, April 9-11, 1985, p. 527.

E. Tanker, A. F. Henry, "Finite Difference Group-Diffusion Theory Parameters That Reproduce Reference Results," Trans. Am. Nucl. Soc. 50, 280 (1985).

3.1.3 LWR Fuel Management

Work continues on methods development and evaluation of reload optimization procedures for PWR cores at a rather modest level of effort. During the past year, a simple nodal formulation which directly links assembly power and reactivity was developed and programmed. Its ultimate use is as a rapid module in a loading pattern optimization program; it is already put to good use as a teaching tool. Much of this work has been based on extensions of the linear reactivity model of reactor core behavior; a technical monograph is being prepared on this subject.

Investigators: Professor M. J. Driscoll; Messrs. I. L. Sauer, M. A. Malik, G. Abu-Zaied, R. W. Fieldhack.

Support: Westinghouse Electric Corporation.

Related Academic Subjects:

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

Recent References:

M. G. Izenson, "Automated PWR Reload Design Optimization," S.M. Thesis, Department of Nuclear Engineering, MIT, June 1983.

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M. A. Malik and M. J. Driscoll, "A Long-term Perspective on the LWR Fuel Cycle," MITNE-265 (also Ph.D. Thesis) (December 1984).

I. L. Sauer and M. J. Driscoll, "A Core Reload Pattern and Composition Optimization Methodology for Pressurized Water Reactors," MITNE-266 (also Ph.D. Thesis) (March 1985).

R. W. Fieldhack, "The Fuel Cycle Economics of PWR Extended Burnup," S.M. Thesis, Department of Nuclear Engineering, MIT, January 1986 (est.).

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

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M. J. Driscoll, T. J. Downar, and E.L. Taylor, "A Microcomputer Program for Coupled Cycle Burnup Calculations," Proc. Topical Meeting on Advances in Fuel Management, Pinehurst, N.C. (March 1986).

3.1.4 LWR Uranium Utilization Improvement

A major series of research projects in this area, carried out for the DOE, which commenced in May 1976, were completed in August 1982. A total of eight doctoral theses, thirteen master's or engineer's theses, and one bachelor's thesis, were completed under this program.

Work continues in the following major areas: methods development for the automated identification and evaluation of candidate PWR reload arrangements, including optimum selection of burnable poison loadings; and a program to determine optimum intermediate and long-range strategy for all key transactions and design/operating decisions in the LWR fuel cycle.

Much of this work has been based on extensions of the linear reactivity method of reactor core behavior. The work at MIT has been sufficiently broad in scope and successful that a technical monograph is being prepared on this subject.

Investigators: Professors M. J. Driscoll and D.D. Lanning; Messrs. T. J. Downar, I.L.Sauer, M.A. Malik, M.G.Izenson, E. Montaldo-Volachec, A. Kamal, W. T. Loh, M. W. Zimmermann, D. W. Charpie, and R. L. Coxe.

Support: U.S. Department of Energy via MIT Energy Laboratory (terminated); Westinghouse Electric Corporation.

Related Academic Subjects:

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

Recent References:

P.E. Cavoulacos and M.J. Driscoll, "Probabilistic Analysis of Nuclear Fuel Cycle Economics", Proc. ANS Topical Meeting on Technical Bases for Nuclear Fuel Cycle Policy, Newport, R.I., September 1981.

M.J. Driscoll, "Methods for the Evaluation of Improved PWR Core Design", Proc. ANS Topical Meeting on Technical Bases for Nuclear Fuel Cycle Policy, Newport, R.I., September 1981.

A. Kamal, M.J. Driscoll and D.D. Lanning, "The Selective Use of Thorium in PWR's on the Once-Through Fuel Cycle", Trans. Am. Nucl. Soc., Vol. 39, November 1981.

M. A. Malik, A. Kamal, M.J. Driscoll, and D. D. Lanning, "Optimization of the Axial Power Shape in Pressurized Water Reactors", DOE/ET/34022-2, MIT-EL-81-037, November 1981. (S.M. Thesis by M.A. Malik.)

W. T. Loh, M.J. Driscoll and D. D. Lanning, "The Use of Burnable Poison to Improve Uranium Utilization in PWR's", DOE/ET/34022-3, MIT-EL-82-014, May 1982. (Ph.D. Thesis by W. T. Loh.)

A. Kamal, M. J. Driscoll and D. D. Lanning, "The Selective Use of Thorium and Heterogeneity in Uranium-Efficient Pressurized Water Reactors", DOE/ET/34022-4, MIT-EL-82-033, August 1982. (Ph.D. Thesis by A. Kamal.)

M.J. Driscoll, "Final Report on Improved Uranium Utilization in PWRs", MIT-EL-82-032, August 1982.

M.J. Driscoll, "A Review of Thorium Fuel Cycle Work at MIT", invited paper, US-Japan Joint Seminar on the Thorium Fuel Cycle, Nara, Japan, October 1982.

D.W. Charpie, "Cost/Benefit Analysis of Stockpiling in the Nuclear Fuel Cycle", S.M. Thesis, Department of Nuclear Engineering, MIT, May 1983.

M.G. Izenson, "Automated PWR Reload Design Optimization", S.M. Thesis, Department of Nuclear Engineering, MIT, June 1983.

M.W. Zimmermann, "A Critique and Simplification of Fuel Cycle Economics Calculations", S.M. Thesis, Department of Nuclear Engineering, MIT, August 1983.

R. L. Coxe, "The Economic Optimization of Uranium Enrichment Tails Assays", S.B. Thesis, Department of Nuclear Engineering, MIT, June 1982.

3.2 Reactor Engineering

Because of the important and 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 applications 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 dealt with include fundamentals of engineering thermodynamics, fluid flow, heat transfer, and elasticity, with examples of applications to various energy sources.

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

22.403: 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.

In the forced convection area emphasis has been on identifying the optimum nodal size for porous body analysis and developing input correlations for friction factors. Proper selection of the node size and its placement in the array is required to assure that the average velocity across a node face which the porous body utilizes has physical significance. A node layout very similar to the subchannel arrangement has been found optimum. A major effort has been completed which provides function factors for individual subchannel types and for the rod bundle. Both bare array and wire-wrapped rod arrays are considered.

In the mixed convection area, work has been concentrated on both obtaining a velocity and temperature data base in heated array water tests and on developing correlations for friction factors and energy transfer mechanisms. The friction factors are being developed for interior and edge subchannels. The energy transfer mechanisms investigated have been circumferential conduction through the insulator material (Boron Nitride) in electric heater rods and turbulent mixing from thermal plumes. In mixed convection conditions using high thermal conductivity insulator materials, rod conduction effects are significant and must be accounted for in interpretation of sodium heated tests using a correlation such as that developed in this work. To investigate the magnitude of the thermal plume effect, an experiment was constructed, and the turbulent mixing was determined by simultaneous measurement of temperature (by thermocouple) and velocity (by laser Doppler anemometry) fluctuations across the gap between rods. Based on these initial measurements, the magnitude of the thermal plume effect appears small.

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 are being performed on fuel and blanket rod arrays.

Investigators: Professors N.E. Todreas, K. Nakajima (Visiting), and W.M. Rohsenow (Mechanical Engineering); Messrs. A. Efthimiadis, S.-K. Cheng, T.-T. Huang, T.S. Ro, and K. Suh.

Support: Department of Energy, Power Reactor Development Corporation (Japan), Westinghouse.

Related Academic Subjects:

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

Recent References:

P.D. Symolon, N.E. Todreas, and W.M. Rohsenow, "Criteria for the Onset of Flow Recirculation and Onset of Mixed Convection in Vertical Rod Bundles," The American Society of Mechanical Engineers, pp. 1-9, August 1984.

N.E. Todreas and T.T. Huang, "Prediction of Temperature and Velocity Fields in Wire-Wrapped Rod Arrays," Progress Report No. 5, Westinghouse Electric Corporation Contract No. 54-7-CAR-319570-94311, Massachusetts Institute of Technology, (December 1984).

A. Efthimiadis and N.E. Todreas, "Generalized Formulation of the Fully-Developed Mixed Convection Flow Problem in Vertical Ducts," presented at ASME National Heat Transfer Conference, Denver, Colorado (August 1985).

T. Okada, A. Efthimiadis, V. Iannello and N.E. Todreas, "Mixed Convection Pressure Drop in Vertical Rod Bundles," Proceedings of Third International Topical Meeting on Reactor Thermal Hydraulics, Vol. 2, pp. 16.C-1 - 16.C-7, Newport, RI, (October 1985).

S.-H. Cheng, T.S. Ro and N.E. Todreas, "Energy Transfer Mechanisms under Mixed Convection Conditions In LMFBR Wire-Wrapped Bundles," Proceedings of Third International Topical Meeting on Reactor Thermal Hydraulics, Vol. 2, pp. 16.E-1 - 16.E-8, Newport, RI, October 1985.

S.K. Cheng and N.E. Todreas, "Hydrodynamic Models and Correlations for Bare and Wire-Wrapped Hexagonal Rod Bundles--Bundle Friction Factors, Subchannel Friction Factors and Mixing Parameters," Nuclear Engineering and Design, in press.

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 designed 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.

At General Electric, decay heat removal in LMRs was investigated with a water model test loop consisting of six parallel-annular flow channels representing various core assemblies plus a return and a bypass channel. A part of the MIT work focused on developing a physical understanding and analytic/numerical prediction of experimental results from this test. In order to numerically predict the GE parallel channel test results, a computercode called MICON was written. MICON solves the 1-D conservation equations for an incompressible liquid flowing in parallel channels. Integration techniques included for user selection are the box method, Turner's method, and the method of characteristics. In addition, models for heat conduction and heat transfer to account for heat losses from the coolant channels to the environment are included. Coolant temperatures and pressures in the plena can be either calculated assuming a uniform profile or input by the user.

Under mixed convection conditions, the constitutive correlations developed for forced convection may no longer apply. An increase in friction factors and heat transfer coefficients has already been experimentally observed in the MIT 19-pin wire-wrapped rod bundle using the ENERGY-IV sub-channel code. Analytical work includes solving for friction factors and Nusselt numbers for annular geometries and infinite arrays with large P/D spacing.

In parallel with this work a small, three-channel experiment is being conducted. This experiment will help in determining mixed convection flow 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.

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
22.36J Two-Phase Flow and Boiling Heat Transfer

Recent References:

S. Kaizerman and N.E. Todreas, "Mixed Convection in Multiple Parallel Channels Connected at Plena," Report No. GE/MIT-1, Massachusetts Institute of Technology, March 1983.

S. Kaizerman, V. Iannello, and N.E. Todreas, "Mixed Convection in Multiple Parallel Channels Connected at Plena," Report No. GE/MIT-2, Massachusetts Institute of Technology, May 1984.

V. Iannello and N.E. Todreas, "Mixed Convection in Multiple Parallel Channels Connected at Plena," Report No. GE/MIT-4, Massachusetts Institute of Technology, December 1984.

V. Iannello and N.E. Todreas, "Mixed Convection in Parallel Channels Connected Only at Plena," Report No. GE/MIT-5, Massachusetts Institute of Technology, January 1985.

V. Iannello and N.E. Todreas, "Mixed Convection in Parallel Channels Connected Only at Plena," Report No. GE/MIT-6, Massachusetts Institute of Technology, April 1985.

V. Iannello and N.E. Todreas, "Mixed Convection in Parallel Channels Connected Only at Plena," Report No. GE/MIT-7, Massachusetts Institute of Technology, August 1985.

3.2.4 Hydrodynamics of Single- and Two-Phase Flow in Inclined Rod Arrays

Required inputs for thermal-hydraulic codes are constitutive relations for fluid-solid flow resistance, in single-phase flow, and interfacial momentum exchange (relative phase motion), in two-phase flow. In this project an inclined rod array air-water experiment was constructed to study the hydrodynamics of multidimensional porous medium flow in rod arrays. Velocities, pressures, bubble distributions, and void fractions were measured in inline and rotational square rod arrays of P/D = 1.5, at 0, 30, 45, and 90 degree inclinations to the vertical flow direction.

Constitutive models for single-phase flow resistance were reviewed, new comprehensive models developed, and an assessment with previously published and new data made. The principle of superimposing one-dimensional correlations proved succcessful for turbulent single-phase inclined flow.

For bubbly two-phase yawed flow through inclined rod arrays a new flow separation phenomena was observed and modeled. Bubbles of diameters significantly smaller than the rod diameter travel along the rod axis, while larger diameter bubbles move through the rod array gaps. The outcome is a flow separation not predictable with current interfacial momentum exchange models. This phenomenon was not observed in rotated square rod arrays. Current interfacial momentum exchange models were confirmed for this rod arrangement.

Models for the two-phase flow resistance multiplier for cross flow were reviewed and compared with data from cross and yawed flow rod arrays. Both drag and lift components of the multiplier were well predicted by the homogeneous model. Other models reviewed overpredicted the data by a factor of two.

Investigators: Professor N. E. Todreas; Messrs. J. Robinson and E. Ebeling-Koning.

Support: Department of Energy

Related Academic Subjects:

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

Recent References:

N.E. Todreas, D.B. Ebeling-Koning, and J.T. Robinson, "Hydrodynamics of Single- and Two-Phase Flow in Inclined Rod Arrays," Report No. DOE/ER/12075-4FR, Department of Nuclear Engineering, MIT, (March 1985).

D.B. Ebeling-Koning, J.T. Robinson, and N.E. Todreas, "Models for the Fluid-Solid Interaction Force for Multidimensional Single Phase Flow Within Tube Bundles," Nuclear Engineering and Design, in press.

3.2.5 Natural Circulation for Decay Heat Removal

This is a new project which is concerned with a key feature of the "passively safe" liquid-metal-cooled reactors currently under evaluation by the DOE and its contractors: the reactor vessel air cooling system (RACS). The function of the RACS is to remove decay heat by convection to ambient air in natural circulation past the guard vessel surrounding the reactor vessel. The system is always on line and designed to remove the entire decay heat load while maintaining the reactor vessel below 1200°F without the need for any external power or control action.

Modeling of system performance is a most interesting and challenging project in thermal-hydraulics, involving as it does all modes of heat transfer--convection, conduction, and radiation, all in a significant way; furthermore, representative system designs tend to operate near the transition regions between laminar and turbulent flow and natural and forced convection.

A first-cut computer model of a generic RACS design has been developed and exercised. It confirms the basic feasibility of the RACS concept. Follow-on work is planned to improve the program with respect to both its physical and numerical features and to employ it to optimize RACS performance.

Investigators: Professors M.J. Driscoll, A.L. Schor, and N.E. Todreas; Mr. J. Senna.

Support: Westinghouse Advanced Energy Systems/DOE.

Related Academic Subjects:

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

Recent References:

J. Senna, "Thermal-Hydraulic Analysis of a Passive Heat Removal System for Advanced Nuclear Reactors," N.E. Thesis, Department of Nuclear Engineering, MIT, August 1985.

3.2.6 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 stablity of the computational algorithm. In particular, the time levels 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) Numerical treatment of condensation

Over the last ten to fifteen years, sustained efforts devoted to mathematical, physical and numerical modeling of two-phase flows have led to a remarkable progress in the ability to realistically simulate such flows. Still, it is fair to state that multi-phase flow calculations while widely used, are not yet "routine," in that unusually severe conditions may lead to extremely long computations or, in extreme cases, to algorithm failure.

The simulation of complete condensation continues to challenge the numerical methods currently used for multi-phase flow modeling; especially at low pressures, the change of phase process from a two-phase mixture to liquid leads to severe pressure field perturbations and often failure of the calculations. During condensation, the local void fraction and pressure decrease rapidly; at the time of complete condensation, the strong intrinsic nonlinearities of the equations at the phase-change point lead to convergence difficulties and/or unacceptably large mass or energy errors.

Various ad-hoc "fixes" for this phenomenon - often referred to as "water packing" - have been proposed and/or implemented over the last few years. However, they have failed to clarify the core of the problem and are still unsatisfactory. Indeed these solutions cast doubt on the numerical predictions and occasionally are unable to prevent the breakdown of the calculations.

The present investigations have focused on the roots of these difficulties, particularly on the nonlinear effects involved. A time-step control strategy was developed which removes or at least, greatly mitigates the aforementioned computational problems. Numerical experiments as well as a mathematical analysis have both demonstrated the existence of a critical time-step size beyond which larger time-steps will accommodate any perturbations to the liquid flow field; smaller time-steps will cause pressure oscillations, out of its physical range as it is indeed noted in condensation simulations where the time-steps are drastically reduced when the two phases are still both present.

This study has led to a greatly improved time step control strategy as well as to elucidating some poorly understood nonlinear effects.

3) Steam Generator Tube Rupture (SGTR) Study

There have been several SGTR events at operating pressurized water reactor (PWR) - equipped power plants. Since such an event represents a break of the primary system, there is an obvious concern about the amount and rate of radioactive material release, as it relates to the offsite doses.

Current Final Safety Analysis Reports generally assume termination of the accident (i.e., cessation of primary-to-secondary leakage) in 30 minutes. However, it has been observed during such events that the primary-to-secondary flow continued over a significantly longer time period, on the order of hours. When considering various factors affecting the unfolding of the accident (i.e., operator action times, equipment malfunction, variations in design and operation, etc.), it is clear that a comprehensive study of this transient is of utmost importance.

The investigation being conducted at M.I.T. focuses on multidimensional effects in flow and heat transfer, generally neglected in overall system simulations. This study is providing support for the much broader analytical effort undertaken by Los Alamos National Laboratory.

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 compatability with the UNIX operating 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.

An upcoming DSNP workshop (January 1986) will be used to introduce and demonstrate this simulation capability to faculty and students.

Investigators: Professor A. L. Schor and Messrs. S. Free, J. Sasson, D. Dorrell and J. Mahannah.

Support: Oak Ridge National Laboratory, Los Alamos National Laboratory, M.I.T. ATHENA project

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:

S.T. Free, A.L. Schor, "A Stable Numerical Method for One-Dimensional Sodium Boiling Simulation," Proceedings of the 11th Meeting of the Liquid Metal Boiling Working Group, Grenoble, France, October 1984.

A.L. Schor, "Physical and Numerical Modeling of Two-Phase Flows," Proceedings of the 1985 Eastern Simulation Conference, Norfolk, Virginia, March 1985.

S.T. Free and A.L. Schor, "A Stable Numerical Method for One-Dimensional Two-Phase Flow," Proceedings of the 1985 National Heat Transfer Conference, Denver, Colorado, August 1985.

J. Sasson and A. L. Schor, "An Investigation of the Numerical Treatment of Condensation," MIT-EL 85-010, August 1985.

3.2.7 Sodium Boiling in LMFBR Fuel Assemblies

The objective of this program is to contribute to the development of an improved understanding of sodium voiding behavior under postulated LMFBR accident conditions. The program consists of development of multidimensional computer models, capable of simulating low flow, low power conditions.

From among the possible two-phase flow models, two models were selected and have been pursued. The first uses a two-fluid (six-equation) representation, which needs more constitutive relations, but provides the potential for the broadest range of applications. The other uses a "mixture" (i.e., less than six-equation) description of the two-phase flow. In particular, a four-equation model is used, assuming thermal equilibrium on the saturation line between co-existing phases, but allowing for unequal phase velocities. This mixture model requires fewer constitutive relations, while still applicable to a wide range of conditions of interest.

The work has emphasized both the physical and the numerical modeling. A significant effort has been devoted to developing a consistent and realistic set of constitutive relationships for the six-equation model, including:

1. description of relative motion of the phases, via interphase momentum exchange and wall friction correlations,

2. flow boiling heat transfer models,

3. mass and heat interphase transfer rate models.

A consistent package of constitutive relations has also been assembled for the four-equation model. The code using this model has been used to test a number of modifications of the basic semi-implicit, non-linear solution scheme, aimed to take advantage of the reduction in the set of governing equations. A much improved understanding of some of the difficulties inherent to numerical modeling of sodium boiling has been gained.

The codes developed under this project have been verified by comparison to existing experimental results on sodium boiling. The results are very encouraging and indicate the general soundness of the approaches taken in this work. They have also helped in pointing out those aspects of both physical and numerical nature that would be most likely to benefit from additional work.

During the last year, a special version of the four-equation code (THERMIT-4E) has been completed and tested. This code version is capable to simulate in detail a one-dimensional flow loop. An analytical investigation of loop stability has been carried out in parallel and compared against the code's prediction.

Investigators: Professors M. Kazimi, A. Schor; Messrs. O. Adekugbe, S. Free, Y. Khalil, J. Sasson.

Support: Oak Ridge National Laboratory (partial).

Related Academic Subjects:

22.313 Advanced Engineering of Nuclear Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer
22.43 Advanced Numerical Methods in Engineering Analysis

Recent References:

S. T. Free, A. L. Schor, "A Stable Numerical Method for One-Dimensional Sodium Boiling Simulation," Proceedings of the 11th Meeting of the Liquid Metal Boiling Working Group, Grenoble, France, October 1984.

A. L. Schor, M. S. Kazimi and N. E. Todreas, "Advances in Two-Phase Flow Modelling for LMFBR Applications," Nuclear Engineering and Design, Vol. 82, No. 2 and 3, October (II) 1984.

O. A. Adekugbe, A. L. Schor and M. S. Kazimi, "Loop Simulation Capability for Sodium-Cooled Systems," MIT-EL 84-013, June 1984.

Yehia Khalil, "Development of the CHEM-THERMIT Code," N.E. Thesis, Department of Nuclear Engineering, MIT, June 1985.

O. A. Adekugbe, A. L. Schor and M. S. Kazimi, "Oscillatory Behavior in a Natural Convection Sodium Loop," Proceedings of the 1985 National Heat Transfer Conference, Denver, Colorado, August 1985.

J. Sasson and A. L. Schor, "An Investigation of the Numerical Treatment of Condensation," MIT-EL 85-010, August 1985.

H. C. No and M. S. Kazimi, "Effects of Virtual Mass on the Mathematical Characteristics and Numerical Stability of the Two Fluid Model," Nucl. Sci. & Eng., 89, 197-206 (1985).

H. C. No and M. S. Kazimi, "On the Formulation of the Virtual Mass Term in Two Fluid Models," accepted for publication in Nuclear Engineering and Design, November 1985.

3.2.8 Incompressible Turbulent Flow Measurements

Over the past decade several student theses have been performed in the measurement of incompressible turbulent flow. The purposes of this work are the following:

- Creation of accurate data sets relevant to industrial applications for use in refinement of numerical models of turbulent flow, and

- Development of improved instruments for measurement of turbulent flows.

In the most recent work, in the Ph.D. thesis work of R.W. Sawdye, three-dimensional measurements of mean flow and binary velocity correlation functions have been made in a steady confined water flow. The geometry is that of a cube where a jet passes through the domain along one corner to an outlet located opposite the inlet.

Throughout the flow domain the data reflect asymmetries which arise in the inlet velocity distribution. They are relevant to many industrial analysis situations.

In a related development a previously-measured set of two-dimensional turbulent flow data obtained in the Ph.D. work of D.R. Boyle was the subject in January, 1985 of a workshop held at the Cadarache Laboratory of the CEA in France by the International Working Group on Refined Modeling of Flows of the International Association for Hydraulic Research.

Investigators: Professor M.W. Golay; Mr. R. Sawdye.

Support: None.

Related Academic Subjects:

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

Recent References:

R. Sawdye, "Measurement of Three-Dimensional Velocity and Turbulence Fields in a Cavity," Ph.D. Thesis, Department of Nuclear Engineering, MIT, June 1985.

D.R. Boyle and M.W. Golay, "Measurement of a Recirculating, Turbulent Flow and Comparison to Turbulence Model Predictions. I: Steady State Case," J. Fluids Engineering, 105, 439-446 (1983).

D.R. Boyle and M.W. Golay, "Measurement of a Recirculating, Two-Dimensional Turbulent Flow and Comparison to Turbulence Model Predictions. II: Transient Case," J. Fluids Engineering, 105, 447-454 (1983).

3.2.9 Modeling of Containment Atmosphere Dynamics

In work recently concluded, a computer code has been developed for modeling of the dynamic behavior of the atmosphere of a nuclear reactor containment building during possible accidents. This work has been motivated by the following factors:

- The need to improve upon the relatively low accuracy of previously-available models for such accidents

- The need for models to describe atmospheric stratification and transport of hydrogen in severe core damage accidents.

In addition to the development of the computer program, LIMIT, for such analysis, the project has been concerned with:

- Development of a method for minimization of errors due to minimal diffusion in the donor cell treatment of convection, and

- Development of a correlation to describe heat removal from the containment atmosphere sprays.

1) The LIMIT Program

The computer program LIMIT was developed in the Ph.D thesis of V.P. Manno. The program has three submodels:

- A 2D continuum fast-blowdown model, which is that of the code BEACON, with a passive hydrogen field added,

- A 3D continuum slow-mixing model (the major emphasis of this work), restricted to cases where the containment atmosphere is approximately isobaric. (This model is useful in severe core damage accidents),

- A 1D lumped parameter model, which is essentially that of the program RELAP with a passive hydrogen field added in the dependent array.

These models can be used to connect different types of spatial domains for transient analysis.

The main focus of the project is upon the slow mixing model. This model uses fully compressible formulations of the mass and energy conservation and state relationships and, the approximate momentum conservation relationship applicable to incompressible fluids. The last refinement permits the program to analyze problems much more economically than would be the case if a fully compressible momentum formulation were used.

The program has been validated against two sets of data: those for the Battelle-Frankfurt-hydrogen mixing tests, and of a similar set of tests performed in the Containment Simulation Experiment facility at Hanford Engineering Development Laboratory. The program is currently in use by several utility and research organizations, and is undergoing continual improvement.

2) Numerical Diffusion

In slow, isobaric containment atmosphere transients, molecular diffusion is an important transport mechanism, while in most flows it is too weak to be significant. By virtue of its simplicity and physical elegance the donor cell treatment of convection is in widespread use and is used in LIMIT. This numerical treatment introduces an error due to an effective non-physical diffusion of passive quantitites in the solution.

In an effort to improve the accuracy of the solutions a corrective scheme has been developed and implemented in LIMIT. To reduce this error in the convective scheme, the value of the effective numerical diffusivity arising in the solution is calculated at each instant on each cell face. The physical diffusivity of the problem is then reduced in magnitude by that of the numerical diffusivity, rendering the net effective diffusivity value approximately equal to the physically correct value. This work was the Ph.D thesis project of K.Y. Huh.

3) Spray Heat Removal

The calculation of heat removed from a containment atmosphere by sprays is laborious, and can be expensive. However, since such sprays are important in controlling the atmosphere state within acceptable limits, an accurate calculation is necessary in safety analysis. Such calculations proceed by describing the histories of individual droplets of different sizes as they fall and remove heat and water vapor from the atmosphere. By summing differential contributions to atmosphere scrubbing according to droplet size internal over a spectrum of droplet sizes one can estimate the overall effects of a spray.

In an effort to render such calculations more economical a correlation for droplet thermalization has been formulated. To do this a numerical model was constructed which describes the heat and mass transfer to an individual turbulent droplet as it falls. After being validated against experimental data this model was used to produce estimates of droplet thermalization behavior over a range of relevant independent variables. Effectively the numerical model was used to produce data much as an experiment would. Then, these data were correlated in order to provide a compact algebraic expression which typically is able to predict the droplet thermalization length with a disagreement of approximately 10% in comparison with results from the detailed numerical model. This project was that of the S.M. thesis of B.K. Riggs.

Investigators: Professors M.W. Golay and V.P. Manno; Messrs. K.Y. Huh and B.K. Riggs

Support: Northeast Utilities, Duke Power Corp., Public Service Electric and Gas Corp., Boston Edison Company

Related Academic Subjects:

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

Recent References:

V.P. Manno and M.W. Golay, "Application of the LIMIT Code to the Analysis of Containment Hydrogen Transport," Nuclear Technology, 67, 302-311 (1984).

V.P. Manno, M.W. Golay and K.Y. Huh, "Analytical Models for Simulating Hydrogen Transport in Reactor Containment Atmospheres," Nuclear Science and Engineering, 87, 349-360 (1984).

V.P. Manno and M.W. Golay, "Hydrogen Transport in Containments: A Survey of Analytical Tools and Benchmark Experiments," Nuclear Safety, 25, 797-814 (1984).

V.P. Manno and M.W. Golay, "Hydrogen Mixing and Stratification in Containment Atmospheres," Nuclear Technology, 70, 124-132 (1985), also presented at Third International Topical Meeting on Reactor Thermal Hydraulics, Newport, RI (1985).

B.K. Riggs, M.W. Golay and V.P. Manno, "A Correlation for Heat and Mass Transfer to Containment Sprays," Third International Topical Meeting on Reactor Thermal Hydraulics, Newport, RI (1985).

K.Y. Huh, M.W. Golay and V.P. Manno, "A Method for Reduction of Numerical Diffusion in the Donor Cell Treatment of Convection," Accepted by Journal of Computational Physics (1985), also presented at 1985 National Heat Transfer Conference, Denver, CO.

3.2.10 LWR Longevity Extension

We have conducted a project to provide an overview of the issues which a utility must consider in planning for LWR longevity extension. The major issues identified are the following:

- Monitoring of components which will be degraded over time through such mechanisms as chemical decomposition, corrosion, fatigue and embrittlement
- Determination of strategies for retarding the effects of such mechanisms
- Evaluation of component design lives and the position of a component in its life cycle.

In most cases, it is found that the basic understanding for identification of such mechanisms is available. However, the records and design information for the last two tasks usually do not exist and are not being created. Typically, investments for longevity extension are substantially suboptimal.

A major area of uncertainty concerns the treatment of longevity extension by safety and financial regulatory agencies. However, the NRC is now granting 40-year operating licenses measured from the start of construction, as had been customary until very recently. Thus, it appears likely that the plants licensed under the latter regulatory treatment can likely expect to receive approximately an additional decade of operational licensing as regulatory practices affecting the older LWR's are made consistent with those of the newer plants. If this were to happen, the largest effects of regulatory uncertainty would be effectively removed. This is because under realistic conditions, most of the net discounted benefits of extended plant operation are those achieved from the first decade of extended life. This fact motivates a planning strategy of planning and investing for efficient plant performance for an indefinite duration, without substantial concern for regulatory uncertainty.

Investigators: Professor M.W. Golay, Mr. John Moinzadeh.

Support: Northeast Utilities.

Related Subjects:

22.312	Engineering of Nuclear Reactors
22.211	Nuclear Reactor Physics I
22.212	Nuclear Reactor Physics II
22.313	Advanced Engineering of Nuclear Reactors
22.32	Nuclear Power Reactors
22.341	Nuclear Engineering Economics and Policy Analysis
22.35	Nuclear Fuel Management
22.37	Environmental Impacts of Electricity
22.38	Reliability Analysis Methods
22.39	Nuclear Reactor Operations and Safety
22.40	Advanced Reliability Analysis and Risk Assessment (A)
22.070J	Materials for Nuclear Applications
22.071J	Physical Metallurgy Principles for Engineers
22.75J	Radiation Effects in Reactor Structural Materials (A)

Recent References:

M.W. Golay and J. Moinzadeh "Extending the Lives of Nuclear Power Plants: Technical and Institutional Issues," Report MIT-EL 85-002 (1985).

3.2.11 Development of the Coupled Neutronic Thermal Hydraulic Code TITAN for LWR Applications

Modeling the behavior of a nuclear reactor core can be considered as consisting of two major parts: the thermohydraulic part and the neutronic part. In reality, the power level needed as input to the thermal codes, and the feedback parameters to calculate the neutronic behavior should ideally be calculated simultaneously. In practice, the situation is simplified in order to facilitate the calculations. TITAN is a code which has the ability to perform three dimensional analysis of the complete core (both thermohydraulic and neutronic parts). TITAN has been developed by combining two advanced codes previously developed at MIT, namely THERMIT and QUANDRY.

The THERMIT computer code is a 3-D, two-fluid, thermohydraulic code. The fluid dynamics model is a porous body model and can be applied to both core-wide or subchannel analyses. A semi-implicit numerical technique is used as a solution method. This method is not limited by the direction of the flow. However, the time step cannot exceed the time it takes the flow to cross a single node to insure stability. THERMIT is also designed to accept readily additional wall heat transfer models or constitutive inter-fluid models.

The QUANDRY computer code is a neutronics code based on a nodal method to solve space-dependent reactor transients based on the two-group diffusion theory. In the nodal method, a one-dimensional diffusion equation for each direction is solved to yield the required neutron flux-current relationships. A quadratic polynomial approximation is used to calculate nodal transverse leakages. Considerable computational time is saved by this approach, relative to a finite difference method. Therefore, QUANDRY is much faster than the MEKIN code which was developed at MIT in the mid 1970s for 3-D analysis.

The coupling, in tandem, of QUANDRY and THERMIT has resulted in the computer code TITAN (Three Dimensional Integrated Thermal-hydraulic And Neutronic Code). Steady-state and transient coupling methodologies based upon a tandem structure were devised and implemented. Additional models for nuclear feedback, equilibrium xenon and direct moderator heating were added. TITAN was tested using a boiling water two-channel problem and the coupling methodologies were shown to be effective. Simulated turbine trip transients and several control rod withdrawal transients were analyzed with good results.

TITAN was also applied to a quarter core PWR problem based on a real reactor geometry. The TITAN results were shown to be reasonable. A pair of control rod ejection accidents were also analyzed with TITAN. The computing time requirements for these analyses were less than 1 hour c.p.u. time on a large mainframe computer. This is reasonable for a severe transient in a large reactor.

A comparison of the TITAN PWR control rod ejection results with results from coupled point kinetics/thermal-hydraulics analyses showed that the point kinetics method used (adiabatic method for control rod reactivities, steady-state flux shape for core-averaged reactivity feedback) underpredicted the power excursion in one case and overpredicted it in the other. It was therefore concluded that point kinetics methods should be used with caution and that three-dimensional codes like TITAN are superior for analyzing PWR control rod ejection transients. Code applications to several problems show that TITAN is correctly coupled, as can be seen from a comparison to QUANDRY and MEKIN.

The capabilities that were added to the code for a steam line break analysis include multi-region core inlet temperature forcing function, total inlet coolant flow rate boundary condition, total inlet coolant flow rate transient simulation capability, boron tracking equations, flow/coolant temperature transient plus control rod transient option, and one-dimensional, fully implicit numerical scheme for thermal-hydraulics calculations. The modifications to TITAN were tested with a ten-channel PWR model. For inlet coolant temperature transients (one of the transients involved in a steam line break accident) test calculations lead to the conclusion that there is no significant difference between the results of closed- and open-channel calculations until boiling occurs.

Other situations relevant to a steam line break accident were investigated. It was concluded that even after boiling occurs, the global parameters, such as total power and assembly power, still show no significant difference between the closed- and open-channel calculations. The open-channel calculations predict lower MDNBR values as compared with the results of closed-channel calculation in a vapor generation process, since the coolant is driven away from the hot spots. On the other hand, during a vapor condensation process, closed-channel calculations predict lower MDNBR results, since no cross flow is allowed to accelerate the condensation process. Also, a closed-channel, uniform inlet coolant temperature transient calculation was performed. The results verify the necessity for a three-dimensional calculation of the accident simulations, since no boiling was predicted by the one-dimensional calculation throughout the simulation period.

Investigators: Professors M. S. Kazimi and A. F. Henry; Dr. C. Shih, Dr. D. Griggs, and Dr. C. Tsai.

Support: Energy Laboratory Electric Utility Program.

Related Academic Subjects:

22.213 Nuclear Reactor Physics III
22.313 Advanced Engineering of Nuclear Reactors
22.36J Two-Phase and Boiling Heat Transfer

Recent References:

C. K. Tsai, M. S. Kazimi and A. F. Henry, "TITAN Code Development for Application to a PWR Steam Line Break Accident," MIT-EL 85-014, July 1984.

D. P. Griggs, M. S. Kazimi and A. F. Henry, "TITAN: An Advanced Three Dimensional Coupled Neutronic/Thermal-Hydraulics Code for Light Water Nuclear Reactor Core Analysis," MIT-EL 84-011, June 1984.

D. Griggs, C. Tsai, A. Henry and M. Kazimi, "TITAN: An Advanced Three Dimensional Coupled Code," Trans. Am. Nucl. Soc. 46, pp. 1984.

C. K. Tsai, M. S. Kazimi and A. F. Henry, "Three Dimensional Effects in Analysis of PWR Steam Line Break Accident," MIT-EL 85-004, March 1985.

3.2.12 Thermal Phenomena in Severe LWR Accidents

The accident at the Three Mile Island (TMI) has prompted numerous investigations of safety aspects of nuclear power plants. As a result of the 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 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.

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 to which fission products may be released from the melt.

Some of the uncertainties in estimating the heat transfer resistances surrounding the melt and the freezing phenomena involved in the pool were investigated. A semiempirical correlation for calculating the downward heat transfer coefficient was derived based on periodic contact between the liquid pool and the underlying solid in simulant experiments of water or benzene on dry ice. The correlation predicts that the downward heat transfer coefficient across the corium/concrete interface increases with superficial gas velocity. The experimental data on interfacial heat transfer between bubble agitated immiscible layers were reviewed and a new model based on the surface renewal concept was proposed. The hydrodynamic instability of a liquid jet was used to determine the onset of bubble induced entrainment at low gas velocity. It was concluded that the bubble induced liquid entrainment will not occur in the Corium/Concrete Interaction at low gas velocity, unlike the observed behavior in oil/water simulant experiments.

The proposed downward and interfacial heat transfer models have been incorporated into an integral analysis code, CORCON/Mod1, developed by Sandia laboratories. The proposed models were qualified by comparison to the results of the German BETA experiments of several hundred kg steel melt internally heated by induction.

Based on these comparisons, the following approach is proposed to calculate the downward heat transfer coefficient of a corium pool. If the temperature of the melt is initially very high, the heat flux will be high enough to stabilize a gas film, and the interaction can be modeled with the CORCON gas film model until the gas velocity decreases below a minimum stable gas film limit. After the film collapses, the heat transfer can be described by the periodic contact model. If the initial temperature is not high enough to generate a film the heat transfer will be via periodic contact throughout the time until freezing takes place. CORCON/Mod1 has been modified accordingly, and the results of BETA high melt temperature tests can be reproduced.

A simplified containment model based on thermal equilibrium among all materials within the containment was developed, and integrated with the modified CORCON/Mod1. The combined model, called CORCELL, was used to study the impact of Corium/Concrete Interaction on containment pressurization. It was found that the downward heat transfer model is very important in determining the concrete erosion rate. For the cases studied, the containment pressurization rate is less sensitive to the amount of gas generated. Should combustion of H_2 and CO occur, the containment pressure would be larger for higher downward heat transfer. For containment pressurization, the interfacial and upward convective heat transfer coefficients are relatively unimportant. However, the temperature profile of the corium pool will be affected by these parameters. It is also found that by considering the heat conducted into the containment concrete wall, the containment pressure can be significantly reduced.

Investigators: Professor M. Kazimi, Messrs. M. Lee, 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:

M. Lee and M. S. Kazimi, "Interfacial Heat Transfer between Bubble Agitated Immiscible Liquid Layers," Proc. of 6th Info. Exchange Mtg. on Debris Coolability, Los Angeles, Nov. 7-9. 1984.

L. Kao and M. S. Kazimi, "Containment Pressure Response to a Meltdown Condition of the Light Water Reactor," Proc. of 6th Info. Exchange Mtg. on Debris Coolability, Los Angeles, Nov. 7-9, 1984.

L. S. Kao, M. Lee and M. S. Kazimi, "Assessment of Heat Transfer Models for Corium-Concrete Interaction," presented at Int'l Conf. on Reactor Thermal Hydraulics, Newport, R.I., Oct. 1985.

M. Lee and M.S. Kazimi, "Modeling of Corium/Concrete Interaction," MIT-NE-267, Department of Nuclear Engineering, MIT (June 1985).

3.2.13 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: Professor N.C. Rasmussen; Dr. W. Vesely; Ms. V. Dimitrijevic and Ms. S. Cooper.

Support: NRC, pending.

Academic Subject:

22.40 Advanced Reliability Analysis and Risk Assessment.

Recent References: None to date.

3.2.14 Modeling of Control Rod Melting and Aerosol Formation in Severe Nuclear Accidents

This work undertakes to model the control rod melting process for Ag-In-Cd rods. The model attempts to calculate the timing of rod failure, the flow of liquid alloy down the outside of the control rod guide tube, and the vaporization rate of Ag, In, and Cd during the process. The timing of the release is also calculated.

A second subroutine is then developed to predict the transition from vapor to the final aerosol distribution using fundamental aerosol physics. The model includes nucleation on ions, as well as homogeneous and heterogeneous nucleation.

The code will be used to help understand the recent SFDI-4 tests on the PBF facility as the results become available.

Investigators: Professors N.C. Rasmussen and R. Lester; Dr. R. Hobbins; Mr. D. Petti.

Support: Idaho National Engineering Laboratory.

Related Academic Subject:

22.40 Advanced Reliability Analysis and Risk Assessment.

Recent References:

D.A. Petti, "Ag-In-Cd Control Rod Behavior and Aerosol Formation in Severe Reactor Accidents," Ph.D. Thesis, Department of Nuclear Engineering, MIT, December 1985.

3.2.15 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 are being studied as a joint program between the Charles Stark Draper Laboratory (CSDL) and MIT. The goal of the program is to utilize 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 comparison of sensors together with the use of models to provide analytic redundancy for an independent check on the sensor values. Although the general techniques exist for taking these inputs and detecting faults, the real time analytic models for the nuclear plant systems are only partially developed. Thus, the MIT/CSDL 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). Future considerations involve the potential for diagnostic information developed from the fault detection, and eventually there is a possibility of more closed loop controls with specific applications to large nuclear power plants or plant components.

In addition to the Nuclear Engineering Department, the MIT group involves contributors from the Mechanical Engineering, Electrical Engineering, and Computer Science Departments. In particular, control display systems are being 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 the studies of the non-linear closed loop digital control methods. 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 Draper Lab. 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 the NSF program.

Draper R&D funded task areas include reactor core modeling, plant component modeling, steam generator FDI application, MIT Reactor Feasibility Study, decision analysis technology transfer, alternate diagnostic concepts, and computer utilization concepts.

An Argonne breeder technology program award has given us the chance to explore new EBR-II applications. The project is intended to result in computer techniques appropriate for sensor validation during EBR-II natural circulation.

A recent program was initiated to investigate potential improvements in power plant performance monitoring. The objective of the study is to determine if the use of signal validation techniques could improve the accuracy of the plant performance monitoring. Initial studies of this program were funded and have been completed. Some studies are continuing on the next phase, at present on a self-supported basis, with the goal of quantifying the potential improvement.

As part of the Reactor Innovation Studies, consideration is being given to multi-modular reactor plants. The control of these plants will be an important aspect of the cost, and it is believed that multi-modular plants of the passively-safe design can be operated by simplified control systems incorporated into a single control room. We have initiated a review and consideration of this multi-modular control topic with funding from G.E. through the DOE LMR program. Our work to date is looking at multi-modular reactor control in general, and includes both Liquid Metal Reactor (LMR) and Modular High Temperature Gas-cooled Reactor (MHTGR) control systems. A report has been prepared for the LMR modular systems and is now being expanded to include the MHTGR considerations. A recommended control system is described. Future work would be to study the recommended control system in more detail.

Investigators: Professors D.D. Lanning, J.E. Meyer, A. Schor, A.F. Henry, M.J. Driscoll, T.B. Sheridan (Department of Mechanical Engineering), L.A. Gould, and F.C. Schweppe (Department of Electrical Engineering and Computer Sciences); Drs. J.A. Bernard (MIT), A. Ray, J.J. Deyst, J.H. Hopps (Draper Laboratory); Messrs. J.A. Alfeo, J.A. Carvajal, J.I. Choi, S.M. Dubnik, G.M. Garner, V.P. George, H.N. Jow, S.P. Kao, K.S. Kwok, J.K. Lao, R.S. Ornedo, A. Parlos, H.P. Polenta, B.W. Rhee, M.J. Schor, L.E. Trip III, G.S. Ueo, R.J. Witt, R.D. Wittmeier, M. Yasuda.

Support: Internal Draper funds (IR&D), self-supporting students with NED computer funding; and Argonne Breeder Technology Program, National Science Foundation, Northeast Utilities Service Company, the Foxboro Company, GE (DOE).

Related Academic Subjects:

22.32 Nuclear Power Reactors
22.363 Two-phase Flow and Boiling Heat Transfer
22.42 Numerical Methods in Engineering Analysis
22.883 Human Factors in Design

Recent References:

H.P. Polenta, "Implementation and Testing of a Microcomputer-based Fault Detection System," S.M. Thesis, Department of Nuclear Engineering, MIT, January 1984.

J.A. Bernard, "Development and Experimental Demonstration of Digital Closed Loop Control Strategies for Nuclear Reactors," Ph.D. Thesis, Department of Nuclear Engineering, MIT, May 1984.

H.-N. J. Jow, "Prioritization of Nuclear Power Plant Variables for Operator Assistance During Transients," Ph.D. Thesis, Department of Nuclear Engineering, MIT, May 1984.

S.P. Kao, "A Multiple-Loop Primary System Model for Pressurized Water Reactor Plant Sensor Validation," Ph.D. Thesis, Department of Nuclear Engineering, MIT, July 1984.

J.A. Bernard, D.D. Lanning, and A. Ray, "Experimental Evaluation of Reactivity Constraints for the Closed-Loop Control of Reactor Power," NRC-EPRI Symposium on New Technologies in Nuclear Power Plant Instrumentation and Control, published by Instrument Society of America, Washington, D.C. (November 1984).

G. Garner, R.S. Ornedo, J.E. Meyer, and S.M. Devakarani, "Robust Technique for Failure Detection and Vessel Level Validation in Boiling Water Reactors," NRC-EPRI Symposium on New Technologies in Nuclear Power Plant Instrumentation and Control, published by Instrument Society of America, Washington, D.C. (November 1984).

R.J. Witt and J.E. Meyer, "Computer Techniques for Sensor Validation during EBR-II Natural Circulation," Report No. MIT-NE-264, Department of Nuclear Engineering, MIT (November 1984).

J.A. Bernard, K.S. Kwok, and D.D. Lanning, "Experimental Evaluation of 'Fuzzy' Logic in Closed-Loop Reactor Control," Transactions of the American Nuclear Society, Vol. 49, pp. 392-93 (June 1985).

D.D. Lanning, J.A. Bernard, H. Hopps, and A. Ray, "MITR-II: Integrated Fault-Tolerant Systems Implementation and Experiments," Transactions of the American Nuclear Society, Vol. 49, pp. 377-78 (June 1985).

B.W. Rhee, "A Dynamic Model of a U-tube Steam Generator for Real Time Simulation," Ph.D. Thesis, Department of Nuclear Engineering, MIT, June 1985.

R.D. Wittmeier, "EBR-II: Natural Circulation Flow Rate Signal Validation Methods and Architecture," S.M. Thesis, Department of Nuclear Engineering, MIT, June 1985.

J.A. Alfeo, "Signal Validation for Performance Monitoring," S.M. Thesis, Department of Nuclear Engineering, MIT, September 1985.

J.A. Bernard and D.D. Lanning, "Experimental Evaluation of the Reactivity Constraint Approach for the Closed-Loop Control of Reactor Power Over a Range of Differential Reactivities," International Topical Meeting on Computer Applications for Nuclear Power Plant Operations and Control, Pasco, Washington (September 1985).

P.M. Blanch and J.E. Meyer, "Northeast Utilities Signal Validation Applications for Safety Parameter Display Systems," International Topical Meeting on Computer Applications for Nuclear Power Plant Operations and Control, Pasco, Washington (September 1985).

G.M. Garner, "Fault Detection and Level Validation in Boiling Water Reactors," Ph.D. Thesis, Department of Mechanical Engineering, MIT, September 1985.

M.J. Schor, "Control of Multi-module Nuclear Reactor Stations," S.M. Thesis, Department of Nuclear Engineering, MIT, December 1985.

S.P. Kao and J.E. Meyer, "A Plant-Computer-Based Pressurized Water Reactor Primary System Thermal Hydraulic Model," Trans. Am. Nucl. Soc., 50, pp. 637-38 (1985).

3.2.16 Engineering for Fusion Systems Studies

As fusion technology develops, it is important that engineering also develops to provide concepts for eventual power applications. This topic covers such studies. The topic also covers near future applications of engineering to design apparatus for fusion experiments.

Investigators: Professor J.E. Meyer; Messrs. R.J. LeClaire and R.J. Witt.

Support: DOE through the MIT Plasma Fusion Center.

Related Academic Subjects:

22.312	Engineering of Nuclear Reactors
22.314J	Structural Mechanics in Nuclear Power Technology
22.33	Nuclear Engineering Design
22.36J	Two-Phase Flow and Boiling Heat Transfer
22.602	Thermonuclear Reactor Design

Recent References:

Y. Nakagawa and J.E. Meyer, "Effects of Pulsed Operation on the Lifetime of Turbine Rotors," Sixth Topical Meeting on the Technology of Fusion Energy, San Francisco, CA, (March 1985).

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 the other subjects described below.

22.070J: Materials 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 an 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.

22.75J: Radiation Effects in Reactor Structural Materials, acquaints both nuclear engineering and metallurgy students with the classes and characteristics of structural materials used in the core and primary circuits of fission and fusion reactor systems. The effects of neutron irradiation and coolant environments on strength, brittle fracture, high-temperature embrittlement, creep and growth, void swelling, and corrosive behavior are discussed in terms of mechanisms and practical consequences to component design and system operation. Emphasis is also given to materials specifications and standards for nuclear service, quality assurance, and reliability assessment.

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:

R.G. Ballinger, J.W. Prybylowski, C.K. Elliott, "Effect of Processing History and Chemistry on the Structure of Nickel Base Superalloys," Second International Degradation of Materials in Nuclear Power Systems - Water Reactors, Monterey, CA (September 1985).

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

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 4.2°K 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

3.3.5 Stress Corrosion Cracking and Hydrogen Embrittlement of HSLA Steels

An investigation is being conducted to evaluate the stress corrosion cracking and hydrogen embrittlement susceptibility of HSLA steels for potential pressure vessel applications. The program is designed to help develop advanced steels for this application.

Investigators: Professor R.G. Ballinger; Mr. W.H. Needham.

Support: David W. Taylor Naval Ship Research and Development Center.

Related Academic Subjects:

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

3.3.6 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 times with minimum error to allow optimization of experimental test programs.

Investigators: Professors N.C. Rasmussen, 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

3.3.7 Phase Stability and Irradiation Effects

Phase stability in nuclear materials is dictated by local composition, local and external field, and microscopic fluctuations. We have studied such effects theoretically and experimentally. The theoretical studies to date have included solute segregation, void nucleation, and irradiation creep/-growth. The experimental study has focused on the magnetic effect on ferritic stainless steels. Good agreement was found between the predicted magnetic effect and our experimental results obtained at the National Magnet Laboratory.

Investigators: Professor I-W. Chen; Messrs. E. Faillace, A. Taiwo and P. Kalish.

Support: National Science Foundation

Related Academic Subject:

22.73J Radiation Effects in Crystalline Solids

Recent Publications:

I-W. Chen "Irradiation Growth Due to Magnetodiffusion," J. Nuclear Materials, 133-134:435-346 (1985).

E. Faillace and I-W. Chen, "The Effect of a Strong Magnetic Field on Age-hardening of Iron-chromium Alloys," J. Nuclear Materials, 133-134:343-346 (1985).

I-W. Chen and A. Taiwo, "Nucleation of Voids--The Impurity Effect," Proceedings of the Twelfth International Symposium on the Effects of Radiation on Materials, ed, F.A. Garner, ASTM STP870, 507-524 (1985).

3.3.8 Deformation and Fracture at Elevated Temperatures

Deformation and fracture at elevated temperatures involve diffusional and grain-boundary processes, in addition to the common mechanisms operational at lower temperatures. Our studies in this area have included the nucleation and growth mechanisms of creep cavitation, diffusional creep, dislocation creep, fine-grain superplasticity, and, most recently, on brittle crack growth found in welded structures.

Investigators: Professor I-W. Chen, Dr. M.H. Yoo (ORNL); Mr. M. Capano

Support: Department of Energy.

Related Academic Subjects:

22.071J Physical Metallurgy Principles for Engineers
22.71J Physical Metallurgy Principles for Engineers

Recent References:

I-W. Chen, "Quasi-static Intergranular Brittle Fracture at 0.5 T_m: A Non-equilibrium Segregation Mechanism of Sulphur Embrittlement in Stress-relief Cracking of Low Alloy Steels," Acta Metall., in press.

I-W. Chen, "Superplastic Flow of Two-phase Alloys," Superplasticity, ed. B. Baudelet, and M. Surey, 5.1-5.20, Paris: Editions du C.N.R.S. (1985).

3.3.9 Martensitic Transformations

Martensitic transformations exist in numerous materials, such as iron, plutonium and zirconia. They have the characteristics of a displacive transformation with a large lattice distortion. These transformations have been studied with the intent of understanding a potential toughening mechanism. Our studies of martensitic transformations have focused on the mechanism for nucleation, and its interrelation with the size statistics, the shape effect and the stress effect. In-situ TEM microscopy in this area has provided the most definitive observation of such transformations. A theory has been formulated and validated by the experiment. More recently, a new experimental technique using high pressure (up to 5K bar) and shear stress was developed to probe transformation plasticity successfully.

Investigators: Professor I-W. Chen and Mr. Y-H. Chiao.

Support: Department of Energy.

Related Academic Subjects:

22.071J Physical Metallurgy Principles for Engineers
22.71J Physical Metallurgy Principles for Engineers

Recent References:

I-W. Chen and Y-H. Chiao, "Theory and Experiment of Martensitic Nucleation in ZrO_2-containing Ceramics and Ferrous Alloys," Acta Metall., 33:1827-1845 (1985).

I-W. Chen, Y-H. Chiao, and K. Tsuzaki, "Statistics of Martensitic Nucleation," Acta Metall., 33:1847-1859 (1985).

I-W. Chen, "Mechanisms of Transformation and Transformation Plasticity in ZrO_2-containing Ceramics," Zirconia Ceramics, 4:55-79, eds. S. Sumiya and M. Yoshimura. Yokohama: Tokyo Institute of Technology, (1985).

I-W. Chen and B. Reyes Morel, "Implications of Transformation Plasticity in ZrO_2-containing Ceramics: I. Shear and Dilatancy Effects," J. Amer. Ceram. Soc., in press.

I-W. Chen, "Implications of Transformation Plasticity in ZrO_2-containing Ceramics: II. Elastic Plastic Indentation," J. Amer. Ceram. Soc., in press.

Y-H. Chiao and I-W. Chen, "In-Situ TEM Observations of the Structures and Migration of Martensitic Interface in Small ZrO_2 Particles," Proc. JIM15-4 Grain Boundary Structure and Related Phenomena, Suppl. Trans. Japan Inst. Metals, in press.

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

High radiation exposures to workers during maintenance of the primary coolant systems of present light water power reactors results in a significant cost which must be borne by the power consumers. The MITR-II is well suited to the development of an experimental facility which would be devoted to studying the basic processes involved in the production, activation and transport of radioactive corrosion products. A technical team comprising MIT staff members, from various relevant disciplines, has developed a proposal for in-core loops at MITR-II which is designed to simulate part of the primary coolant system of a PWR and BWR. These facilities will be used for tests designed to understand the basic mechanisms of radioactive corrosion product, generation, transport and deposition. This understanding is needed to achieve important dose decreases for operating personnel at LWRs.

Investigators: Professors O.K. Harling, M.J. Driscoll, D.D. Lanning, R.M. Latanision (Department of Materials Science and Engineering), and R.G. Ballinger; Drs. J.A. Bernard and G. Kohse.

Support: U.S. Energy Research and Development Administration via Energy Laboratory and MIT Internal funds.

Related Academic Subjects:

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

Recent References:

N. Kanani, L. Arnberg and O.K. Harling,"Pre-Irradiation Spatial Distribution and Stability of Boride Particles in Rapidly Solidified Boron Doped Stainless Steels," J. Nucl. Mater., 103 & 104, 1115-1120 (1981).

E. Testart, J. Megusar, L. Arnberg and N.J. Grant, "Mechanical Properties and Structure of Rapidly Solidified High Titanium Stabilized 316 Stainless Steel," J. Nucl. Mater., 103 & 104, 833-838 (1981).

L. Arnberg, J. Megusar, D. Imeson, H.J. Frost, J.B. Vander Sande, O.K. Harling and N.J. Grant, "The Microstructure of Neutron Irradiated Rapidly Solidified Path A Prime Candidate Alloys," J. Nucl. Mater., 103 & 104, 1005-1010 (1981).

L. Arnberg, J. B. Vander Sande, H.J. Frost and O.K. Harling, "The Microstructure of Rapidly Solidified Path A Prime Candidate Alloys Following Irradiation with Fe and He Ions," J. Nucl. Mater., 103 & 104, 1069-1074 (1981).

J. Megusar, L. Arnberg, J.B. Vander Sande and N.J. Grant, "Microstructures of Rapidly Solidified Path A Prime Candidate Alloys," J. Nucl. Mater., 103 & 104, 1103-1108 (1981).

O.K. Harling, G.P. Yu, N.J. Grant and J.E. Meyer, "Application of High Strengh Copper Alloys for a Fusion Reactor First Wall," J. Nucl. Mater., 103 & 104, 127-132 (1981).

A.O. Adegbulugbe and J.E. Meyer, "Failure Criteria for Fusion Reactor First Wall Structural Design," J. Nucl. Mater., 103 & 104, 161-166 (1981).

M.P. Manahan, A.S. Argon and O.K. Harling, "The Development of a Miniaturized Disk Bend Test for the Determination of Postirradiation Mechanical Properties," J. Nucl. Mater., 103 & 104, 1545-1550 (1981).

J. Megusar and N.J. Grant, "Stabilization and Strengthening of $Pd_{80}Si_{20}$ Metallic Glass," Mat. Sci. Eng., 49, 275-283 (1981).

J. Megusar, L. Arnberg, J.B. Vander Sande and N .J. Grant, "Optimization of Structure and Properties of Path A Prime Candidate Alloy (PCA) by Rapid Solidification," J. Nucl. Mater., 99, Nos. 2 & 3, 109-202 (1981).

H.J. Frost and K.C. Russell, "Particle Stability with Recoil Resolution," Acta Met., 30, 953-960 (1982).

H.J. Frost and K.C. Russell, "Precipitate Stability Under Irradiation," to appear in "Phase Transformations and Solute Redistribution in Alloys During Irradiation," a Res Mechanica Monograph.

M.P. Manahan, "A New Postirradiation Mechanical Behavior Test-The Miniaturized Disk Bend Test," ANS Trans. 23, 352-354(1982).

J. Megusar, O.K. Harling and N.J. Grant, "Lithium Doping of Candidate Fusion Reactor Alloys to Simulate Simultaneous Helium and Damage Production," J. of Nucl. Mater, 115 192-196 (1983).

J. Megusar, D. Imeson, J.B. Vander Sande and N.J. Grant, "Dynamic Powder Compaction of Rapidly Solidified Path A Alloy with Increased Carbon and Titanium Content," Fifteenth ADIP Semiannual Progress Report, October 1981-March 1982.

A.I. Ibrahim, J. Megusar and N.J. Grant, "Mechanical Properties and Structure of Y_2O_3 Dispersion Stabilized, Rapidly Solidified 316 Type Stainless Steel," Fifteenth ADIP Semiannual Progress Report, October 1981-March 1982.

D. Imeson, C. Tong, J.B. Vander Sande and O.K. Harling, "The Effect of Neutron Irradiation on the Titanium Carbide Distribution in Rapidly Solidified Austenitic Stainless Steels of Varying Titanium and Carbon

Content," a paper submitted at the symposium on the Chemistry and Physics of Rapidly Solidified Materials, 1982 TMS-AIME Fall Meeting, St. Louis, Missouri, October 24-28, 1982.

D. Imeson, M. Lee, J.B. Vander Sande, N.J. Grant and O.K. Harling, "Irradiation Response in Titanium Modified Austenitic Stainless Steels Prepared by Rapid Solidification Processing, Part I: Microstructural Response to Neutron Irradiation," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-23, 1983, J. Nucl. Mater, 122 & 123, 266-271 (1984).

C.H. Tong, D. Imeson, J. Megusar, J.B. Vander Sande, N.J. Grant and O.K. Harling, "Irradiation Response in Titanium Modified Austenitic Stainless Steels Prepared by Rapid Solidification Processing, Part II: Dual Ion Irradiations," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-23, 1983, J. Nucl. Mater, 122 & 123, 272-277, (1984).

D. Imeson, C.H. Tong, C.A. Parker, J.B. Vander Sande, N.J. Grant and O.K. Harling, "Irradiation Response in Titanium Modified Austenitic Stainless Steels Prepared by Rapid Solidification Processing, Part III: A Model for the Effect of Titanium Addition," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-23, 1983, J. Nucl. Mater, 122 & 123, 278-283 (1984).

M. Lee, D.S. Sohn, N.J. Grant and O.K. Harling, "Miniaturized Disk Bend Tests of Neutron Irradiated Path A Type Alloys," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-22, 1983, J. Nucl. Mater, 122 & 123, 146-151 (1984).

J. Megusar, E. Lavernia, P. Domalavage, O.K. Harling and N.J. Grant, "Structures and Properties of Rapidly Solidified 9Cr-1Mo Steel," a paper presented at the Third Topical Meeting on Fusion Reactor Materials, Albuquerque, New Mexico, September 19-22, 1983, J. Nucl. Mater, 122 & 123, 789-793 (1984).

O.K. Harling, M. Lee, D.S. Sohn, G. Kohse and C.W. Lau, "The MIT Miniaturized Disk Bend Test," an invited paper presented at the Symposium on Use of Non-Standard Sub-Sized Specimens for Irradiated Testing, Albuquerque, New Mexico, September 23, 1983, to be published in ASTM Special Technical Publication 888.

3.3.11 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 if 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 alloy requirements based on an analysis of fusion reactor 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 material 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: See Section 3.3.10.

3.4 Nuclear Chemical Technology

The Department's efforts in the ex-reactor sector of the nuclear fuel cycle have evolved in the face of current realities. Thus, while nuclear waste disposal and safeguards continue as focal points for teaching and research activities (see elsewhere in this report), less emphasis is currently placed on topics such as reprocessing, and on front-end processes in general.

3.4.1 Subject of Instruction

22.76J Introduction to Nuclear Chemical Engineering, was offered for the last time in the fall term, 1984, due to declining student interest. Important fuel cycle topics formerly covered in 22.76J will, however, now be given enhanced coverage in other continuing subjects on nuclear waste disposal and fuel management.

3.4.2 Extraction of Uranium from Seawater

Work continues on the evaluation of ion exchange resin and contactor system concepts for the recovery of uranium from seawater, but at a reduced level, in view of the projected oversufficiency of moderate cost terrestrial reserves for the next several decades. During the past year, work has been focused on the evaluation of low cost procedures for the production of acrylic amidoxime ion exchange fiber. Samples prepared in the laboratory at MIT are currently undergoing long-term sea trials at the New England Aquarium. It is anticipated that this project can be brought to a successful conclusion within the next 18 months.

Investigators: Professor M.J. Driscoll; Mr. J. R. Jimenez.

Support: Internal and MIT UROP.

Related Academic Subjects:

22.35 Nuclear Fuel Management
22.81 Energy Assessment

Recent References:

J. Varela, "Mass and Momentum Transfer in Uranium-from-Seawater Sorption," S.M. Thesis, Department of Nuclear Engineering, MIT, May 1983.

N.A. Ismail, "Engineering System Analysis of Uranium Recovery from Seawater," N.E. Thesis, Department of Nuclear Engineering, MIT, May 1983.

J. Borzekowski, M. J. Driscoll, and F. R. Best, "Uranium Recovery from Seawater by Ion Exchange Resins," Trans. Am. Nucl. Soc., 44, June 1983.

M.J. Driscoll, "Recent Work at MIT on Uranium Recovery from Seawater," International Meeting on Recovery of Uranium from Seawater, Atomic Energy Society of Japan/IAEA, Tokyo, Japan (October 1983).

M.J. Driscoll, "An Artificial Kelp Farm Concept for the Extraction of Uranium from Seawater," MITNE-260 (April 1984).

F.R. Best and M.J. Driscoll, "Prospects for the Recovery of Uranium from Seawater," Nuclear Technology (to be published: March 1986).

3.4.3 LWR Dose Rate and Corrosion Reduction

A major initiative has been pursued in this area over the past several years, through the MIT Reactor and Energy Laboratories, to create an in-pile loop facility for experiments on corrosion product activation and transport. A loop simulating PWR conditions has been designed using in-house resources; utility funding to create a parallel BWR design has recently been secured; and a comprehensive research proposal to construct and operate these facilities has been submitted to the Empire State Electric Energy Research Corporation and the Electric Power Research Institute. If these initiatives bear fruit, MIT will be equipped to make important contributions to methods for the reduction of LWR maintenance doses by suppressing radionuclide deposition--a problem of long standing, which is estimated to cost U. S. utilities some tens of millions of dollars in additional downtime annually. The facility can also be used to investigate phenomena such as stress corrosion cracking, which is a major contributor to failure of reactor coolant system materials, and hence a major cause of the need for maintenance activities in high dose environments.

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

Support: PSE&G/Duke Power/Boston Edison.

Related Academic Subjects:

22.39 Nuclear Reactor Operations and Safety
22.58 Health Physics II
22.75J Radiation Effects in Reactor Structural Materials

Recent References:

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

3.5 MIT Reactor

The MIT Reactor has operated since 1958, most recently at a 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 preplanned 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. Operations 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 physics calculations, neutron transport measurements in a mock-up of the new beam port and reflector configuration, fluid flow measurements on a hydraulic mock-up, heat transfer measurement and theoretical calculations 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 Reactor 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, G.L. Brownell, I.W. Chen, S.H. Chen, M.J. Driscoll, F.A. Frey, O.K. Harling, D.D. Lanning, P.M. Newberne, A.F. Sarofim, G.M. Simmons, C.G. Shull, R.M. Snapka, N.E. Todreas, V.R. Young, A. Zeilinger; Drs. C.V. Berney, L.J. Caruso, C.H. Handwerker, P. Ila, N. Istfan, M. Janghorbani, G. Kohse, M. Lee, A. Nahapetian, B. Ting, B.W. Wessels; Messrs. H. Andresen, J. Arthur, D. Atwood, T. Beatty, J. Bernard, C.Y. Chen, M. Christensen, L. Clark, S. DePietro, W. Fecych, K. Finkelstein, L. Gulen, M. Horne, M. Izenson, J. Kirsch, K. Kwok, M. Manahan, T. Nguyen, W. Pergram, G. Ray, M. Roden, T. Sando, P. Sirichakwal, H. Stockman, T. Takala; Mses. M. Ashtari, R. Hickey, S. Reilly, M. Sirichakwal, P. Sirichakwal, A. Sundaresan.

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: (reactor engineering and reactor physics only):

S.M. Reilly, "Reducing Emission of Argon-41 from the MIT Reactor," S.M.Thesis, Department of Nuclear Engineering, MIT, (1984).

J.A. Bernard, Jr., "Development and Experimental Demonstration of Digital Closed Loop Control Strategies for Nuclear Reactors," Ph.D Thesis, Department of Nuclear Engineering, MIT, (1984).

J.E. Deplitch, "Reduction of Argon-41 Produced by the MITR-II," S.M. Thesis, Department of Nuclear Engineering, MIT, (1985).

NOTE: References shown here emphasize reactor physics and engineering and do not include a large number of papers, reports and theses in research areas such as beam tube research in physics and chemistry, trace analysis and radiochemistry studies in nutrition, geochemistry, nuclear medicine, materials research, etc. Much more comprehensive information about research activities at the MITR-II is contained in references such as MITNRL-001, Report of Educational and Research Activities for Academic Years 1975-76, 1976-77, 1977-78, and the Proceedings of an International Symposium on the Use and Development of Low and Medium Flux Research Reactors, published as a Supplement to Atomkernenergie-Kerntechnik, Vol. 44 (1984).

3.6 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 (Sect. 3.7), the Radiation Health Physics program (Sect. 3.8) and the physical metallurgy part of the Nuclear Materials program (Sect. 3.3).

3.6.1 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: Introductory Nuclear Measurements Laboratory, deals with the basic principles of interaction of nuclear radiation with matter. Statistical methods of data analysis, introduction to electronics in nuclear instrumentation; counting experiments using Geiger-Muller counter, gas-filled proportional counter, scintillation counter, and semiconductor detectors. A term project emphasizes applications to experimental neutron physics, radiation physics, health physics and reactor technology.

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.

22.112: Nuclear Physics for Engineers II, is a continuation of 22.111 with emphasis on detailed studies of nuclear reactions, gamma and charged particle interactions. Cross section calculations using optical models. Neutron thermalization, inelastic scattering and radiative capture. Charged particle emissions, photonuclear reactions. Fusion reactions. Availability and accuracy of current nuclear data files.

22.29: Nuclear Measurements Laboratory, deals with the principles of interaction of nuclear radiations with matter. Principles underlying instrumental methods for detection and energy determination of gamma rays, neutrons and charged particles. Applications to applied radiation physics, health physics, and reactor technology. Laboratory experiments on gas-filled, scintillation, and semiconductor detectors; nuclear electronics such as pulse amplifiers, multi-channel analysers, and coincidence techniques; applications to neutron activation analysis, X-ray fluorescence analysis, thermal neutron cross sections and radiation dosimetry.

22.44J: Computational Methods in Materials Science and Engineering, covers the principles and applications of methods for computing materials properties and behavior; atomistic simulation techniques of molecular statics, molecular dynamics and Monte Carlo as applied to crystalline solids with and without defects. Continuum modeling of fluid flow phenomena in materials processing. Finite element methods. Statistical techniques of error propagation and multivariate error analysis in experimental design. Hands-on experience using existing computer programs and programs developed during the term.

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.

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 22.112, 22.29, and 22.51.

3.6.2 Neutron Spectrometry and Molecular Dynamics in Solids and Fluids

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

Support: National Science Foundation.

Related Academic Subject:

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).

3.6.3 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 from 1 sec to 1 μsec which covers the useful range of fluctuation phenomena from neutron population in a reactor core to flow of particles in turbulent fluids. In the past, the method has been applied to the study of slow fluctuations of the concentration in a binary liquid mixture near the critical point with a great deal of success. We also applied this technique to the measurement of isotropic random motion of bacteria in liquid media and also to directed biased motions when a chemotactic agent is present. More recently, the critical slowing-down of concentration fluctuations in three-component ionic micellar solutions (lithium dodecyl sulfate/butanol/water system) has been studied, and the critical exponents have been determined. We have also observed a glass-like transition in dense microemulsions (AOT/water/decane) by measuring the density fluctuations of microemulsion droplets when the volume fraction of the droplets are increased to above 0.6.

Investigators: Professor S.H. Chen, Messrs. Y.S. Chao, and E.Y. Sheu.

Support: Petroleum Research Fund of the American Chemical Society (1982-1985).

Related Academic Subjects:

22.51 Radiation Interactions and Applications
8.442 Statistical Optics and Spectroscopy

Recent References:

S.H. Chen, C.C. Lai, J. Rouch and P. Tartaglia, "Critical Phenomena in a Binary Mixture of n-hexane and Nitrobenzene--Analyses of Viscosity and Light Scattering Data," Phys. Rev. A27, 1086 (1983).

S.H. Chen and F.R. Hallett, "Determination of Motile Behavior of Prokaryotic and Enkaryotic Cells by Quasielastic Light Scattering," Quart. Rev. Biophys. 15, 1 (1982).

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, Department of Nuclear Engineering, MIT, January 1985.

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

3.6.4 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 ν, 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, and also 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. Y.S. Chao, T.L. Lin, E.Y. Sheu, C.F. Wu.

Support: National Science Foundation.
Petroleum Research Fund of the American Chemical Society (1982-1985).

Related Academic Subjects:

22.51 Radiation Interactions and Applications
8.442 Statistical Optics and Spectroscopy

Recent References:

M. Kotlarchyk, S.H. Chen, J.S. Huang and M.W. Kim, "Structure of Three-Component Microemulsions in the Critical Region Determined by Small Angle Neutron Scattering," Phys. Rev. A29, 2054 (1984).

K. Kotlarchyk, J.S. Huang and S.H. Chen, "Structure of AOT Reversed Micelles Determined by SANS," J. Phys. Chem., 89, 4382 (1985).

Y.S. Chao, E.Y. Sheu and S.H. Chen, "Experimental Test of a Theory of Dressed Micelles--The Case of Monovalent Counter-ions," J. Phys. Chem., 89, 4862 (1985).

Y.S. Chao, E.Y. Sheu and S.H. Chen, "Intermicellar Interactions in Lithium Dodecyl Sulfate Solutions--Effects of Divalent Counter-ions," J. Phys. Chem., 89, 4395 (1985).

S.H. Chen and D. Bendedouch, "Structure and Interactions of Proteins in Solution Studied by Small Angle Neutron Scattering," an article to appear in Enzyme Structure, a volume of Methods in Enzymology, edited by H.S. Hirs and S.N. Timasheff, Academic Press.

3.6.5 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. Problems currently under study 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 involves an external collaborator who is a scientist at an industrial research laboratory or a national laboratory.

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

Support: Argonne National Laboratory (proposal pending), National Science Foundation (proposal pending),Schlumberger-Doll Fellowship (1982-), IBM Graduate Fellowship(1983-), DOE NSEHPWM Fellowship (1984-).

Related Academic Subjects:

22.44J Computational Methods in Materials Science and Engineering
22.71J Physical Metallurgy Principles for Engineers

Recent References:

J.A. Combs and S. Yip, "Molecular Dynamics Study of Lattice Kink Diffusion," Physical Review, B29, 438 (1984).

A.J.C. Ladd, W.G. Hoover, V. Rosatto, G. Kalonji, R. Harrison, S. Yip, "Grain Boundary Free Energy of a Two-Dimensional Bicrystal," Physics Letters, 100A, 195, (1984).

T. Kwok, P.S. Ho and S. Yip, "Molecular Dynamics Studies of Grain Boundary Diffusion: I. Structural Properties and Mobility of Point Defects," Physical Review, B29, 5354, (1984).

T. Kwok, P.S. Ho and S. Yip, "Molecular Dynamics Studies of Grain Boundary Diffusion: II. Vacancy Migration Diffusion Mechanism and Kinetics," Physical Review, B29, 5363, (1984).

K. Toukan, F. Carrion, S. Yip, "Molecular Dynamic Study of Structural Instability of Two Dimensional Lattices,": Journal of Applied Physics, 56, 1455 (1984).

R. Najafabadi and S. Yip, "Mechanical Response of a Stressed Two-Dimensional Bicrystal," Scripta Metallurgica, 18, 159 (1984).

T. Kwok, P.S. Ho, S. Yip, "Computer Simulation of Vacancy Migration in a FCC Tilt Boundary," Surface Science, 144, 44 (1984).

G. Kalonji, P. Deymier, R. Najafabadi, S. Yip, "A Molecular Dynamics Study of Grain Boundary Phase Equilibria: The Case of the Σ=13 Boundary," Surface Science, 144, 77 (1984).

S. Yip, "Atomistic Simulation Studies of Grain Boundaries," Comments on Solid State Physics, 11, 125 (1984).

P.S. Ho, T. Kwok, T. Nguyen, C. Nitta, S. Yip, "Observation of Local Melting in an Aluminum Bicrystal by Molecular Dynamics Simulation," Scripta Metallurgica, 19, 993 (1985).

S. Yip, "Atomistic Simulations in Materials Science," Lectures at International Summer School of Physics 'Enrico Fermi,' Varenna, Italy, 1985, to appear in proceedings published by North Holland, Amsterdam, 1986.

3.6.6 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. Another part of the project deals with fluctuations in model systems which undergo exothermic chemical reactions; in particular, the problem of thermal ignition is being treated by molecular dynamics and Monte Carlo simulations, as well as by stochastic theory.

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

Support: National Science Foundation, Argonne National Laboratory.

Related Academic Subjects:

22.443 Computational Methods in Materials Science and Engineering
22.51 Radiation Interactions and Applications
22.71 Physical Metallurgy for Engineers

Recent References:

J.J. Ullo and S. Yip, "Molecular Dynamics of Dense Gases: Effects of Continuous Potentials," Physical Review, A29, 2092 (1984).

J-C. Lerment and S. Yip, "A Generalized Semenov Model for Thermal Ignition in Nonuniform Temperature Systems," Combustion and Flame, 57, 41 (1984).

D-P. Chou and S. Yip, "Molecular Dynamics of Thermal Ignition in a Reacting Hard Sphere Fluid," Combustion and Flame, 58, 239 (1984).

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 an 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).

3.7 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.

3.7.1 Subjects of Instruction

The basic subjects of instruction in the radiological sciences field include the undergraduate subject 22.04, Radiation Effects and Uses, and the three 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.

3.7.2 Tumor Strangulation

Studies are being conducted on the effects of ionizing radiation on tumor vasculature. A novel approach of plastic injection into treated tumor vasculature and subsequent analysis under high resolution scanning electron microscopy has been developed. The results provide new insights into tumor treatment and into the mechanisms of tumor growth.

Investigators: Professor Alan C. Nelson; Ms. M. Chackal, Messrs. T. Nguyen, A. D'Amico, and R. Heft.

Related Academic Subjects:

- 22.04 Radiation Effects and Uses
- 22.55J Biological and Medical Applications of Radiation and Radioisotopes
- 22.57J Radiation Biophysics

Support: Whitaker Health Sciences Fund, National Heart, Lung and Blood Institute, Athwin Foundation, Whitaker Foundation.

Recent References:

A. Shah, "Analysis of Tumor Vasculature and Radiation Effects," Ph.D. Thesis, Department of Nuclear Engineering, MIT, (1983).

A.C. Nelson, A. Shah-Yukich, and R. Babayan, "Radiation Damage in Rat Kidney Microvasculature," Scanning Electron Microsopy/84, 1273-1277 (July 1984).

R.K. Babayan, A.C. Nelson, and A.V. D'Amico, "A Novel Approach to the Study of Microvasculature in Solid Tumors," Surgical Forum of the American College of Surgeons, XXXVI, 639-641 (October 1985).

3.7.3 Microstructural Cell Damage Due to Heavy and Other Ion Radiations

This is a continuation of research in conjunction with the Lawrence Berkeley Laboratory where irradiations with heavy ion beams are accomplished on cyclotron and synchrotron accelerators. We are studying damage to cell membranes and cytoplasm in tissues and tumors with scanning microscopy.

Investigators: Professor A.C. Nelson; Messrs. H. Lorie, B. Strauss, D. Cohen, and C. McConnell

Related Academic Subjects

- 22.04 Radiation Effects and Uses
- 22.51 Radiation Interactions and Applications
- 22.55J Biological and Medical Applications of Radiation and Radioisotopes
- 22.57J Radiation Biophysics

Support: Lawrence Berkeley Laboratory, Whitaker Foundation.

Recent References:

A.C. Nelson, T.L. Hayes, C.A. Tobias, and T.C.H. Yang. "Some Indications of Structural Damage in Retina by Heavy Ion Radiation," Scanning Electron Microsopy/81, 79-85 (June 1981).

A.C. Nelson and C.A. Tobias, "Rapid Development of Corneal Lesions in Rats Produced by Heavy Ions," Adv. Space Res., 3, 195-209, (April 1983).

A.C. Nelson, A. Shah-Yukich, and R. Babayan, "Radiation Damage in Rat Kidney Microvasculature", Scanning Electron Microscopy/84, 1273-1277 (July 1984).

A.C. Nelson and H.R. Wyle, "Morphological Changes in Neutron Irradiated Red Blood Cells," Scanning Electron Microscopy/85, 1623-1630 (November 1985).

3.7.4 Image Science and Technology

Research in the area of image formation in electron microscopy is aimed at obtaining information using newly developed technologies. These studies emphasize hardware development and image analysis including quantitation, standardization, feature extraction, and automated collection. These new technologies facilitate research radiology, materials science, and medical diagnostics.

Investigators: Professor A.C. Nelson, Dr. L. Sher, Dr. R. Hughes; Ms. D. Chien, Messrs. D. Kennedy and T.S. Chu.

Related Academic Subjects:

22.04 Radiation Effects and Uses
22.57J Radiation Biophysics
22.56J Principles of Medical Imaging

Support: Whitaker Health Sciences Fund, Sloan Foundation, Athwin Foundation, Ginisco Corp., National Cancer Institute, National Heart, Lung and Blood Institute.

Recent References:

A.C. Nelson, "Computer Aided Microtomography with True 3-D Display in Electron Microscopy," J. Histochemistry and Cytochemistry, 34, #1.

3.7.5 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. Kariento (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. Kirsch, and J. Kehayias, "Accelerator Production of Epithermal Neutrons for Neutron Capture Therapy," Proceedings of the 2nd 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 1st 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 1st International Symposium on Neutron Capture Therapy, pp. 304-314, (October 1983).

3.7.6 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:

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 & Stratton (eds.) (1985).

G.L. Brownell, C.A. Burnham, and D.A. Chesler, "High Resolution Tomograph Using Analog Coding," The Metabolism of the Human Brain Studied with Positron Emission Tomography, T. Greitz, et al. (eds.) Raven Press, New York (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, 619-626 (1982).

3.8 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.

3.8.1 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.

22.29: Nuclear Measurements Laboratory, covers basic principles of interaction of nuclear radiations with matter. Principles underlying instrumental methods for detection and energy determination of gamma-rays, neutrons and charged particles are discussed. Other topics include applications to applied radiation physics, health physics, and reactor technology; laboratory experiments on gas-filled, scintillation and semiconductor detectors; nuclear electronics such as pulse amplifiers, multi-channel analyzers and coincidence techniques; applications to neutron activation analysis, X-ray fluorescence analysis, thermal neutron cross sections, and radiation dosimetry.

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.

22.58: Health Physics II, uses the 5 MW MIT Research Reactor extensively to provide students with real experience in radiation measurement, management, and control. Other facilities include a cyclotron, linear accelerator, and power reactors. Reviews applicable standards for radiation exposure. Covers theory and use of α, β, γ, and n detectors and spectrometers. Covers preparation and handling of isotopes, shielding, analysis and design of radiation protection systems and procedures, in applications including nuclear power generation, medical and research uses of radiation.

3.8.2 Control of Argon-41 at the MIT Research Reactor

This research is designed to identify, quantify and mitigate the sources of Argon-41 emitted from the MIT Research Reactor.

Investigators: Professor O.K. Harling; Messrs. L. Clark, Jr. and John Deplitch.

Support: U.S. Army and MIT Nuclear Reactor Laboratory.

Recent Reference:

J.E. Deplitch, Jr., "Reduction of Argon-41 Produced by MITR-II," S.M. Thesis, Department of Nuclear Engineering, MIT, June 1985.

3.8.3 Improved Methods to Remove Radon-222 and Its Decay Products from Indoor Air.

Radon-222 and its daughter products cause a major part of the normal background radiation exposure to the general population. In some cases the radiation exposure from this source greatly exceeds normal background and in some buildings reaches dangerously high levels. According to recent publications, ten thousand excess fatal lung cancers may result from this source each year in the USA.

This research involves the development of improved technology for removal of Radon from indoor air. Emphasis in this work will be placed on electrostatic precipitator development.

Investigators: Professor O.K. Harling; Dr. Dade W. Moeller, Harvard School of Public Health and Mr. Claudio Rubio.

Support: Chilean Atomic Energy Commission, MIT Nuclear Reactor Lab and Florida Institute of Phosphate Research.

Recent Reference:

C.A. Rubio, "The Effect of Enhanced Convection on Radon Decay Product Concentration," S.M. Thesis, Department of Nuclear Engineering, MIT, June 1985.

3.9 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.

3.9.1 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 analyses 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 fermious, bosons, black-body radiation, electrons in metals, crystals, rate processes, and relaxation phenomena.

3.9.2 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 in both these efforts. Several publications have appeared in the scientific literature.

The possibility of critical experiments that distinguish between reducible and irreducible mixed quantum states is being investigated.

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 Publications:

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, 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, 77-97 (1985).

3.10 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.

3.10.1 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 Engineering 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.

22.85J: Case Studies in Energy, Technology, Economics and Management, gives students with diverse backgrounds an opportunity to study the multi-dimensional (i.e., technological, economic and environmental) nature of complex energy issues in a concrete context. Class is divided into working groups for specific case studies. Investigates one or more topics of current interest involving fossil fuel, nuclear, and renewable energy sources.

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.

3.10.2 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 prospects for the development of an international regime for spent fuel storage featuring fuel supplier takeback schemes.

Investigator: Professor R.K. Lester.

Related Academic Subjects:

22.81 Energy Assessment
22.341 Nuclear Energy Economics and Policy Analysis
17.841 The Technology and Politics of Nuclear Weapons and Arms Control

Recent References:

R.K. Lester, "Foreign Policy Preaching and Domestic Practice," Society, Vol. 20, No. 6, 48-52, (September/October 1983).

R.K. Lester, "Structural Change in the Nuclear Power Plant Industry in the Pacific Basin Region," Columbia Journal of World Business, (1983).

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

3.10.3 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. Other models have been developed to assess the economic consequences of storing the high-level waste in engineered surface facilities for an extended period of cooling prior to final disposal.

During the last year a technical assessment of the regulations governing the geologic disposal of high-level waste recently promulgated by the Nuclear Regulatory Commission and the Environmental Protection Agency has been completed. Also during this period work has begun, in collaboration with the Tennessee Valley Authority, on the development of a decision analytic method for evaluating alternative strategies for interim storage, packaging and transportation of spent power reactor fuel.

Investigators: Professor R.K. Lester; Ms. S. Reilly, Messrs. J. Lee, S.R. Allen, P.H. Seong, and C. Malbrain.

Support: U.S. Department of Energy (terminated); Tennessee Valley Authority.

Related Academic Subjects:

22.77 Nuclear Waste Management

22.341 Nuclear Energy Economics and Policy Analysis

Recent References:

S.M. Reilly, "Radiation Damage to Cation, Anion, and Mixed Bed Ion Exchange Resins," S.B. Thesis, Department of Nuclear Engineering, MIT, 1983.

J. Lee, "Economic Evaluation of Low-Level Radioactive Waste Volume Reduction Systems," N.E. Thesis, Department of Nuclear Engineering, MIT,(1983).

S.R. Allen, "A Technical Assessment of Uranium Mill Tailings Management," N.E. Thesis, Department of Nuclear Engineering, MIT, (1984).

P.H. Seong, "Optimization of Waste Age and Canister Diameter for Minimum Waste Management System Cost," S.M. Thesis, Department of Nuclear Engineering, MIT, (1984).

C.M. Malbrain, "Risk Assessment and the Regulation of High-Level Waste Repositories," Ph.D. Thesis, Department of Nuclear Engineering, MIT, (1984).

C.M. Malbrain and R.K. Lester, "An Improved Environmental Pathway Model for Assessing High-Level Waste Repository Risks," Department of Nuclear Engineering Working Paper, MIT, (1985).

3.11 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.

3.11.1 The Light Water Reactor (LWR) Innovation Project

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

- New plant performance requirements
- Conceptual design innovation

TABLE 1

LWR INNOVATION PROJECT
(Current Activities)

- Conceptual Design
  - o GE - Small BWR Project
- Utilities Requirements for New Plants
  - Simplification
    - o CVCS
    - o Condensate/Feedwater System
- Human Error
  - o Condensate/Feedwater System
  - o Pump Seal Maintenance
  - o Robotic Compatibility
  - o Dose Reduction
- Technological Advances
  - Safety Rationalization
    - o Leak-Before-Break
    - o Functionally-Oriented Regulation
- New Technology
  - o Automatic Reactor Control
  - o Fault-Tolerant Sensor Validation and Operator Aid
  - o Artificial Intelligence-Tech Specs.
  - o Information Processing
- Improved Designs
  - o CVCS
  - o Condensate/Feedwater System
- Troublesome Components
  - o Pump Seals

- 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 with substantial achievements to date: In work with substantial achievements to date, the most important have been the following - all in the area of independent technological advances:

- Leak-Before-Break project

- Fault-tolerant operator aid and automatic control project - Use of New Technologies in LWRs

- Functionally-Oriented Nuclear Safety Regulation

- Power Station Design Simplification project

Separate discussions of each of these areas of work follow.

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 becausc the failure mode of this piping is such that it will leak before it will break, and the leakage of reactor coolant is 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 pipe. 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 leak rates that would ensue. We then consider the sensitivity of conventional leak detection systems and 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 would 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 low 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 analyses 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, Department of Nuclear Engineering, MIT, September 1985.

2) Use of New Technologies in LWRs

Since the inception of the current generation of LWRs, much new technology, especially in the areas of information processing and transmission, has been developed. The best use of this technology in new plants is not clear. It is the focus of this effort.

In information processing, the major emphasis has been in the areas of:

- fault-tolerant sensor validation,
- automatic control, and
- system diagnosis.

Specific past projects and ongoing work in these areas are described in Section 3.2.15, Advanced Instrumentation and Control Systems.

Some new projects are now being initiated under the innovation program support. The effort in human error reduction concerning digital control of steam generator liquid level is also an outgrowth of this program. In future work, the focus is upon identification of the most promising targets for application of currently available microprocessor technology, and determination of optimal instrumentation strategies, even recognizing that immediate utilization of signals which can be provided may not be feasible.

In the area of signal transmission, the most important technological advances have concerned optical fiber transmission and multiplexing. The benefits of use of such technology in terms of improved signal quality and plant simplification are clearly large. Our major focus is concerning optically-based instrumentation. To date, the standard utilization of such technology has used electronic sensors to produce the original signals which are then converted to optical form prior to multiplexed transmission.

Several proposals for optically-based sensors to replace electronic sensors have been developed. Their investigation is the concern of future directions in this area.

Investigators: Professors E. Beckjord, J. Meyer, D. Lanning, E. Gyftopoulos, and M. Golay; Messrs. J. Outwater, J. Choi, and P. Seong.

Support: EPRI and see Section 3.2.15.

Recent References:

See Section 3.2.15.

3) 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 different 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 in specifying performance requirements which such systems must meet. In such systems the regulatory literature is generally small and easily understood.

The regulatory system of the United States is very different from such systems. It is 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 system.

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

- Formulation of a proposed regulation for LOOP events.
- 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.
- Execution of a mock licensing with 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:

- $f_{cd} \leq 10^{-4} yr^{-1}$ for all accident sequences
- $f_{cd} \leq 2x10^{-5} yr^{-1}$ for all LOOP accident sequences

As an illustration we have examined a reference PWR plant in order to identify the most attractive design improvements 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:

- Station blackout with loss of the steam turbine-driven auxiliary feedwater system due to exhaustion of the emergency battery DC power supply, and

- Creation of an equivalent small break in the primary 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 is to be reviewed by the NRC staff in the context of the proposed regulation. The purpose of this exercise is to identify problems of implementation of functionally oriented regulation at the NRC.

The project is due to terminate in Spring, 1986. If it is extended we shall try to focus 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).

4) 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 simplification has been undertaken. Ultimately, it is intended to provide a methodology to guide design simplification and 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 should be approached.

The specific examples which have been worked on to date are the following:

- The chemical and volume control system (CVCS) of a PWR,
- the condensate-feedwater systems of both PWRs and BWRs, and
- the steam generator level controller of a PWR.

From this work several general insights have been learned. Most importantly, it is essential to be clear concerning the goal being pursued under the name of simplification. Different goals require different approaches, all of which could be classed as attempts at simplification.

- The basic principle of separating systems according to the task to be performed is basic to simplification. In some cases doing this may require use of more hardware than if an integrated multipurpose system were used.
- The common denominator of all approaches to simplification examined in this work are that of understandability. Simplification and ease of understanding the condition of a system appear to be synonymous.
- In trying to define better what is meant by understandability, we have evolved the concept that understandability varies immensely with the number of analytic operations necessary to answer the questions:

  1) In the event of an error in the operation of a system, what is the condition of the system, and

  2) having answered question No. 1, what must be done in order to bring the system into the desired condition?

With simple systems these two questions can be answered with less effort and time (and to a greater level of confidence) than with complex systems. The number of operations involved in answering such questions is proportional to the number of "states" or degrees of the system. Consequently, simple systems are distinguished by having fewer degrees of freedom than complex systems.

From this discussion it is 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.

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

Support: Electric Power Research Institute

Recent References:

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

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

Recently Initiated Projects: With funding which was obtained recently from EPRI several new projects have been initiated. The titles of these projects are as follows:

- Design Implications of Use of Horizontal Steam Generators,
- Design Approaches to Reduction of Opportunities for Human Error, and
- Design of a Small BWR.

These projects are described in the following discussions.

5) Horizontal Steam Generators for Pressurizer Light Water Reactors

This is a new project in which the advantages and disadvantages of utilizing horizontal steam generators in pressurized light water reactors is to be 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. The experience with the horizontal steam generators in early North American plants (Shippingport, Indian Point I, Savannah and NPD) as well as current experience in Russian designed plants will be investigated.

Investigators: Professor N.E. Todreas; Messrs. S. Baker and J. Guillen.

Support: EPRI

Recent References: None.

6) Design Approaches to Reduction of Opportunities for Human Error

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 this effort is to identify design means of reducing opportunities for commitment of errors 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 toward reduction of opportunities for human error in accomplishing a particular function are the following:

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

In this effort we are working on a set of examples in order to illustrate how elimination of human error can occur through design. In the current generation of LWRs human errors occur with approximately equal frequency in operations and in maintenance procedures. Consequently, we have structured this effort with a focus upon each source of error. The specific projects which we are working on are the following:

- Control of steam generator water level from startup to full power.
- Control of an LWR condensate-feedwater system and auxiliary feedwater systems in startup, full power, and shutdown.
- Maintenance of reactor coolant system pump seals.

In each phase of this work the example used is chosen because of its importance in power station operation and because of the importance of human error in affecting such examples. 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.

<u>Investigators</u>: Professors M.W. Golay, E. Beckjord, E. Gyftopoulos, J. Meyer, and D. Lanning; Messrs. E. Love, J. Outwater, and Y.L. Choi.

<u>Support</u>: EPRI

<u>Recent References</u>: None.

7) <u>Design of a Small BWR</u>

In the area of design innovation the major activity in the project is concerned with design of an intermediate sized BWR. This work is part of the EPRI 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, provided that it survives a design-team elimination competition which will be resolved among the various EPRI contractors in spring, 1986.

In this work 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.

In this work departmental faculty and students are currently involved in a consulting role and expect to change in the next stage of work to a mode emphasizing individual projects leading to student theses. Areas in which departmental personnel are currently active include assessment of a passive steam injector for use in a high pressure safety injection system, use of heat pipes for vapor suppression pool cooling, construction methods, natural convection in core recirculation flow, control room habitability, robotic refueling, and strategies for dealing with ATWS events.

Investigators: Professors M.W. Golay, V.P. Manno, E. Beckjord, M. Driscoll, D. Lanning, M. Kazimi, and N.E. Todreas.

Support: EPRI

Recent References: None.

Related Academic Subjects:

Academic subjects of special relevance to the LWR Innovation Project include all of those concerned with Fission Engineering. The Department offers approximately 46 such subjects.

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.

3.11.2 Modular High Temperature Gas-Cooled (MHTGR) Project

In response to the conclusions reached in "Nuclear Power Plant Innovation in the 1990s: A Preliminary Assessment," (September 1983), we have initiated a comprehensive study of the MHTGR passively safe concept. Our initial intent is to help determine whether this MHTGR is suitable for commercial deployment in the decade of the '90s and, if so, how best to achieve this goal. Our longer range plan is to contribute to developing the ultimate potential of the MHTGR concept.

Because we cannot be equally active across the entire spectrum of issues involved in MHTGR research, we are concentrating initial efforts on safety, investment, and licensing issues. Our current projects involve issues of

TABLE 2

LWR INNOVATION PROJECT

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

source-term/core-design interaction, applicability of safety goals, incentives for fuel quality improvement, and determination of design goals. We are also initiating studies to consider such questions as operational optimization and high temperature designs for direct cycle gas turbines. Current 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 will be 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 offsite 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 MHTGRs 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 MHTGR is better developed and tested, reliance on new regulations at this time seems premature. We are studying the application of existing regulations to the MHTGR 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 MHTGR deployment.

4) Probabilistic Risk Assessment. A scoping level probabilistic risk assessment (PRA) of the modular high temperature gas-cooled reactor has been initiated. This project, supported by G. A. Technologies, is 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 MHTGR 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 modular HTGR 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 40%) 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.

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.J. Fellows, M.G. Izenson, H. Kaburaki, R. Sanchez, A. Sich; Ms. J.L. Maneke, M.C. Fordham (UROP).

Support: Energy Laboratory Utilities Program (primarily from Gas-Cooled Reactor Associates (GCRA)), G. A. Technologies, and NRC Advanced Reactor Program.

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:

L.M. Lidsky, "The Reactor of the Future?" Technology Review, 52-56, (February-March 1984).

D.D. Lanning and L.M. Lidsky, "The Modular High Temperature Gas-cooled Reactor: Current Status, Commercial Potential, and a Plan for Near-term Action," published in National Strategies for Nuclear Power Reactor Development by Lester et al., Department of Nuclear Engineering, MIT-NPI-PA-002, pp. 13-81 (March 1985).

J.L. Maneke, D.D. Lanning, and L.M. Lidsky, "MHTGR Confinement Analysis: A Computer Code for Initial Assessments," Department of Nuclear Engineering, MIT-NPI-TR-001 (April 1985).

R.L. Coxe, R.K. Lester, and L.M. Lidsky, "Modular Gas Reactor Cost Estimation," Department of Nuclear Engineering, MIT-NPI-TR-002 (April 1985).

3.11.3 Liquid Metal Reactor Studies

This is a new project, which has the objective of evaluating licensing issues germane to the "inherently safe" liquid metal-cooled reactors currently being designed by several groups under DOE auspices. Points investigated include the relation of past LWR and LMFBR licensing practice to the new LMR designs, and the potential impact of new licensing approaches. Issues relevant to unique features of the LMR, such as the reactor vessel air cooling system (RACS or RVACS in the current jargon), were also addressed. A report has been issued on the first year's endeavors, and further work is under discussion with the sponsor. It appears likely that the next area of focus will be the ability of advanced design features to mitigate the evacuation planning problem.

Investigators: Professor M.J. Driscoll; Mr. R.L. Coxe.

Support: Rockwell International/DOE.

Related Academic Subjects:

22.32 Nuclear Power Reactors
22.38 Reliability Analysis Methods
22.39 Nuclear Reactor Operations and Safety

Recent References:

R.L. Coxe and M.J. Driscoll, "Licensing Strategies for Innovative LMR Designs," MIT-NPI-PA-003 (September 1985).

3.11.4 National Strategies for Nuclear Power Reactor Development

The economic and political difficulties presently confronting the U.S. nuclear power industry raise fundamental questions regarding the purpose and organization of the nation's efforts to develop advanced nuclear power plant technologies. What kind of effort to develop advanced reactor technology is appropriate under the present circumstances? What should be the goals of this effort? What should be its technical focus? And what are the appropriate roles for the Federal government, utilities, and suppliers in carrying it out? Over the last two years, an analysis of these questions has been conducted under the sponsorship of the National Science Foundation.

Based on this analysis, several specific recommendations have been made concerning what should be done in the reactor development field by both government and private industry over the next several years.

Investigators: Professors R. Lester, M. Driscoll, M. Golay, D. Lanning, and L. Lidsky; Messrs. R. Coxe, R. Davies, M. McCabe, P. Seong, and G. Stairs.

Support: National Science Foundation

Related Academic Subjects:

22.32 Nuclear Power Reactors
22.33 Nuclear Engineering Design
22.341 Nuclear Energy Economics and Policy Analysis
22.81 Energy Assessment

Recent References:

R.K. Lester, "The Need for Nuclear Innovation," Technology Review, (March 1984).

R.K. Lester, M.J. Driscoll, M.W. Golay, D.D. Lanning, and L.M. Lidsky, "National Strategies for Nuclear Power Reactor Development," Department of Nuclear Engineering, MIT, MIT-NPI-PA-002 (March 1985).

R.K. Lester, "Organization, Structure, and Performance in the U.S. Nuclear Power Industry," Energy Systems and Policy (forthcoming).

3.11.5 Cross-National Comparative Analysis of Nuclear Industry Performance

This is a new research project which is designed to provide insights into the factors that have contributed to international variations in industrial performance in nuclear power plant design and construction. The research will focus on two factors in particular which it is hypothesized will turn out to explain a substantial portion of these variations: (1) industrial organization and structure, and (2) safety and environmental regulation. The Japanese, West German, French, Swedish, and U.S. industries are to be studied. In the first phase of research, an international database containing current information on power plant construction costs, commodities and labor requirements is being assembled. In the second phase, a limited number of comparative technical case studies will be conducted. The case studies will be developed through interviews with government and industry officials in each country.

Investigators: Professor R. Lester; Ms. M. Crocker; Messrs. M. McCabe, P. Poole, and J. Kindinger.

Support: Andrew W. Mellon Foundation.

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.

3.12 Applied Plasma Physics

The role of controlled fusion power among possible long range solutions to the world's energy supply problem has become more obvious and the pace of research is quickening. International efforts in controlled fusion research has converged on several key experiments to be constructed during the next decade; the theoretical analyses are beginning to yield the results needed to predict reactor behavior; the engineering constraints have been determined and the extremely difficult task of designing an economical, power-producing reactor is occupying experts in many fields. The Nuclear Engineering Department is increasing its efforts in all of these areas, and in so doing has strengthened its ties with those national laboratories engaged in the controlled fusion program. MIT's fusion related program has gained stature and momentum with the consolidation of the MIT Plasma Fusion Center. The Nuclear Engineering Group has been well represented in the Center since its formation, and we expect our research programs to be appreciably strengthened.

The Department's Fusion Research Group is engaged in experimental research via participation in the Alcator projects, in several plasma physics and diagnostic development projects funded by the National Science Foundation, and in a new divertor simulation study as part of the Fusion Center's overall responsibility for the national divertor program. Our fundamental theoretical studies of plasma turbulence are continuing and are adding expertise in "device oriented" theoretical analysis. The Technology Group has played an important role in the National Magnet Laboratory's High Field Tokamak Reactor Design and is engaged in an EPRI funded study of comparative reactor economics. The methodology of the Reactor Safety Study of fission reactor safety has been applied to questions of fusion reactor safety and some particularly important questions raised in this effort have been singled out for further research.

The program is carrying on a large Torsatron program following on demonstration that the force-reduced torsatron configuration offered substantial potential benefits as the basis for a full-scale fusion reactor. The first phase of this work culminated in "Torsatron Reactor Reference Design--T-1" interest. As possibly important results of our work on helically stabilized systems is the Alcator-A Conversion Study. This project is studying the inclusion of the helical winding in the Alcator Bitter Plate and could lead to a major new MIT program.

3.12.1 Subjects of Instruction

The Department offers the following subjects in the area of applied plasma physics.

22.03: Engineering Design of Nuclear Power Systems, considers the principles of component and system design, and the operating characteristics of nuclear reactors for central station and marine power generation. A study is made of the application of the various engineering disciplines contributing to reactor design, to examine tradeoffs involved in the realization of system performance objectives. Examples are selected from current and projected U.S. reactor designs.

22.031: Engineering of Nuclear Reactors, engineering analysis of nuclear reactors, with emphasis on 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. Three lecture hours per week concurrently with 22.312 but separate assignments.

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.

22.601: Fusion Energy I, introduces controlled fusion concepts: 1) fundamental plasma physics required to understand fusion reactors; 2) basic methods of producing and confining fusion plasmas; 3) description and critique of proposed fusion reactor schemes. Includes appropriate reviews of electromagnetic theory and other necessary skills to prepare students for more specialized fusion studies in the Department of Nuclear Engineering.

22.602: Fusion Energy II, discusses basic engineering and technology of controlled thermonuclear reactors. Other topics covered include current confinement devices, thermonuclear reactors, reactor technologies and present reactor designs. Reviews safety and environmental aspects.

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 particules 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; Ulasov 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 the 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 Lamor radius stabilization of ideal MHD modes and rotationally driven instabilities; the Kruskal-Oberman Energy Principle for the Guiding Center MHD plasma and its application to simple axisymmetric mirrors, non-axisymmetric mirrors and the tandem mirrors.

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 superconduction 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 enhance 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 in 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 stellarators) 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, introduction to 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. Meets with 22.069, but assignments differ.

Most undergraduate students interested in the area of applied plasma physics take 22.03, 22.031, and 22.062. For graduate students specializing in this field, recommended subjects would be 22.601, 22.611J, 22.612J, 22.615J, 22.64J and 22.69.

3.12.2 Fusion Reactor Environmental and 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 admissible environmental risks.

1) Safety Cost-Benefit Assessment Methodology

A methodology was developed to determine if a proposed fusion power plant design directed at improving plant safety is cost effective. Economic risks related to both normal plant operation and accident situations can be evaluated. The incremental costs involved with a dose reduction measure for normal plant operation or an accident situation are identified and models for their assessment are developed. An approach for evaluating the maximum justified spending on safety was also outlined. By comparing the actual spending on the design modification to the expenditure ceiling, the appropriate decision can be made.

The utility of this approach for assessing cost effectiveness was illustrated through two examples. In the first application, the cost effectiveness of changing the steel alloy PCA to low activation silicon carbide in the STARFIRE design was assessed. If the cost of high purity silicon carbide is less than 116 \$/kg, then the low activation design is cost effective. (The current cost is ~300 \$/kg, but should go down in a mature economy.)

A second example served to illustrate how the methodology can be applied to an accident situation. Four emergency detritiation options for INTOR, with zero, one, two or three clean up units, were compared to determine which was most cost effective. The evaluation was based on a release of 25 g of tritium into the reactor building. The analysis indicated that if the probability of the accident occurring over the plant lifetime exceeds 0.036 the most cost effective option would be the option using one detritiation unit. For lower probabilities, the use of an emergency detritiation system is not cost effective.

2) Lithium Fire Kinetics

A series of experiments have been run with the aim of measuring the reaction rate of lithium and nitrogen over a wide spectrum of lithium pool temperatures. In these experiments, pure nitrogen was blown at a 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.

The reaction rate was very small - approximately 0.002-0.003 g Li/min cm^2 for lithium temperatures below 500°C. Above 500°C the reaction rate began to increase sharply and reached a maximum of approximately 0.80 g Li/min cm^2 above 700°C. It dropped off beyond 1000°C and seemed to approach zero at 1150°C. The maximum reaction rate observed in these forced convection experiments was higher by 60 percent than those previously observed in experiments where the nitrogen flowed to the reaction site by means of natural convection.

During a reaction, a hard nitride layer built up on the surface of the lithium pool -- its effect on the reaction rate was observed. The effect of the nitrogen flow rate on the reaction rate was also observed.

3) Power Flattening In Blankets

An investigation aimed at identifying methods of flattening the power distribution in D-T blankets has been carried out. Three methods were identified which when used in conjunction produce power distributions which are significantly flatter than those produced by typical blankets. The peak-to-average power density ratio is reduced by over 50%, and the peak-to-minimum power fall-off is reduced by a factor of five. Power flattened blankets achieve tritium breeding ratios and blanket multiplication which could be somewhat higher than those of typical blanket designs.

Investigators: Professors M.S. Kazimi and L.M. Lidsky; Ms. S. Brereton and Ms. D. Hanchar; Messrs. J. Massidda, E. Yachimiak, T.K. Gil, R. Rozier, N. Seshan, and D. Gessel.

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

Related Academic Subjects:

22.38 Reliability Analysis Methods
22.602 Thermonuclear Reactor Design

Recent Publications:

A. General Safety and Risk Assessment

S. Piet, M.S. Kazimi and L.M. Lidsky, "The Materials Impact on Fusion Reactor Safety," Nucl. Tech/Fusion, 5 (3), 382-392, (May 1984).

M.S. Kazimi, "Safety Aspects of Fusion," An Invited Critical Review, Nuclear Fusion, 24 (11), 1461-1483, (November 1984).

S.J. Brereton and M.S. Kazimi, "A Methodology for Cost/Benefit Safety Analyses for Fusion Reactors," PFC/RR-85-3, Plasma Fusion Center, MIT, (March 1985).

S.J. Brereton and M.S. Kazimi, "Cost/Benefit Safety Analysis for Fusion Reactors," Fusion Technology, accepted for publication, (1985).

B. Lithium Reactions

E. Yachimiak and M.S. Kazimi, "Safety Analysis of Liquid Lithium-lead Breeders in Fusion Reactors Geometries," PFC/RR-84-10, Plasma Fusion Center, MIT, (June 1984).

W.J. Ijams and M. S. Kazimi, "Temperature Effects on Lithium-Nitrogen Reaction Rates," PFC/RR-85-6, Plasma Fusion Center, MIT, (August 1985).

W. Ijams and M.S. Kazimi, "The Kinetics of Lithium-Nitrogen Reactions," Trans. Am. Nucl. Soc., 48, 385 (1985).

C. Electromagnetic Considerations

M.S. Tillack, M.S. Kazimi, and L.M. Lidsky, "Structural Response to Plasma Disruptions in Axisymmetric Toroidal Shells," 6th Top. Meeting on the Technology of Fusion, (March 1985).

M.S. Tillack and M.S. Kazimi, "Measurement of Small Strains in a Noisy Environment," Review of Scientific Instruments, 56 (9), 1706 (1985).

D. Others

J.E. Massidda and M.S. Kazimi, "Power Flattening in D-T Blankets," 6th Top. Meeting on the Technology of Fusion Energy, (March 1985).

3.12.3 Theory of Magnetically Confined Toroidal Plasma

One purpose of this activity is to determine the important MHD equilibrium and stability limits (both ideal and resistive) of magnetic confinement systems, in particular tokamaks, torsatrons, EBT and tandem mirror. Specifically, one needs to calculate β limits and current limits for MHD stability to determine whether or not extrapolation of reactor size and economics are favorable. Equally important, one must learn how the critical plasma parameters (i.e., β, q, helical current, etc.) scale with basic geometries and technological constraints (i.e., aspect ratios, ring current, beam energy, etc.) in order to optimize the design of future experiments and possible reactors. The approach to be used consists of solving the ideal and resistive MHD equilibrium and stability equations primarily by analytic, asymptotic techniques. The calculations are carried out for special simple profiles as well as for general diffuse profiles. Small to moderate computations are required for evaluation purposes.

Another purpose of this activity is to develop a self-consistent microturbulence theory for magnetic confinement systems, primarily toroidal (tokamak and stellarator) systems. Such turbulence often gives rise to anomalous transport which can far exceed the classical collisional transport. Successful reactor designs will depend largely on our ability to predict and/or scale these anomalous transport processes theoretically. Although our present understanding of the anomalous loss processes in tokamaks is minimal (the <u>mechanism</u> of anomalous losses is not known), several recent developments appear to be converging on the solution to this problem. They are: (a) appreciation of the importance of very small magnetic perturbations in electron transport, (b) experimental evidence (through understanding the soft x-ray anomaly) from Alcator and T10 that magnetic fluctuations are the <u>mechanism</u> of anomalous heat loss, and (c) development of a self-consistent turbulence theory for the magnetic fluctuations associated with the universal drift instability in a screw pinch.

The predicted transport coefficients (anomalous electron thermal conductivity) have many similarities with experimental observations including absolute magnitude, and scaling with density, temperature, magnetic field and ion mass. This activity is the subject of continuing development, with work in progress on the determination of the saturated spectrum, comparison with experimental data, and inclusion of effects associated with toroidal geometry and the ambipolar field, as well as the determination of the complete Onsager matrix of anomalous transport coefficients.

<u>Investigators</u>: Professors J.P. Friedberg, K. Molvig, Dr. A.B. Rechester, M. Gerver; Messrs. K. Swartz, K. Hizanidis, D. Thayer, E. Esarey, W.H. Choe, P. Hakkarainen, G. Hilfer.

<u>Support</u>: U.S. Department of Energy.

<u>Related Academic Subjects</u>:

22.611J Introduction to Plasma Physics I
22.615J MHD Theory of Magnetic Fusion Systems I
22.64J Plasma Kinetic Theory
22.65J Advanced Topics in Plasma Kinetic Theory

Recent References:

None to date.

3.12.4 Theory of Nonlinear and Turbulent Fluctuations in Plasma

Most plasmas of laboratory or astrophysical interest contain a non-thermal spectrum of fluctuations. These fluctuations are generally non-linear and turbulent and play a major role in determining the important properties of the plasma. For example, in plasmas of thermonuclear interest, such fluctuations can transport heat and particles across the magnetic field lines at a rate greatly in excess of the collisional rate. Also, non-linear fluctuations can enhance the rate of plasma heating for a given current in the plasma. The study of these fluctuations is not only worthwhile from the point of view of practical applications, but is an important problem in many-body physics. For example, our work is closely related to problems in fluid turbulence and the dynamics of self-gravitating systems. Generally speaking, non-linear and turbulent fluctuations are the end result of linear instabilities, which have grown past the linear stage. Unfortunately, the resulting fluctuations frequently bear little resemblance to the linearly unstable waves which drive them. Our research is concerned mainly with discovering and identifying the types of nonlinear excitations that can exist and studying their properties. This research relies on two basic approaches, that of analysis and of numerical simulation. Although the numerical simulations is expensive, it provides unlimited diagnostic information concerning the microscopic properties of the system. Such information is not available in laboratory experiments. The analytic portion of the research consists of three parts: (1) deriving and solving kinetic equations which predict the time evolution of the fluctuations, (2) the extension of statistical mechanical arguments to apply to nonequilibrium situations, and (3) the deduction of exact nonlinear time independent solutions to the Vlasov equation in the hopes that such solutions might approximate turbulent fluctuations in some cases.

Investigators: Professor T.H. Dupree; Drs. J.J. Tetreault, R.H. Berman and H.M. Hamza.

Support: U.S. Department of Energy, National Science Foundation and Office of Naval Research.

Recent References:

T.H. Dupree, "Large Amplitude Ion Holes," Phys. Fluids, submitted (June 1985).

T.H. Dupree, "Growth of Phase Space Holes Near Linear Instability," Physics of Fluids, submitted (July 1985).

R.H. Berman, D.J. Tetreault, and T.H. Dupree, "Simulation of Phase Space Hole Growth and the Development of Intermittent Turbulence," Phys. Fluids, 28, 155 (1985).

R.H. Berman, D.J. Tetreault, and T.H. Dupree, "Double Layers in Linearly Stable Plasma," to be published in Proceedings of the Chapman Conference on Ion Acceleration in the Magnetosphere and the Ionsphere (June 1985).

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 degree program in nuclear engineering is to provide the student with a thorough mastery of scientific and engineering fundamentals together with comprehensive experience in their applications to problems in the field of nuclear engineering. This is accomplished through a curriculum under which the student completes Institute Science and Humanities requirements; coordinated subjects (in thermodynamics, fluid flow, heat transfer, strength of materials and computer modeling) taught by several of the other engineering departments; and subjects in nuclear engineering which include a design course 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. In the graduate level nuclear engineering case, the student will have already completed all of the core curriculum subjects now required of our S.M. students who enter without a nuclear engineering background.

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

4.2 Fields of Study

Although each student's program of study is arranged to suit her/his individual interests and objects, 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 Alternative 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
22.001	Seminar in Nuclear Engineering
22.002	Management in Engineering
22.003	Nuclear War: Threat and Avoidance
22.006	Computer Models of Physical and Engineering Systems
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	Introductory Nuclear Measurements Laboratory
22.091	Special Topics in Nuclear Engineering
22.092	Engineering Internship

Graduate Subjects

Nuclear Physics

22.111	Nuclear Physics for Engineers I
22.112	Nuclear Physics for Engineers II

Nuclear Reactor Physics

22.211	Nuclear Reactor Physics I
22.212	Nuclear Reactor Physics II
22.213	Nuclear Reactor Physics III
22.29	Nuclear Measurements Laboratory

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 Impacts 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
22.44J	Computational Methods in Materials Science and Engineering

Applied Radiation Physics

22.51	Radiation Interactions and Applications
22.55J	Biological and Medical Applications of Radiation and Radioisotopes
22.56J	Principles of Medical Imaging
22.57J	Radiation Biophysics
22.58	Health Physics II

Plasmas 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
22.75J	Radiation Effects in Reactor Structural Materials
22.77	Nuclear Waste Management

General

22.81	Energy Assessment
22.82	Engineering Risk-Benefit Analysis

22.821	Engineering Systems Analysis
22.841	Technology of Nuclear Weapons and Arms Control
22.86	Entrepreneurship
22.87J	Cases and Issues in Technology Management
22.901 to	Special Problems in Nuclear Engineering
22.904	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
1.78	Quantitative Methods for Water Resource Policy Formation

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 Deformation and Fracture of Solids I
3.26J	Physics of Deformation and Fracture of Solids II
3.38	Behavior of Metals at Elevated Temperatures
3.39	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

Management

15.065	Decision Analysis
15.081J	Introduction to Mathematical Programming
15.084J	Nonlinear Programming and Discrete-Time Optimal Control

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 Norm Rasmussen presented a session on "Engineering WAGS (Wise Astute Guesses)," designed to challenge engineering minds by teaching how to use rough approximations to get answers quickly. Environmental and safety concerns in fusion reactor design were discussed in the "Fusion Safety Seminar," which was offered by Professor Mujid Kazimi. In the area of applied radiation physics, Professor Sidney Yip offered the following topics: "Atomistic Simulation of Materials Properties," and "Computer Simulations in Condensed Matter Science: Molecular Dynamics and Monte Carlo."

Professor Sow-Hsin Chen conducted an activity entitled, "Experiment and Theory on Critical Phenomena in Micellar Solutions."

The industry perspective was the focus of the session, "Hardware Can be Harder Than You Expected," organized by Professors David Lanning and Neil Todreas. A well-attended workshop, sponsored by Professor Michael Golay, on "Innovative Light Water Reactor Design," discussed potential areas of design improvement.

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 Ron Ballinger is the Nuclear Engineering Department Coordinator.

4.6 Changes in Nuclear Engineering Subjects

Since our last Activities Report, the Department has not offered any new subjects of instruction. However, some minor changes have occurred and these changes are listed below.

A. Subjects Retitled

The following subjects have been renamed as follows:

22.003 - Nuclear War: Threat and Avoidance
22.061 - Fusion Energy I
22.062 - Fusion Energy II
22.572J - Quantum Thermodynamics

B. Subjects - Renumbered and Retitled

Two subjects have been renumbered and retitled. They are

22.601 (formerly 22.610) - Fusion Energy I
22.602 (formerly 22.621) - Fusion Energy II

C. Subjects No Longer Offered

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

22.622 - Special Topics in Thermonuclear Reactor Design
22.76J - Introduction to Nuclear Chemical Engineering
22.85J - Case Studies in Energy, Technology, Economics and Management
22.88J - Cases and Projects in Engineering Management
22.89 - Basic Electronics
22.94J - Seminar on Technology and Development

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 by using already 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 any of these options, the curriculum contains four major components. The first is the Institute Science Requirement, which provides the student with the appropriate foundation in physics, mathematics, and chemistry. The second component is the Institute Humanities requirement which is included in all MIT bachelor's degree programs. The third component is Engineering Principles, in which a student is expected to become familiar with the foundations of engineering practice. The particular areas the student is required to study include strength of materials, fluid flow, thermodynamics, heat transfer, and computer modeling of physical systems. The fourth component of the undergraduate curriculum is a broad-based introduction to the specialities of nuclear engineering. Thus, students take subjects dealing with the phenomena of interest from the viewpoint of the pertinent physics (e.g., neutron physics or plasma physics). Much of the introduction also deals with the study of design and system integration concepts.

This program has remained small since its inception in 1975. However, it has produced a number of quality graduates who have continued to make contributions 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:

22.001: Seminar in Nuclear Engineering, surveys the technology and applications of nuclear power. This includes an introductory discussion of the basic phenomena of fission and fusion power and related aspects of reactor design, a discussion, by guest lecturers from the appropriate discipline, of the many applications of reactors as research tools in biology, earth sciences, medicine and physics. A demonstration of the MIT Reactor as a research tool is given.

22.006: Computer Models of Physical and Engineering Systems, reduction of physical and engineering systems to simplified physical and mathematical models; representation using networks; graphs and finite element methods. Process simulations using random variables (Monte Carlo techniques) and Linear and Dynamic Programming. Manipulation of the resulting models using algorithms on digital computers. Examples drawn from fields primarily of interest to scientists and engineers, with some attention to styles of problem solving. Extensive "hands-on" computing experience. (Working knowledge of FORTRAN expected. This subject is an Engineering School-wide Elective).

22.02: Introduction to Applied Nuclear Physics, is an introduction to nuclear physics and neutron physics, with emphasis on those aspects of the subject which are applied in nuclear engineering. Topics 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-model, liquid-drop model), nuclear fission (properties of fission and their relation to the feasibility of nuclear power and its problems), slowing-down and diffusion of neutrons, neutron-induced chain reactions, thermonuclear reactions and the possibility of energy from nuclear fusion, and an introduction to radiation dosimetry.

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 placed on the nuclear physics bases of reactor design and their relation to reactor engineering problems. Three lecture hours per week meeting concurrently with graduate subject 22.211, plus a separate recitation; assignments and quizzes are different from those in 22.211.

22.03: Engineering Design of Nuclear Power Systems, considers the principles of component and system design, and the operating characteristics of nuclear reactors for central station and marine power generation. A study is made of the application of the various engineering disciplines contributing to reactor design, to examine tradeoffs involved in the realization of system performance objectives. Examples are selected from current and projected U.S. reactor designs.

22.031: Engineering of Nuclear Reactors, engineering analysis of nuclear reactors, with emphasis on 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. Three lecture hours per week meeting concurrently with graduate subject 22.312 but with separate assignments.

22.033: Nuclear Systems Design Project, is a group design project involving integration of reactor physics, thermal hydraulics, materials, safety, environmental impact and economics. Students apply the knowledge acquired in specialized fields to practical considerations in design of systems of current interest. Meets concurrently with graduate subject 22.33 but assignments differ.

22.04: Radiation Effects and Uses, studies current problems in science, technology, health, and the environment which involve radiation effects and their utilization. Topics include material properties under nuclear radiations, medical and industrial applications of radioisotopes, radiations and lasers in research, radioactive pollutants and their demographic effects. Laboratory demonstrations of methods and instruments in radiation measurements are given at the MIT Reactor. The material is presented in an essential descriptive manner, and is suitable for students interested in a general appreciation of the physical phenomena and their uses.

22.05: Introduction to Engineering Economics, introduces methods used by engineers for the economic analysis 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 applications are presented.

22.061: Fusion Energy I, introduces controlled fusion concepts: 1) fundamental plasma physics required to understand fusion reactors; 2) basic methods of producing and confining fusion plasmas; 3) description and critique of proposed fusion reactor schemes. Includes appropriate reviews of electromagnetic theory and other necessary skills to prepare students for more specialized fusion studies in the Department of Nuclear Engineering. Meets three lecture hours a week with graduate subject 22.601 but with different assignments and quizzes.

22.062: Fusion Energy II, covers the following topics: Systems analysis and design of controlled thermonuclear reactors, development of criteria for CTR feasibility on basis of economic and technical considerations, detailed critical review of DOE's prototype reference reactor designs, non-Maxwellian reactors, laser-induced fusion, blanket neutronics, fission-fusion symbiosis, radiation damage, environmental hazards. Meets with graduate subject 22.602, but assignments and exams differ.

22.069: Undergraduate Plasma Laboratory, covers basic engineering and scientific principles associated with experimental plasma physics. Investigation of 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 are also covered.

22.070J: Materials 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 graduate subject 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 graduate subject 22.71J, but assignments differ.

22.08: Energy, studies energy from a holistic point of view: provision, rational utilization and conservation, regulation, environmental effects, and the interconnectedness of energy with other societal sectors. Topics include resources of petroleum, natural gas, coal, nuclear and other energy forms, the technologies of providing energy from these forms, the utilization of energy in various sectors (transportation, industrial, commercial and domestic), regulatory, tax, and other institutional arrangements that affect production and use patterns, environmental costs and opportunities associated with exercising various energy strategies, both existing and proposed, and the domestic and international political, strategic and economic implications. Meets with graduate subject 22.81, but some assignments differ.

22.088J: Human Factors in Design, presented jointly with the Mechanical Engineering Department, 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: Introductory Nuclear Measurements Laboratory, deals with the basic principles of interaction of nuclear radiation with matter, statistical methods of data analysis, introduction to electronics in nuclear instrumentation, counting experiments using Geiger-Muller counter, gas-filled proportional counter, scintillation counter, and semiconductor detectors.

22.091: Special Topics in Nuclear Engineering, is a subject for undergraduates who desire to carry out a one-term project of theoretical or experimental nature in the field of nuclear engineering in close cooperation with individual staff members.

22.092: Engineering Internship, provides academic credit for 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 nine students--two graduate, four seniors and three 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 during the past year: Controlled Fusion (K. Molvig), Applications of Radiation in Science, Technology, and Medicine (R. Ballinger, G. Brownell, I.-W. Chen, S.-H. Chen, O. Harling, A. Nelson, K. Russell, and S. Yip); Word Engineering (M. Driscoll); Innovative Nuclear Reactor Designs (M. Driscoll); and Nuclear Science and Engineering: A Sampling (D. Lanning).

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

Many computer facilities exist at MIT. While some are owned by and restricted in use by individual departments and research groups, others are available to the entire community.

Among the available mainframe systems which offer both interactive and batch processing are: MULTICS running on a Honeywell DPS 8/70, CMS and OS/VS1 on an IBM 4381 and VAX/VMS on VAX 11/780s. Undergraduate and curriculum development accounts are available on microVAX II clusters through Project Athena.

A campus-wide network permits file transfer and electronic mail between all campus mainframes. BITNET, MAILNET, ARPANET and others enable communications with computers at other universities and national laboratories.

Within the Department of Nuclear Engineering, two computer rooms are now available to meet the needs of our students. Since our last Activities Report, a new facility in Building 24-208 has been equipped and is now in full operation. Also within the past year, the computer room in Building NW12-234 has been completely refurbished and equipment upgraded. Between both of these locations, nuclear engineering students now have a variety of equipment available for their use. Such equipment includes CRTs, printers, plotters, and microcomputers.

A collection of widely used reactor design and analysis codes exists in a departmental code library where students are given assistance and instruction.

5.3 Nuclear Engineering Department Laboratories

The Nuclear Engineering Department laboratories are specially equipped rooms located in Buildings NW12, NW13 and 24. One room is located in the rear of the first floor of Building NW12, and the others are on the second floor of NW13. The room in NW12 is used for physics experiments associated with counter developments and activation analysis. It has been arranged to permit setting up and checking out large pieces of experimental equipment prior to putting them in the reactor.

The rooms in NW13 are equipped with laboratory-type benches and hoods, service air, water and electricity connections. These rooms are presently used for projects in medical applications and chemical engineering. In addition, there are two laser systems being used to study fluid dynamics and cooling tower drift.

General facilities also available at the laboratory include a 4096-channel analyzer, a high vacuum system, computer terminals, and a mini-computer with a CRT graphics display and hard copy capability.

The plasma teaching laboratory in Building 24 is used primarily for the joint graduate and undergraduate lab course and provides a variety of small experiments by which students can gain experience in the laboratory techniques of plasma and fusion physics.

The laboratories and the Reactor are supported by well-equipped machine and electronics shops, a low-level radioactivity counting room, a drafting room, and a reading room stocked with nuclear engineering texts, references and journals.

6. DEPARTMENT PERSONNEL

6.1 Faculty

Neil E. Todreas

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

Ronald G. Ballinger

Assistant 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.

I-Wei Chen

Assistant Professor of Nuclear Engineering; S.B. '72 National Tsing-Hua Univ.; M.S. '75 University of Pennsylvania; Ph.D. '79 (metallurgy) MIT;
Radiation effects on materials.

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 (elec. - phys.) Polytechnic Institute of Brooklyn;
Theoretical plasma physics.

Michael W. Golay

Associate 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.

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

Associate 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; multiphase flow and heat transfer.

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 London; Ph.D. '79 (nuclear engineering) MIT;
Nuclear power economics and policy analysis; nuclear waste management.

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.

Alan C. Nelson

Associate Professor of Nuclear Engineering and the Whitaker College of Health Sciences, Technology, and Management; B.A. '72 University of So. California; M.A. '76 University of Calfornia; Ph.D. '80 (radiation biophysics and medical physics) University of California.
Radiation biophysics; biomedical applications.

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.

Andrei Schor

Assistant Professor of Nuclear Engineering; Ph.D. '83 (nuclear engineering) MIT;
Numerical methods; mathematical modeling; thermal-hydraulic analysis.

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, materials science, statistical mechanics.

6.2 Complete Listing of Personnel (as of December 1985)

Professor

E. Beckjord (Visiting)
M. Benedict (Institute Emeritus)
G.L. Brownell
S.H. Chen
M.J. Driscoll
T.H. Dupree (joint w/Physics)
J.P. Freidberg
E.P. Gyftopoulos (joint w/Mech.)
K.F. Hansen
O.K. Harling
A.F. Henry
I. Kaplan (Emeritus)
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

M.W. Golay
I.H. Hutchinson
M.S. Kazimi
R.K. Lester
K. Molvig
T. Nakajima (Visiting)
A. Nelson (joint w/Whitaker College of HS, T&M)

Assistant Professor

R.G. Ballinger (joint w/MS&E)
I.W. Chen (joint w/MS&E)
A. Schor

Adjunct Professor

D.J. Sigmar

Senior Research Engineer

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

Senior Research Scientist

D.R. Cohn (joint w/PFC)

Principal Research Scientist

M.M. Miller

Sponsored Research Staff

R. Morton

Research Affiliate

D.C. Aldrich
R. Hobbins
J.H. Hopps, Jr.
W.E. Vesely
L. Wolf

Administrative Officer

J.B. deVries Gwinn

Administrative Staff

C.M. Egan
W.J. Fitzgerald

Support Staff

L. Arduino
L. Bedirian
K. Harper
A. Hudson
G. Jacobson
E. Kehoe
M. Levine
C. Lydon
J. Pagan
E. Parmelee
G. Rook
L. Suter

6.3 Complete List of Graduate Student Staff (as of Fall 1985)

Teaching Assistants

Alfeo, Joseph
Barnett, D. Sean
Carney, Charles
Cheema, Mahmood
Chu, Tak-Sum
Cooper, Susan
Kupfer, Kenneth
Mogstad, Torkil
Paschal, Cynthia
Pendergast, Kenneth
Reese, Timothy (P.T.)*
Rempe, Ken (P.T.)
Sanchez, Rene (P.T.)
Scott, Robert (P.T.)
Sich, Alex (P.T.)
Suh, Kune Yull
Taiwo, Ademola (P.T.)
Warren, Gordon
Zraket, David

Research Assistants

Baker, R. Scott
Choi, Jung In (P.T.)
Coxe, Ray
Depiante, Eduardo
Esarey, Eric
Farish, Thomas
Foord, Mark
Free, Scott
Gamino, Ray
Gil, Tae Kyung
Goodrich, Phillip
Hilfer, Godehard
Hsieh, Horngming
Huang, Tsing-Tung
Hwang, Il Soon
Iannello, Victor
Kao, Lainsu
Kato, Kosuke
Labombard, Brian
Laughton, Peter
LeClaire, Rene
Lee, Che-Wu
Lin, Tsang-Lang
Liu, Dilys
Machuzak, John
Mahannah, Jeff
Malinovic, Boro
Maneke Joy
Melvin, Mark
Meyers, Kenneth (P.T.)
Miller, Ron
Ornedo, Renato
Outwater, John
Pachtman, Arnold
Parlos, Alexander
Peng, Scott
Petillo, John
Petti, David
Psaila, Maureen
Reese, Timothy (P.T.)
Rempe, Ken (P.T.)
Ro, Tae Sun
Russo, Gilberto
Sands, Mark
Seong, Poong
Shedd, Gordon
Spira, Susan
Texter, Scott
Tinios, Gerasimos
Vlahoplus, Chris
Wan, Alan
Wang, Ching
Wang, Pei-Wen
Wenzel, Kevin
Wilson, Chris
Witt, Robert
Wolford, Andrew
Wong, Frank

* (Part-time)

7. DEPARTMENTAL STATISTICS

Statistical Summary

Academic Year Sept - June	September Registration: Undergraduate	Graduate	Special	Total	Degrees Granted: B.S.	S.M.	Nucl. E.	Sc.D., Ph.D.	Total	No. of Professors	No. of Subjects
51 - 52	---------none---------				----------------------					1	none
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	1	25	3	19	48	23	64
82 - 83	33	164	0	197	8	30	4	15	57	24	67
83 - 84	27	167	3	197	9	38	11	29	87	26	70
84 - 85	18	164	0	182	10	28	2	18	58	26	75
		TOTALS			73	961	145	421	1600		

Note: AY 1973/74 - 1983/84 statistics updated to agree with Bruce Report, March 1985.

8. STUDENTS

Chapter 8 presents statistical information about the 153 full-time graduate students registered in the Department during the fall term 1985. 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 closely by physics and electrical engineering majors.

The distribution of schools from which our domestic students are drawn is very widespread. Approximately 18% of our domestic graduates entered the Department with degrees from MIT. Our international student population represents approximately 38% of our total graduate enrollment. This number reflects a decline in our international representation since the last report.

Table 8.2 summarizes the various sources of financial support available for the fall term 1985. 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 September 1985.

Table 8.1

Background of Graduate Students Registered in Nuclear Engineering Department (Fall 1985)

By Profession (153)

Applied Physics (2)
Armament (1)
Biology/Physics (1)
Biomedical Engineering (3)
Chemical Engineering (4)
Earth & Planetary Science (1)
Electrical Engineering (16)
Electronics (1)
Energy Engineering (1)
Engineering (2)
Engineering Physics (3)
Engineering Science (2)
Mathematics (3)
Mechanical Engineering (9)
Medicine (1)
Naval/Marine Engineering (1)
Nuclear Engineering (84)
Nuclear Physics (1)
Physics (16)
Sanitary Engineering (1)

By College (U.S. citizens only) (95)

Colby (1)
Columbia (2)
Cornell (3)
Duke (1)
Fordham (1)
Georgia Inst. of Technology (3)
Harvard (2)
Iowa State (1)
Kansas State University (4)
Lowell Tech. Institute (1)
MIT (17)
North Carolina State (1)
Northeastern (2)
Norwegian Tech. U. (1)
Penn State (2)
Polytechnic Inst. of NY (1)
Princeton (2)
Purdue (1)
RPI (4)
Rutgers (1)
Shanghai Medical College (1)
Texas A&M (1)
University of Arizona (2)
University of California (5)
University of Florida (4)
University of Illinois (4)
University of Lowell (3)
University of Michigan (6)
University of Missouri (2)
University of Oklahoma (1)
University of Pennsylvania (1)
University of Rochester (1)
University of South Carolina (1)
University of Texas (1)
University of Virginia (2)
University of Wisconsin (1)
UCLA (2)
USMA (1)
USNA (1)
Western Illinois (1)
Wheaton (1)
Worcester Polytechnic Institute (1)
Youngstown U. (1)

Table 8.1 (continued)

By Country (153)

Argentina (3)
Brazil (4)
Canada (4)
Chile (2)
Egypt (1)
Finland (1)
France (1)
Germany (1)
Greece (1)
India (2)
Iran (1)
Italy (1)
Japan (2)
Korea (10)
Nigeria (1)
Poland (1)
Republic of China (16)
Turkey (3)
United Kingdom (1)
United States of America (95)
Yugoslavia (1)

Table 8.2

Sources of Financial Support
(as of Fall Term 1985)

Research Assistantships (56)
Teaching Assistantships (15)
Schlumberger Fellowship (1)
NIH Trainee (6)
Exxon Fellowship (1)
Sherman Knapp Fellowship (1)
DOE Fusion Technology Fellowship (7)
DOE Nuclear Science & Engineering Fellowship (4)
DOE Waste Management Fellowship (1)
Draper Fellow (1)
GEM Fellowship (1)
NSF Fellowship (3)
NASA Fellowship (1)
Thompson Fellowship (1)
IBM Fellowship (1)
Benedict Fellowship (1)
Rockwell Fellowship (1)
Hughes Fellowship (1)
INPO Fellowship (1)
TRW Fellowship (1)
Graduate Professional Opportunity Program (2)
McAfee Award (1)
U.S. Army (2)
U.S. Air Force (1)
U.S. Navy (1)
Government of Egypt (1)
Government of Nigeria (1)
Government of Canada (1)
Government of Chile (2)
Government of Korea (5)
Government of Brazil (5)
Government of Republic of China (3)
Government of Argentina (2)
Government of Japan (1)
Government of Turkey (2)
Self-supported (14)
Outside support (4)

Table 8.3

Activities of Nuclear Engineering Department Graduate Students

(Place of first employment -- information current as of September 1985)

U.S. Industry and Research (404) (28.9%)

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)
Avco (6)

Babcock & Wilcox (8)
Battelle Columbus
Battelle Northwest (9)
Bechtel (4)
Bell Telephone Lab
Bendix
Berkeley Research Associates
Bettis (4)
Booz, Allen & Hamilton
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 University (research)

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 (6)
EPM, Inc. (4)

Fauske & Associates, Inc.

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

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

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

Jackson & Moreland
Jet Propulsion Lab

Lane Wells
A.D. Little (4)
Lockheed
Long Island Lighting Co.

Management & Tech. Cons.
Martin-Marietta (3)
Mass. General Hospital (5)
Maxson Electric
McKinsey & Co.
MIT (research) (23)
Mobil Oil
Monsanto
MPR Associates (3)

National Nuclear Corp. (2)
National Academy of Eng.
New England Nuclear Corp.
New England Power Service Co.
New York Law Firm
North American Rockwell (2)
Northeast Utilities Service (4)

Table 8.3 (continued)

Northern Research & Eng. (3)
Nortronics
Nuclear Fuel Service (2)
Nuclear Mater. & Equipment
Nuclear Products
Nuclear Utility Services (4)
NUS Corporation (2)
NUTECH Engineers

Perkin-Elmer Co.
Philco
Pickard, Lowe & Garrick (2)
Planning Research Corp.
Princeton (research) (5)
Public Service Elec. & Gas
Purdue (research)

Radiation Tech.
Rand Corp.
RCA Research Lab
Resources for the Future

Sanders Corp.
Science Applications (6)
Scientific Data Systems
Sloan Kettering Memorial Hospital
Smithsonian Astrophys. Obs.
Southern Calif. Edison (4)
Spire Corp.
Stanford Research Institute
S.M. Stoller Assoc.
Stone & Webster (14)
Systems Sci. & Eng.
Systems Control

Texaco
Texas Instruments
Thermo Electron (2)
TWR Systems (2)

Union Carbide
United Aircraft (3)
United Eng. & Constr. (2)

United Nuclear (5)
Univ. of Calif. (research) (2)
Univ. of Maryland (research)
Univ. of Texas (research)
Univ. of Wisconsin (research) (2)

Vacuum Industries

Wastechem
Watkins-Johnson
Westinghouse (31)

Yale (research) (2)
Yankee Atomic (17)

<u>National Laboratories (94) (6.7%)</u>

Argonne (18)
Brookhaven (7)
Knolls Atomic Power (17)
Lawrence Livermore (4)
Lawrence Radiation (5)
Los Alamos (12)
Oak Ridge (17)
Sandia (9)
Savannah River (5)

<u>Further Study (229) (16.3%)</u>

MIT (196)
Other (33)

<u>U.S. Government (204) (14.6%)</u>

Atomic Energy Commission (22)
Air Force (16)
Army (83)
Army Nuc. Def. Lab.
Army Research Lab (2)
Ballistic Research Lab
CIA
Coast Guard
Dept. of Commerce
Energy Res. & Dev. Admin. (5)
Environmental Prot. Agency (2)
NASA
National Bureau of Standards (1)
Naval Research Lab
Navy (59)
Nuclear Regulatory Comm. (4)
Peace Corps
Picatinny Arsenal
Dept. of Public Health

Table 8.3 (continued)

Teaching (64) (4.6%)

American University (Wash., D.C.)
Brooklyn College (CCNY)
Calif. State (Long Beach)
Carnegie Mellon Univ.
Case Institute
Catholic Univ. of America
Cornell
El Rancho High School
Georgia Inst. of Technology
Howard University
Iowa State
Kansas State
Lehigh
Lowell Tech (4)
Loyola University
Mass. Maritime Academy
Michigan State University
MIT (13)
Northeastern University
Northwest Nazarene
Pennsylvania State
Princeton
Purdue
Radford College
Rensselaer Polytech.
Swarthmore
Texas A & M
U.S. Military Academy
Univ. of British Columbia
Univ. of California (8)
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

Foreign (231) (16.5%)

Algeria (4)
Argentina (6)
Belgium (10)
Brazil (26)
Canada (13)
Chile (10)
Columbia, S.A. (2)
England (2)
France (23)
Germany (3)
Greece (6)
India (13)
Indonesia
Iran (26)
Israel (3)
Italy (5)
Japan (16)
Jordan
Korea (6)
Libya (1)
Malaysia (2)
Mexico
Nigeria
Norway
Pakistan (4)
Philippines
Poland
Republic of China (12)
Saudi Arabia
Spain (14)
Switzerland (7)
Turkey (4)
Venezuela (5)

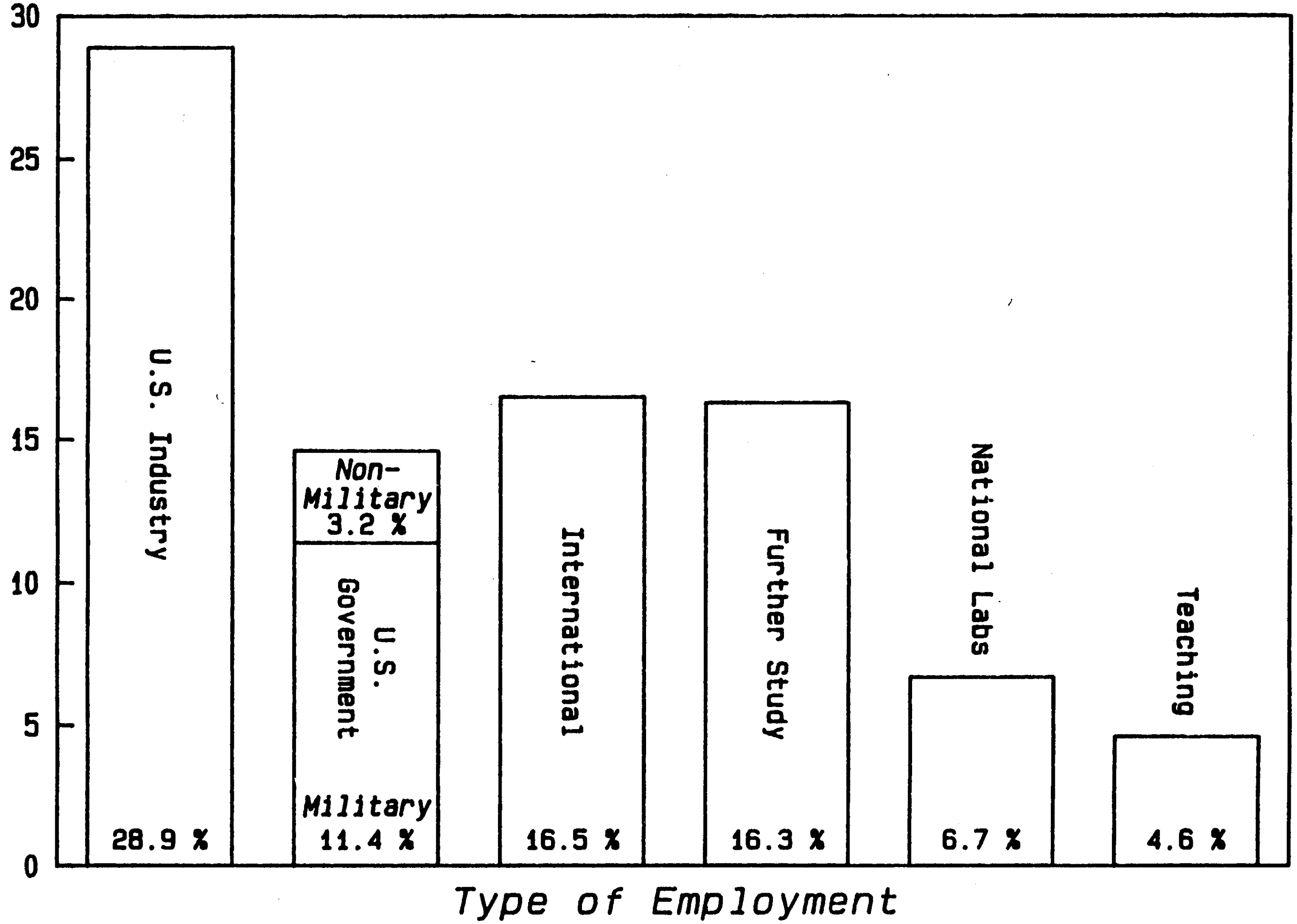
Not Reported (173) (12.4%)

TOTAL 1399*

*Records from early years are incomplete

Figure 8.1
Distribution of First Place of Employment
of Nuclear Engineering Graduates*

(As of September 1985)



* Excludes 173 (12.4 %) Students Not Reporting

9. LIST OF THESES

The following theses were submitted to the Department of Nuclear Engineering in September 1984:

O.A. Adekugbe, "Loop Simulation Capability for Sodium Systems," SM Thesis.

S.K. Cheng, "Constitutive Correlations for Wire-Wrapped Subchannel Analysis Under Forced and Mixed Convection Conditions," PhD Thesis.

S.P. Kao, "A Multiple-Loop Primary System Model for Pressurized Water Reactor Plant Sensor Validation," PhD Thesis.

Y. Nakagawa, "Significance of Thermal Fatigue in Commercial Fusion Reactor Turbines," SM Thesis.

M. Sarratea Saint-Lawrence, "Conceptual Model for Evaluating the Impact of Nuclear Plant Size on the Bus-Bar Cost of Electricity," NE/SM Thesis.

D.S. Sohn, "Further Development of the Miniaturized Disk Bend Test Approach for Post-Irradiation Mechanical Property Testing," PhD Thesis.

The following theses were submitted to the Department of Nuclear Engineering in February 1985:

G.K. Branan, "Single- and Two-Phase Flow on the Shell Side of a Baffled Heat Exchanger," SM Thesis.

S.J. Brereton, "Cost/Benefit Safety Analysis for Fusion Reactors," SM Thesis.

M. Castillo-Bonet, "Hydro-Thermal Integration in Power Systems Planning," PhD Thesis.

M.H. Chang, "The Application of Nodal Methods to the Transport Equation," PhD Thesis.

Y. Chao, "Studies of Interactions and Critical Behaviour of Ionic Micellar Systems by Light and Neutron Scatterings," PhD Thesis.

S.E. Cooper, "Molecular Dynamics Simulation of the Liquid Structure of a Polydisperse System," SM Thesis.

W.J. Ijams, "Temperature Effects on Lithium-Nitrogen Reaction Rates," SM/SB Thesis.

P.A. Arnold, "Determination of Nuclear Fuel Bundle Materials Using Neutron Tomography Data," SM/SB Thesis.

C. Malbrain, "Risk Assessment and the Regulation of High-Level Waste Repositories," PhD Thesis.

M.A. Malik, "A Long Term Perspective on the LWR Fuel Cycle," PhD Thesis.

W.P. Marable, "Linear Stability Analysis of Free Electron Laser Instabilities Near Cyclotron Resonance," PhD Thesis.

J.H. Moinzadeh, "Extending the Life of Nuclear Power Plants: Technical Issues," SM Thesis.

A.G. Parlos, "Steam Generator Carryover and Heat Transfer During a Steam Line Break Accident," SM Thesis.

B.K. Riggs, "Modelling of Condensation Processes in Nuclear Reactor Containments," SM Thesis.

K.Y. Suh, "An Experimental Correlation for Cross-flow Pressure Drop in Rod Bundles With Displacers," SM Thesis.

A.O. Taiwo, "The Effects of Solute Segregation on Void Nucleation Under Irradiation," SM Thesis.

T.A. Taiwo, "The Quasi-static Nodal Method for Reactor Core Kinetics," PhD Thesis.

C.K. Tsai, "Three Dimensional Effects in Analysis of PWR Steam Line Break Accident," PhD Thesis.

The following theses were submitted to the Department of Nuclear Engineering in June 1985:

C.A. Besen, "Advanced Fusion Fuels," SM/SB Thesis.

K.W. Burkholder, "An In-Pile Loop for Corrosion Transport Studies in a PWR," SM Thesis.

P.M. Cordeiro Mateo, "Advanced Fusion Fuels," SM/SB Thesis.

J.E. Deplitch, Jr., "Reduction of Argon-41 Produced by MITR-II," SM Thesis.

J.C. Doyle, Jr., "Economic Evaluation of Fissile Fuel Production Using Resistive Magnet Tokamaks," ScD Thesis.

Y.F. Khalil, "One Dimensional Analysis of Pipe Break Accidents in Fusion Reactor Blankets," NE/SM Thesis.

J.P. Kindinger, "Analysis of Led Times and Causes of Delays in US Nuclear Power Plant Projects Under Construction or Completed Since 1980," SM Thesis (Joint Management of Technology).

A. Kodaka, "Dryout Region Modelling for PWR Steam Generators," SM/SB Thesis.

S.A. Lanzendorf, "Time Dependent Unavailability Analysis of BWR Diesel Generator System," SM/SB Thesis.

M. Lee, "Modelling of Core-Concrete Interaction," PhD Thesis.

L.Y. Liao, "Heat Transfer, Carryover and Fall Back in PWR Steam Generators During Transients," PhD Thesis.

J.S. Machuzak, "Study of a High Power, Submillimeter Wave, Ammonia Laser for Ion Temperature Plasma Diagnostics," SM Thesis.

J.E. Massidda, "Power Flattening in D-T Tokamak Fusion Reactor Blankets," SM Thesis.

P.E. Reyes, "Deformation of Magnesia-Partially-Stabilized-Zirconia Under Triaxial Compression," SM Thesis.

B.W. Rhee, "A Dynamic Model of a U-tube Steam Generator for Real Time Simulation," PhD Thesis.

L.G. Riniker, "RETRAN Modeling of the Westinghouse Model D Steam Generator," SM/SB Thesis.

J.T. Robinson, "An Experimental Investigation of Single and Two Phase Flow Through Rod Arrays," PhD Thesis.

C.A. Rubio, "The Effect of Enhanced Convection on Radon Decay Product Concentration," SM Thesis.

J. Sasson, "Investigation of Numerical Treatment of Condensation," SM Thesis.

I.L. Sauer, "A Core Reload Pattern and Composition Optimization Methodology for Pressurized Water Reactors," PhD Thesis.

R.W. Sawdye, "Measurement and Simulation of a Three-Dimensional Turbulent Recirculating Flow," ScD Thesis.

R.D. Wittmeier, "EBR-II Natural Circulation Flowrate Signal Validation Methods and Architecture," SM Thesis.

The following theses were submitted to the Department of Nuclear Engineering in September 1985:

J.A. Alfeo, "Signal Validation for Performance Monitoring," SM Thesis.

S.E. Best, "The Effect of Ion Irradiation on Phase Stability in Ni-C and Fe-Ni-C Alloys," PhD Thesis.

J.A. Carvajal Guerra, "Modeling of a Feedwater Heater," SM Thesis.

D.E. Cortes, "The Effect of Stress and Texture on the Morphology of Hydrides in Zirconium Alloys," SM Thesis.

W.H. Choe, "Magnetohydrodynamic Equilibrium and Stability of Advanced Toroidal Fusion Systems," PhD Thesis.

C.K. Elliott, "Effect of Thermal Treatment on the Fracture Properties of Alloy X-750 in Aqueous Environments," ScD Thesis.

D.A. Miller, "Monte Carlo Dosimetry and Activation Calculation for a Proposed Fusion Device -- MCNP Analysis of Alcator C-Mod," SM Thesis.

P.E. Roege, "Potential Effects of Leak-Before-Break on Light Water Reactor Design," NE/SM Thesis.

J.B. Schutkeker, "Design of a High Frequency, Megawatt Gyrotron," SM/SB Thesis.

J.G.S.M. Senna, "Thermal Hydraulic Analysis of a Passive Energy Removal System for Advanced Nuclear Reactors," NE/SM Thesis.