MITNE-286

ACTIVITIES IN NUCLEAR ENGINEERING AT MIT

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

August 1989

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Prepared by the Staff of the

Nuclear Engineering Department

Massachusetts Institute of Technology

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1. INTRODUCTION

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

1.1 Academic

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

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

During the fiscal year ending June 30, 1988, departmental faculty supervised a research volume of more than $3 million. This figure includes research funded through the Department, the Biotechnology Process Engineering Center, the Energy Laboratory, the Harvard/MIT Division of Health Sciences and Technology, the Materials Processing Center, the Center for Materials Science and Engineering, the Department of Materials Science and Engineering, the Nuclear Reactor Laboratory, the Plasma Fusion Center, the Research Laboratory of Electronics, and the Whitaker College of Health Sciences, Technology and Management.

The Department's graduate program enrolled 150 domestic and international students during the fall semester of the academic year 1988-89.

Table 1

Enrollment in MIT 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	180
1985	173
1986	171
1987	170
1988	180

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

Table 2

Applications for Graduate Admission
to MIT 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
1986	88
1987	72
1988	80
1989	72

Of this number, approximately 37% expressed interest in the fission area, 29% were involved in plasma and controlled fusion, 29% registered in the radiation program, and 5% in energy economics and policy. In September 1988, our undergraduate enrollment totaled 28 students.

The Department awarded 45 advanced degrees during the academic year 1988-89. This included 13 doctorates, 3 nuclear engineers, and 29 masters of science degrees. Six bachelor degrees were awarded, three of which were joint SM/SB degrees.

1.2 Graduate Student Financial Aid

During the academic year 1988-1989, approximately two-thirds of our graduate student body were appointed to the graduate student staff, receiving financial aid in the form of full- and part-time research and teaching assistantships. The Department awards three departmentally administered graduate fellowships annually--the Sherman R. Knapp, sponsored by Northeast Utilities, the Theos J. Thompson Memorial, and the Manson Benedict. Other sources of financial aid were graduate fellowship awards sponsored by Argonne National Laboratory, the Institute of Nuclear Power Operations, Stone & Webster, the Materials Processing Center, SURDNA, and the Wolfe Fellowship. In addition, the Department receives an annual allocation from the MIT Graduate School College Work Study Program. Scholarship support was also provided by the National Aeronautics and Space Administration, TRW, and the United States Departments of the Army, Navy, and Energy.

The governments of Chile, Korea, Brazil, the Republic of China, Saudi Arabia, and Turkey have provided support for the education of their citizens.

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

1.3 Organization of Activities Report

Section 2 of this report contains a summary of developments within the Department since September 1987. Research and educational activities are presented in Section 3. Section 4 discusses our curriculum, including the undergraduate program. Departmental facilities are listed under Section 5. In Section 6 there is a summary of Departmental personnel. Sections 7 and 8 provide statistical information about the Department and its students. The final section, 9, contains a listing of graduate theses submitted to the Department during the period September 1987 through June 1989.

2. SUMMARY OF DEVELOPMENTS SINCE AUGUST 1987

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

2.1 Academic Program

An extensive review of the Department's undergraduate program was completed by the undergraduate committee under the chairmanship of Professor John Meyer. Resulting actions included: major changes to our radiological sciences track; evolutionary changes to our fission track and our fusion track; and judging acceptability of these actions by use of the goals developed by the School of Engineering.

The NED computer committee, chaired by Professor Nathan Siu, was established to investigate means to improve the use of computers in NED courses. The committee surveyed faculty, students, and members of other MIT departments, as well as nuclear engineering programs of other universities. As a result, the committee initiated and stimulated a number of actions to improve the use of computers in NED courses. These included the development and presentation of an IAP seminar on software available on NED computers, the acquisition of more modern machines for the department, the introduction of advanced numerical analysis software into a number of courses, and the review of a number of potentially useful software programs (one of which will be adopted by the proposed course on simulation).

In the area of curriculum development, seven new subjects have been developed since our last report. At the recommendation of the Department's undergraduate committee, three new undergraduate subjects, 22.055 Biological and Medical Applications of Radiation and Radioisotopes, 22.056 Principles of Medical Imaging, and 22.057 Radiation Biophysics, will be offered by members of the RST area during the coming academic year. Graduate subject 22.53 Statistical Processes and Atomistic Simulation was developed and taught by Professor Sidney Yip during the fall 1988 semester. During the spring term 1989, Professor Richard Lester organized a new graduate course 22.843J Technology, Productivity, and Industrial Competition, which was derived from his service as Executive Director of the MIT Commission on Industrial Productivity. Professor Kent Hansen and several colleagues have organized a new subject, 22.44 Modeling and Simulation, that will be presented this coming fall semester. Next spring 1990, Professor Sow-Hsin Chen is planning to offer 22.52J Statistical Thermodynamics of Complex Liquids.

An extensive review of the plasma physics and fusion technology curriculum is currently underway. Initial studies indicate that it may be desirable to decrease the frequency with which our advanced courses are offered so as to free up the faculty time to teach our core fusion courses 22.601, 22.602, and 22.69.

2.2 Student Activities

The MIT Student Chapter of the American Nuclear Society (ANS) has continued its fine tradition of providing service and support to students, faculty, and staff. For the Monday afternoon seminar series, they arranged for guest lecturers from the utilities, industry, and education so that a wide range of topics were presented. They prepared monthly student/faculty pizza meetings, a holiday party, and a departmental steak cookout. They organized the Department's orientation activities, provided student speakers for high school groups, and participated in intramural sporting events.

The Alpha Nu Sigma honor society updated and distributed a booklet, "Student Guide to the Nuclear Engineering Department," which provides students with useful information on all aspects of the Department. Ten new student members (three undergraduate and seven graduate students) were inducted at the 1989 spring banquet.

2.3 Faculty Activities

The Nuclear Engineering Department faculty have continued to be actively involved in numerous activities, both on and off campus. Because of space limitations, only a sampling of these accomplishments can be listed.

Professor Yip organized an informal faculty seminar series, the "Brunel Seminars," during the spring semester 1989. During the summer session, Professors Norman Rasmussen and Neil Todreas have continued to offer their annual two-week course entitled, "Nuclear Power Reactor Safety." This session continues to be well attended by members of the US nuclear industry as well as those of the international community. Also during the summer session, Professor Allan Henry has presented a week-long course on "Modern Nodal Methods for Analyzing Light-Water Reactors." This presentation continues to be very well received. Professors Nathan Siu and Mujid Kazimi offered for the first time in the summer of 1989 a new one-week course on risk assessment of nuclear power plants entitled "Individual Plant Evaluations: A Primer."

In September 1988, Professor Mujid Kazimi was host to two scientists from the Kurchator Institute in Moscow. Their three-week visit to MIT was organized under the bilateral cooperative agreement with the Soviet Union in the area of fusion research and development.

Since our last report, departmental administrative responsibilities have been handled by the following faculty. Professor Todreas, who announced his intention to step down as Department Head as of July 1, 1989, was succeeded by his colleague Professor Kazimi. In anticipation of this appointment, Professor Kazimi turned over the role of Financial Aid Officer to Professor David Lanning on June 1. Professor Jeffrey Freidberg continued to serve as the Graduate Admissions Officer. Professor Michael Driscoll, who plans to retire next October, completed his term as Graduate Recruiting Officer on June 30; Professor Michael Golay will assume this position for the coming academic year. Professor Henry continues to serve as the Department representative on the Committee on Graduate School Policy.

The Department's doctoral qualifying exams were coordinated by Professor Kim Molvig. Professor Meyer, who chaired the Committee on Undergraduate Students, also served as the faculty advisor for the honorary Alpha Nu Sigma Society. Besides serving on the computer committee, Professor Siu was the faculty advisor for the American Nuclear Society (ANS) Student Chapter. He also coordinated the Department's Independent Activities Period (IAP). Professor Ron Ballinger continued to supervise the UROP program and the Engineering Internship Program, and also served as the Undergraduate Financial Aid Officer. Professors Gordon Brownell, Freidberg, Elias Gyftopoulos, Lester, and Rasmussen, the Graduate Registration Officers, assisted the students during the academic year. Professor Todreas, who served in this capacity during the summer term, will advise Professor Lester's students during his sabbatical.

In addition to departmental assignments, faculty have made significant contributions to both School of Engineering and Institute activities. Professor Lester continued his appointment as Executive Director of the MIT Commission on Industrial Productivity. The Commission, consisting of 16 leading social scientists, engineers, and physical scientists on the Institute faculty, was charged with the task of analyzing the causes of productivity weakness in US industry and developing recommendations, particularly regarding education and research, in support of the national goal of strong, sustained productivity growth. The Commission's final report, "Made in America: Regaining the Productive Edge," was published by the MIT Press in May and has attracted widespread interest. As a result, Professor Lester has participated in an extensive series of presentations of the Commission's findings before numerous industrial, Congressional, Executive Branch, and academic groups in the US and overseas. He also serves on the Program Board of the Center for Energy Policy Research and the faculty advisory board of the Center for Technology, Policy and Industrial Development.

Professor Hutchinson continues in his role as Division Head of the Alcator C-MOD experiment, the major fusion experiment at the Plasma Fusion Center. Professor Yip was invited to be a House Fellow of Ashdown House. He also began serving as a member of the Athletic Board. Professor Gyftopoulos continued his services as Faculty Chairman of the MIT Sustaining Fellows Program, as a member of the Review Group on Context Subjects, and as a member of the advisory committee of the Center for Advanced Engineering Study.

Besides serving as departmental CGSP representative, Professor Henry holds membership on the Institute's Advisory Committee on Shareholder Responsibility. Professor Larry Lidsky completed his term as chair of the Institute's Committee on Curricula; he also serves as a member of the Review Group on Context Subjects. Professor Molvig continues on the Faculty Club Advisory Board.

The Committee on Outside Professional Activities is chaired by Professor Golay. Professor Todreas is also a member of this committee. Professor Todreas chairs the Committee on Radiation Exposure to Human Subjects and both he and Professor Rasmussen are members of the Institute Council of Environmental Health and Safety. Professor Rasmussen continues to serve as chairman of the Committee on Reactor Safeguard. He is assisted on this committee by Professors Ballinger, Otto Harling, Kazimi, and Lanning. Professor Harling also directs the Nuclear Reactor Laboratory, an interdepartmental facility.

Nuclear engineering faculty have continued to expand their professional horizon by their involvement in off-campus professional conferences and speaking engagements. Professor Ian Hutchinson visited the People's Republic of China under the auspices of the US Department of Energy to participate in a review of Chinese research activities in controlled fusion.

During 1988 Professor Golay was actively presenting the results of work on the reactor innovation project. Such presentations included lectures and visits to industrial firms and research installations in Taiwan, Japan, Korea, France, West Germany, and Italy.

Professor Lidsky was invited to an international workshop on greenhouse phenomena held in Aachen, Germany. In conjunction with this workshop, Professor Lidsky also presented invited papers at KFA in the Federal Republic of Germany and at Framatome in France. The environmental impact of second generation nuclear systems was also discussed at a meeting of the Edison Electric Institute.

Dr. Marvin Miller renewed his activities--begun in the early 1980's with the late David Rose--on the energy policy implications of greenhouse warming. Dr. Miller gave talks on this subject at a meeting of the International Motor Vehicle Program in Acapulco, Mexico, and at an ILP-sponsored symposium at MIT.

Professor Gyftopoulos participated in an international conference on Biopolitics in Athens, Greece. He was also the keynote speaker at an international symposium on Thermodynamic Analysis and Improvement of Energy Systems, held in Beijing, China.

Professor Todreas was a keynote speaker at the Third International Meeting on Reactor Thermal Hydraulics and Operations, held in Seoul, Korea. The title of his talk was "Nuclear Reactor Thermal Hydraulic Research, Why Can't We Do It Better?" Professor Kazimi also presented an invited lecture at this conference entitled "Recent Developments in Thermal Hydraulics of Severe Accidents." He also served on the Steering Committee of the seminar on fission product transport in severe accidents which was held at the International Center for Heat and Mass Transfer in Yugoslavia.

Professor Harling organized and chaired an international workshop on epithermal beam development for neutron capture therapy. He also acted as a reviewer for DOE's new program in support of academic research in nuclear engineering. In addition, he continued to represent the entire US university research reactor community in efforts to obtain a rational base of funding from the federal government. He also gave testimony before two subcommittees of the US Congress on this matter.

Professor Ballinger participated as co-leader of the MIT "Cold Fusion" team. In this capacity he testified before the US House of Representatives Committee on Science, Space, and Technology. Professor Chen was a major invited speaker in a NATO Advanced Study Institute, "Hydrogen-Bonded Liquids," held in Cargese, Corsica, France, during the month of April.

Professor Freidberg was asked to give talks at Cornell University and the Courant Institute at New York University concerning a novel approach to the understanding of ignition physics and burn control in tokamaks. Professor Molvig was invited to give the Magneto-Fluid Dynamics Seminar which was also hosted by the Courant Institute.

Dr. Miller gave seminars on the subject of nuclear-powered submarines in non-nuclear weapons states at Princeton University, the University of Montreal, and the Oak Ridge and Brookhaven National Laboratories. He also presented an invited paper on tritium verification and safeguards at a symposium on the tritium factor in arms control at the American Academy of Arts and Sciences in Cambridge.

Professor Kazimi presented an invited lecture entitled "Fusion and the Environment" at the Radioactivity and the Environment Meeting of the American Nuclear Society. Professor Henry presented papers at ANS meetings held in Jackson and Santa Fe. Professor Siu participated as a member of the Technical Program Committee for PSA'89, the ANS's International Topical Meeting on Probability, Reliability and Safety Assessment.

Since the last report, several members of the faculty and staff have been recognized for their contributions to the field of nuclear energy. The Nuclear Reactor Safety Division of the American Nuclear Society presented the George Laurence Award to Professor Rasmussen. This distinguished award is given to an individual for his "pioneering leadership in the field of reactor safety."

Professor Hutchinson was elected a Fellow of the American Physical Society. Dr. John Bernard, Director of Reactor Operations at the NRL, received the ANS's "Young Member Engineering Achievement Award." This award recognizes Dr. Bernard's pioneering work in the field of computer control of reactors.

Professor Todreas was elected to the National Academy of Engineering. He and his former student, Dr. Victor Iannello, received the Conference Award for the best paper presentation at the 1987 National Heat Transfer Conference. This paper, which reported the results of Dr. Iannello's PhD thesis research, was titled "Mixed Convection in Parallel Channels with Application to the Liquid Metal Reactor Concept." This paper also received the Best Paper Award for 1988 from the Thermal Hydraulics Division of the ANS.

Professor Brownell received the Coolidge Award from the American Association of Physicists in Medicine. This is the highest award given by the AAPM for accomplishments in medical physics. Professor Gyftopoulos was awarded an honorary doctorate by the Technical University of Athens.

Professor Ballinger received a patent for the development of Incoloy 908. This is a new high strength low coefficient of expansion alloy for cryogenic structural applications.

The Outstanding Teacher Award for the academic year 1987-88 was presented to Professor Siu. Professor Freidberg was chosen to receive this award for the academic year 1988-89.

3. RESEARCH AND EDUCATIONAL ACTIVITIES

3.1 Fission

3.1.1 Nuclear Reactor 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 advanced instrumentation and control analysis. Each of these program elements are described in more detail in the following sections.

The overall scope of effort has been concerned with participation in the full set of advanced reactor development programs in the nation. This has been done with an effort focused upon each of the current advanced reactor concepts, and has also involved a major effort in advanced instrumentation and control. This project has featured strong student thesis research involvement in research projects. Over the life of the Reactor Innovation Project, a total approximately 102 students have participated in thesis and non-thesis research projects. The breakdown of student involvement according to topic area and type of project is summarized in Table 1. The performance of research in the context of student projects is central to the Reactor Innovation Project. This reflects the goals of producing both good research and high quality graduates from the Institute.

A major recent initiative to establish the Center for Advanced Nuclear Power Studies has focused upon increasing the scale of the Reactor Innovation Project, and reorganizing its structure. This reorganization would involve a focus upon generic approaches to improvement for advanced reactor technologies; with the specific reactor concepts entering the program as examples to which such generic approaches would be applied.

Related Academic Subjects:

Academic subjects of special relevance to the Reactor Innovation Project include all of those concerned with fission engineering.

Table 1

REACTOR INNOVATION PROJECT
STUDENT INVOLVEMENT

Degrees	LWR	MHTGR	LMR	Advanced Control
B.S.	1	0	1	3
S.M.	10	5	3	18
Nuclear Engineer	1	1	1	1
Ph.D./Sc.D.	5	9	1	13
TOTALS	17	15	6	35
Non-Thesis				
Undergraduate	4	3	1	0
Graduate	5	2	13	1
TOTALS	9	5	14	1

3.1.1.1 The Light Water Reactor (LWR) Innovation Project

In the Light Water Reactor (LWR) Innovation Project, the important areas of activity are those of:

- New plant performance requirements;
- Conceptual design innovation; and
- Independent technological advances.

In Table 2 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 order to illustrate the benefits which can be obtained from such an 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.

Table 2

CURRENT PROJECTS OF THE LWR INNOVATION PROJECT

- Methodology for Nuclear Power Plant Modularization
- Human Reliability Improvements
  - Design simplicity and diagnostic success
  - Pattern recognition by nuclear power plant operators
  - Human memory limitations
- SBWR Design
  - Advanced containment heat transfer
  - Preliminary PRA-based design refinement

The LWR Innovation Project has been pursued since 1983. It has progressed through several prior projects, as listed in Table 3. The current projects are summarized in the following discussions.

Table 3

PREVIOUSLY COMPLETED EFFORTS IN THE LWR INNOVATION PROJECT

- Leak-Before-Break
- Functionally-Oriented Nuclear Safety
- Design Simplification
- Human Error in Reliability
- Design of the SBWR
  - Conceptual review
  - Stratification in containment performance
  - A passively conditional emergency control center
- Automatic Steam Generator Control

3.1.1.1.1 Methodology for Nuclear Power Plant Modularization

Modularization has been identified as an important design avenue for speeding the nuclear power station construction process, with attendant savings expected in plant capital costs. In order to define a systematic method for creation of a modular design, a recently completed project was undertaken. This work has addressed the following issues:

- Formulation of a method for plant layout, resulting in the placement of plant systems and major components in natural functional proximity.

- Creation of a set of plant layout-dependent economic performance measures, for use in economic optimization of plant layout.

- Definition of a method for fabrication of plant modules and the construction of the modular plant.

This general work has been refined through application to the specific example of the Sharon Harris PWR power station. In this work the conventionally-designed Sharon Harris NPS was redesigned for modular construction. Then the differential economic savings of these two designs were estimated. Subsequently, the differential economic savings of constructing the redesigned Sharon Harris plant were estimated, comparing building this modular plant using conventional construction techniques and using modular techniques. It was found that total capital cost savings of the order of 15% could be achieved through modularization. Approximately half is achieved through material cost savings resulting from use of modular design, and half is obtained through use of modular construction techniques.

Investigators: Professors M.W. Golay and A. Amsden (Civil Engineering); C. Lapp and S. Howard

Support: EPRI

Recent References:

C.W. Lapp, "A Methodology for Modular Nuclear Power Plant Design and Construction," Ph.D. Thesis, Nuclear Engineering Department, MIT, June 1989.

S. Howard, "Economic Modeling of Nuclear Power Plant Design Alternatives Using Improved Constructability Techniques," S.B. Thesis, Nuclear Engineering Department, MIT, May 1989.

3.1.1.1.2 Human Reliability Improvements

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

As with simplification, human reliability improvement is not a design goal in itself. Rather, it is an attribute of a design formulated for fulfillment of the higher level goal of safety and economic improvements.

The basic design approaches for 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 (automation); and
- Reduction of human stress in performance of the function (means for accomplishing this include increasing the time over which actions are required, simplifying of system, and providing supporting information and performance verification systems as operator aids).

In this project we are working on a set of examples in order to illustrate how elimination of human error can occur through design. This is done through investigations into the following areas.

Design Simplicity and Diagnostic Success: An outcome of prior work concerning plant design simplification was the identification of the informational entropy, H, as a measure of system complexity. In subsequent work, the value of this measure has become recognized concerning the ability of an analyst to diagnose failures of a system, particularly when rapid diagnosis is required. It became recognized that this class of failure would be most sensitive to system complexity, which is to say that systems which are complex are also difficult to understand and diagnose. Stated differently, systems which are difficult to diagnose have a high uncertainty regarding the actual condition of the system. This is equivalent to having many possible alternative system configurations, or states, with the relative likelihoods of these different states being approximately uniform. Such uncertainty is measured by the informational entropy of the system which is defined as:

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

where
H = system entropy
i = i^{th} system state
n = the number of possible states of the system
p_i = the probability of the system being in the i^{th} state.

It has been shown in the work of the project that the number of interrogations necessary to diagnose the true state of a system increases approximately exponentially as a function of the informational entropy, according to the relationship:

$$\langle n \rangle \simeq \tfrac{1}{2}\, 2^{H}, \qquad (2)$$

where <n> is the expected number of interrogations which must be made to identify the true state of a failed system, given that the search for this state is performed in order of descending state probability.

From this work the main insights to be derived concerning design which will enhance human reliability are that systems which will promote high reliability have:

- Few possible states,
- A high reliability of being in the intended or "desired" state, and
- Highly reliable instrumentation, targeted upon detection of a system being in the more likely undesirable states (e.g., through monitoring of particularly unreliable system components).

This work has been refined through several application examples and tests involving human subjects who were asked to diagnose failed nuclear power plants systems--particularly the condensate-feedwater system of a PWR.

Pattern Recognition in Instrument Responses to Transients by Nuclear Power Plant Operators: As an aid in plant operator response to nuclear power plant transients, it has been recognized that plant instrument response patterns may be useful indicators of different categories of plant transients. An investigation has been undertaken to identify the categories of such patterns which could be expected in association with a spectrum of PWR transients. Using a plant simulator to describe plant transient responses, the resulting patterns have been categorized. This has been done focusing upon the following classes of transients:

- Power transients, and
- Power transients in combination with small primary systems leaks with and without the functioning of the plant pressurizer, respectively.

Examining patterns in the combined variation of the pressurizer liquid level and primary coolant pressure, it has been found that distinct sets of dependent variable transients can be observed for these different classes of system transients. These resulting classes of patterns can be useful to plant analysts in identifying plant transient conditions.

The Effects of Human Memory Limitations upon Human Reliability in System Diagnosis: An aspect of human, rather than automatic, diagnosis of failed systems is the inability of humans to use more than a small number of facts in the deductive solution of a problem. This limitation can be important in the "trouble shooting" of a complex failed system, such as is found in a nuclear power plant.

Current work has been undertaken to understand better the effects upon human reliability in diagnosis of memory limitations, and to link these effects into guidance given to nuclear power plant designers. The problem examples being used are variations of the deductive game "Mastermind," and trouble shooting of the PWR condensate-feedwater system. In this work, variations of this game are presented to human subjects, and the resulting methods of attack are studied. Results obtained to date indicate the following:

- The observed average number of interrogations agrees well with the value of <n> indicated in Equation 2.

- When the number of facts which an analyst may use in an incremental attack upon a problem exceeds approximately ten, the method of analysis remains limited to the use of approximately ten facts, even though more than ten facts are available to be used; this limitation results in the problem attack proceeding more slowly to solution than when all available facts are used.

- Previously verified facts remain available for use in a deductive solution when the total number to be remembered remains less than approximately ten, but above this limit previously identified facts will tend to be forgotten in the process of a solution.

The main guidelines to designers identified to date are the following:

- The probability of successful failed system diagnosis decreases rapidly as the amount of information characterizing a problem increases.

- When an analyst must remember more than ten facts simultaneously in a problem solution, the problem may never be solved.

- Success in system analysis is enhanced by minimizing system uncertainty (entropy) and the number of facts which must be remembered.

<u>Investigators</u>: Professors M.W. Golay and V.P. Manno (Tufts University); Dr. P. Seong; J. Outwater, W. Hi, and T. Hiltz

<u>Support</u>: EPRI

<u>Recent References</u>:

J.O. Outwater III, "Operator Error in Control of the Steam Generator Liquid Level of a Pressurized Water Reactor," S.M. Thesis, Nuclear Engineering Department, MIT, June 1989.

T. Hiltz, "Reducing Diagnostic Error in Nuclear Power Plant Operations," S.M. Thesis, Nuclear Engineering Department, MIT, September 1989.

3.1.1.1.3 Design of a Small BWR

In the area of design innovation the major activity in the project is concerned with design of a small BWR. This work is part of the EPRI and US Department of Energy Advanced LWR program. In this project we are aiding the General Electric Company team in development of a conceptual design for a BWR of approximately 600 MWe capacity. This work is expected to continue in the future.

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

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

Recent work concerning the SBWR has been focused on the passive containment design and use of PRA in design refinement.

LWR Containment Heat Rejection: This work has been concerned with conceptual designs, the rate of heat transfer from the containment vapor suppression pool and wetwell atmosphere to the environment and with the role of stratification in these systems in affecting such heat transfer. The particular concern of current containment-related work is development of new correlations for condensing heat transfer in the presence of non-condensible gases. This work is intended to supplant the Uchida and Tagami correlations which have long been used in containment design analyses. For this work, a heat transfer experimental facility (CELTIC) has been constructed which permits tests to be performed over the range from ambient conditions to maximum containment atmosphere conditions of p_{max} = 75 *psig* and T_{max} = 300°F, and naturally convective flow conditions ranging from laminar to turbulent. Construction of this facility has been completed recently, and initial tests are expected to begin shortly.

SBWR Probabilistic Risk Analyses (PRA): In an exercise aimed at better understanding the role of PRA as a design refinement tool and at contributing to the design improvement of the SBWR, an effort has been undertaken to refine a preliminary PRA which had been performed for the SBWR. Some general conclusions which were reached regarding use of PRA as a design tool include the following:

- The available information regarding a design is too incomplete to permit estimation of plant risks until the detailed design is roughly complete.

- The primary value of PRA in design refinement is through providing a systematic method for identifying outstanding design vulnerabilities and informational uncertainties.

- The most difficult aspects of use of PRA in design refinement is quantification of human reliability and factoring such reliability concerns early into the design evolution.

Investigators: Professors M.W. Golay, N.O. Siu, M.S. Kazimi; M. Siddique, A. Dehbi, and I. Kato

Support: EPRI, USDOE

Recent References:

J.W. Keffer and M.S. Kazimi, "Passive Cooling of a Sealed BWR Containment," MITNPI-TR-025, October 1987.

E.E. Sasson, "Fluid Flow and Stratification in BWR Containment Cooling," S.M. Thesis, Nuclear Engineering Department, MIT, September 1987.

A.A. Dehbi, "A Two-Region Model for the Analysis of Steam Injectors," S.M. Thesis, Nuclear Engineering Department, MIT, February 1988.

I. Kato, "Use of Probabilistic Risk Assessment in Nuclear Power System Design Refinement," S.M. Thesis, Nuclear Engineering Department, MIT, June 1988.

M. Siddique, M.W. Golay, and M.S. Kazimi, "The Effect of Hydrogen on Forced Convection Steam Condensation," AIChE Symposium Series, National Heat Transfer Conference, Philadelphia, PA, August 6-9, 1989.

Related Academic Subjects:

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

3.1.1.2 Liquid Metal Cooled Reactors

During recent years the Reactor Innovation Project has lacked an effort concerned with liquid metal cooled reactors (LMR). This deficiency has been remedied with the recent start of a project concerned with defining the promise of the Integral Fact Reactor (IFR) concept for future energy needs. This work involves the following tasks:

- Identification of plausible roles for the IFR in national and world future energy supply scenarios.

- Examination of the possibilities and important problems in use of the IFR to consume high level radioactive wastes from other reactors as well as from itself. Among the problems being addressed are those concerning efficient transformation of such wastes into chemical forms usable in the IFR and design of IFR cores which could be used feasibly for this purpose.

This work is being pursued in collaboration with the IFR program of Argonne National Laboratory.

Investigators: Professors M.W. Golay and L. Lidsky; Dr. M. Miller; W. Holloway and M. Zhang

Support: USDOE

3.1.1.3 The Center for Advanced Nuclear Power Studies

A current initiative within the Reactor Innovation Project concerns an effort to supplant that project by the Center for Advanced Nuclear Power Studies. The current initiative is being pursued through proposals to the National Science Foundation and to the Department of Energy. The responses to these proposals should be known by the end of 1989.

The purpose of the Center is to expand the Institute's activities in reactor innovation by a factor of approximately five, and to re-orient such activities in terms of generic efforts which are common to the various reactor concepts, to focus upon them separately. The reason for this change is promotion of information sharing among concepts and formulation of a greater advanced reactor development strategy. The individual reactor concepts enter this framework as examples to which generic results are applied in the refinement of a generic approach.

The major areas of activity in this proposal are summarized in Table 4. This effort has been supported by the great majority of leading organizations of the US nuclear power enterprise as summarized in Table 5. If funded, this Center will be established as an Engineering Research Center. Preparation of this proposal was a major undertaking for Professor M.W. Golay, involving an overtime commitment of effort for approximately four months. He was assisted in this work by approximately 30 faculty members from the departments of Civil Engineering, Mechanical Engineering, Materials Science and Engineering, and Economics in addition to Nuclear Engineering.

Table 4
Major Products

	Technological Advances			
	Techno-logical Options	Design Models & Methods	Performance Requirements	Basic Knowledge Advances
1. NUCLEAR POWER STATION TECHNOLOGY				
o Advanced Reactor Concepts	x	x	x	x
o Generic Technology Improvements				
o Passive Safety	x	x	x	x
o Man-Machine Interaction	x	x	x	x
o New Technologies				
o Advanced Instrumentation and Control				
– Diagnostic Systems	x	x	x	x
– Automatic Control	x	x	x	x
– Sensor Validation	x	x		x
o Power Conversion	x	x	x	
o Fiber Optics	x			x
o Materials	x	x	x	x
o Seismic Design	x	x		x
2. QUANTITATIVE DESIGN OPTIMIZATION METHODS				
o Safety	x	x	x	x
o Economic Value of Safety	x	x	x	x
o Economics	x	x	x	x
3. NUCLEAR FUEL CYCLE REQUIREMENTS FOR POWER STATIONS				
o Waste Disposal	x		x	
o Nuclear Weapons Proliferation	x		x	
4. SOCIETAL/INSTITUTIONAL REQUIREMENTS FOR POWER STATIONS				
o Public Acceptance			x	x
o Economic Regulation			x	
o Safety Regulation	x	x	x	x
o Industrial Organization Alternatives			x	

Table 5

Outside Industrial Organizations Participating in the Center for Advanced Nuclear Power Studies

Organization Type Organization Name	Funding ($K/Year)	Contribution to the Center Collaborative Projects
Reactor Manufacturers		
General Electric*	---	Yes
Westinghouse Electric	---	Yes
Combustion Engineering	---	Yes
GA Technologies*	---	Yes
Architect/Engineers		
Stone & Webster Engineering Corp.*	---	Yes
Burns & Roe	---	Yes
Electric Utility Organizations		
Electric Power Research Institute*	>200	Yes
Institute for Nuclear Power Operations	---	Yes
Yankee Atomic Electric Co.	---	Yes
Commonwealth Edison Co.	---	Yes
Gas-Cooled Reactor Associates*	Yes	Yes
Nuclear Power Oversight Committee	---	Yes
Federal Government Agencies		
Department of Energy*,**	>600	Yes
National Laboratories	---	
Argonne National Laboratory		Yes
Los Alamos National Laboratory		Yes
Oak Ridge National Laboratory		Yes

* = Participant in the Reactor Innovation Project
** = Proposal under review

3.1.1.4 Modular Gas-Cooled Reactor (MGR) 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 Modular High Temperature Gas-Cooled Reactor, now designated as the MGR. This MGR has unique passive safety features, and our initial intent is to help determine whether a suitable design can be established for commercial deployment. Our longer range plan is to contribute to developing the ultimate potential of the MGR concept.

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

1) Reactor Core Design

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

2) Economies of Scale and Licensing

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

3) Source Term Effects

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

4) Probabilistic Risk Assessment

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

5) Passive Safety Heat Transfer Sensitivity Studies

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

6) Direct Cycle Gas Turbine

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

7) Water Ingress Effect

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

8) Fission Product Deposition and Lift-Off

Passive safety features of the MGR prevent the release of significant fission products over a wide spectrum of accidents. Hence, the major potential for fission product activity release becomes a lift-off during a depressurization blowdown, of any loosely deposited fission products that have been deposited with time from low-level activity in the primary helium circulation system. This potential deposition and accidental lift-off is an important uncertainty in safety studies and could impact on the fuel quality requirements for future MGR designs. Planning and designs are being made to build a simple, experimental, pressurized helium circulation system for controlled experimental lift-off studies to be done at MIT by the Nuclear Engineering Department.

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

Support: Energy Laboratory Utilities Program (primarily from Gas-Cooled Reactor Associates [GCRA]), GA Technologies, Oak Ridge National Laboratories

Related Academic Subjects:

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

Recent References:

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

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

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

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

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

J.L. Maneke, D.D. Lanning, L.M. Lidsky (MIT); J.M. Oddo, J.S. Baron, and A. Drozd (SWEC), "MHTGR Confinement Radiation Releases," Transactions of the American Nuclear Society, Vol. 53, pp. 362-64, November 1986.

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

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

3.1.1.5 Liquid Metal Reactor Safety Studies

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

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

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

Support: Rockwell International/DOE

Related Academic Subjects:

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

Recent Reference:

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

3.1.1.6 Advanced Instrumentation and Control Systems

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

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

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

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

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

Enhancement and demonstration of this controller has continued along with some thermal dynamic studies of the PIPE fuel for space nuclear power plants.

A new series of studies has been initiated on the automatic control of multi-modular nuclear power plants. Proposed passively safe advanced reactors include use of small reactor modules combined into a single power plant. Methods to automatically control such power plants are needed to provide safe and economic operation. Initial funding for these studies has been received from Oak Ridge National Laboratories. A method for controlling the system to provide a constant (demand) pressure at a common steam header has been investigated. These studies are being continued, including combined test by use of simulation and the MIT Reactor.

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

Automation improvements of many types can contribute to the PWR upgrade portion of the Reactor Innovation Studies. In particular, great operational benefit (in terms of a large decrease in the number of plant trips) is expected to accompany improvements in automatic control of steam generator water level. We have, therefore, embarked on developing new methods for digital computer control of water level, concentrating on the especially crucial range below about 15% reactor power. Our evolving control method is a strongly physically based one that incorporates an analytic steam generator model developed earlier (Strohmayer, Ph.D. Thesis, 1982). The resulting controller does not use steam flow and feedwater flow measurements at all and has exhibited good performance characteristics in all calculational tests to date. A special feature of the ongoing study is its heavy reliance on actual operating data that we have obtained from an existing 1150 MWe PWR plant.

Investigators: Professors D.D. Lanning, J.E. Meyer, A.F. Henry, and T.B. Sheridan (Department of Mechanical Engineering); Drs. J.A. Bernard (MIT-NRL) and J.H. Hopps (Charles Stark Draper Laboratory); B.N. Aviles, E.L. Cabral, J-I. Choi, M. Houts, P-W. Kao, M.H. Kim, K.S. Kwok, E.S.H. Lau, M. McMahon, P.T. Menadier, R. Tuddenham, M. Waltrip, and M.L. Zerkle

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

Related Academic Subjects:

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

Recent References:

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

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

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

J.A. Bernard, "Human Approach to Process Control and the Provision of Predictive Information," Transactions of the American Nuclear Society, Vol. 53, pp. 139-40, November 1986.

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

J.A. Bernard, "An Experimental Comparison of Reactor Power Controllers Based on the Standard and Alternate Formulations of the Dynamic Period Equation," IEEE Transactions on Nuclear Science, Vol. NS-34, No. 1, pp. 548-52, February 1987.

R.S. Ornedo, J.A. Bernard, D.D. Lanning, and J.H. Hopps, "Design and Experimental Evaluation of an Automatically Reconfigurable Controller for Process Plants," Proceedings of the American Control Conference, Minneapolis, Minnesota, Vol. 3, pp. 1662-68, June 1987.

J.A. Bernard, "The Relation of the Inhour and the Dynamic Period Equation," Transactions of the American Nuclear Society, Vol. 55, pp. 69-71, November 1987.

J.A. Bernard, "Evaluation of 'Period-Generated' Control Laws for the Time-Optimal Control of Reactor Power," IEEE Transactions on Nuclear Science, Vol. NS-35, No. 1, pp. 888-93, February 1988.

J.A. Bernard, A.F. Henry, and D.D. Lanning, "Application of the 'Reactivity Constraint Approach' to Automatic Reactor Control," Nuclear Science and Engineering, Vol. 98, No. 2, pp. 87-95, February 1988.

S.H. Lau, J.A. Bernard, K.S. Kwok, and D.D. Lanning, "Experimental Evaluation of Predictive Information as an Operator Aid in the Control of Research Reactor Power," Proceedings of the American Control Conference, Atlanta, Georgia, Vol. 1, pp. 214-20, June 1988.

B.N. Aviles, J.A. Bernard, and D.D. Lanning, "The Design and Experimental Evaluation of a Non-Linear State-Variable Feedback Controller for Nuclear Reactors," Proceedings of the American Control Conference, Atlanta, Georgia, Vol. 1, pp. 263-65, June 1988.

H.P. Polenta, A. Ray, and J.A. Bernard, "Microcomputer-Based Fault Detection Using Redundant Sensors," IEEE Transactions on Industry Applications, Vol. IA-24, No. 5, pp. 905-12, September/October 1988.

J.A. Bernard, "Use of a Rule-Based System for Process Control," IEEE Control Systems Magazine, Vol. 8, No. 5, pp. 3-13, October 1988.

T. Washio and J.A. Bernard, "Stability Considerations and Noise Reduction in the Implementation of the MIT-SNL Period-Generated Minimum Time Control Laws," Transactions of the Sixth Symposium on Space Nuclear Power Systems, CONF-890103-Summs., Albuquerque, New Mexico, pp. 476-79, January 1989.

J.A. Bernard, K.S. Kwok, D.D. Lanning, A.F. Henry, and J.E. Meyer, "Transient Control of Reactor Power Generation for Rapid Maneuvering," in Space Nuclear Power Systems 1987, M.S. El-Genk and M.D. Hoover, eds., Orbit Book Co, Malabar, Florida, pp. 299-309, February 1989.

J.A. Bernard, "Progress Towards a Generic Methodology for the Closed-Loop Digital Control of Nuclear Reactor Power," Proceedings of the ANS/NIST Conference, "Fifty Years with Nuclear Fission," April 26-28, 1989, Gaithersburg, Maryland.

J.A. Bernard, "Applications of Artificial Intelligence to Reactor and Plant Control," Nuclear Engineering and Design, Vol. 130, No. 2, pp. 219-27, April 1989.

M. Waltrip, "Multi-modular Nuclear Reactor Plant Simulation and Control," S.M. Thesis, MIT Department of Nuclear Engineering, May 1989.

R.S. Tuddenham, S.H. Lau, T. Washio, J.A. Bernard, and D.D. Lanning, "Experimental Demonstration of Proportional-Integral-Derivative Feedback in the Closed-Loop Digital Control of Reactor Neutronic Power," Proceedings of the Seventh Power Plant Dynamics, Control, and Testing Symposium, May 15-17, 1989, Knoxville, Tennessee.

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

3.1.1.7 Automated Reasoning: Applications of PROLOG

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

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

Investigators: Professors L.M. Lidsky and D.D. Lanning; A. Dobrzeniecki

Support: US Department of Energy

Recent Reference:

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

3.1.1.8 Space Nuclear Power Applications

A program has been initiated on the study of applications of small nuclear power systems in space. The present program is supported by the Air

Force (Kirtland Air Force Base). The study involves a review of a "STAR-C" type high temperature reactor, utilizing thermionic conversion to electric power. Design variations are being assessed, and control methods are being studied.

Investigators: Professors D.D. Lanning and M.S. Kazimi; M. Houts, S. Chen (UROP)

Support: US Air Force

Related Academic Subjects:

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

3.1.1.9 Cross-National Analysis of Nuclear Industrial Performance

An abundance of statistical and case study evidence indicates the presence of systematic variations in industrial performance in nuclear power plant design, construction, and operation within and among nations. By studying the origins of these differences, useful lessons can be drawn for nuclear industry practitioners seeking to bring their performance to worldwide levels of "best practice." Such studies can also provide more general insights into the effects of managerial, organizational, cultural, and other factors on productive performance across a range of industries. During the last two years, our research has continued to focus on the relationships between managerial and regulatory practices, industrial organization, and construction and operating performance in the United States, France, Japan, and West Germany. We have refined the statistical technique developed previously to quantify the contribution of "learning by using" to the improvement of operating performance. We have also conducted case studies of steam-generator corrosion in PWRs and intergranular stress corrosion cracking in BWRs in the United States, West Germany, Japan, and France in order to compare technical problem-solving approaches in these countries.

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

Investigators: Professor R.K. Lester; M.B. Crocker and M.J. McCabe

Support: MIT Center for Energy Policy Research

Recent Reference:

R.K. Lester and M.J. McCabe, "The Effects of Industrial Structure on Learning by Using in Nuclear Power Plant Operations," Center for Energy Policy Research Working Paper, MIT, November 1988.

3.1.2 Reactor Physics

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

3.1.2.1 Subjects of Instruction

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

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

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

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

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

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

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

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

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

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

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

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

3.1.2.2 Reactor Physics Research

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

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

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

1) Nodal Methods - Static Applications

The first successful nodal code developed at MIT was QUANDRY, It is the basis of several production codes now being used in the utility industry and has been extended in several ways at MIT.

One extension has been to add the ability to model the presence of an extraneous neutron source in any desired number of nodes. Thus QUANDRY can now compute flux shapes in subcritical reactors or follow a start-up transient.

Another extension has been to provide for computation of the static (source-free) adjoint flux and to use the adjoint flux shapes that result in order to compute the so-called point kinetics parameters, reactivity, prompt neutron lifetime and effective delayed neutron fraction.

The same mathematical manipulations that yield the point kinetics parameters also permit implementation of the "point synthesis method," according to which three-dimensional neutron flux shapes for a range of reactor conditions can be constructed from a fixed, predetermined set of "expansion flux shapes." We have successfully tested the point synthesis method for static cases and now plan to extend it to the analysis of transients, the ultimate goal being to analyze three-dimensional transient behavior in real time.

In the derivation of the QUANDRY nodal equations, the few-group flux shapes within each homogenized node are represented approximately by analytic functions. This representation results in great algebraic complexity and makes it very difficult to treat more than two energy groups of neutrons. Moreover, for heavy water and graphite-moderated reactors, much simpler flux shapes appear to yield accurate results. Accordingly, we have recently completed work on a static, two-dimensional multigroup nodal code in which the nodal flux shapes are represented by quadratic functions. The application of discontinuity factors computed automatically within the code by running a sequence of one-dimensional problems permits the use of very large nodes for the two-dimensional cases. In so doing we found that the numerical iteration schemes for solving nodal equations embodied in QUANDRY were inefficient when applied to graphite systems. Much effort was required to devise acceptable alternatives, and, although the code now provides converged solutions in a reasonable time, we feel that further study is called for in this area.

2) Transient Analysis

QUANDRY can analyze three-dimensional transient problems involving thermal-hydraulic feedback and control rod motion. However, for large power reactors the computation time is long. We have been partially successful in overcoming this difficulty by using "supernodes" (40 x 40 x 60 cm^3), homogenized cross sections and discontinuity factors for the supernodes being found from static, fine-node calculations. However, for transients of less than 100-second duration, the computation time on a work station computer (MicroVAX) still exceeds real time. As mentioned above, we hope to decrease running time further by going to a transient point-synthesis method.

For many problems a model of reduced dimensionality (hence much faster running time) is quite adequate. Several years ago we tested such a model derived systematically from the three-dimensional QUANDRY equation. Until the accuracy of the scheme was established, however, we made no attempt to improve its efficiency. We have now made such an attempt, essentially by finding "temperature coefficients" for the complicated algebraic coefficients associated with the QUANDRY equations. However, finding more than the first derivative with respect to temperature of these coefficients is so complicated algebraically that it was not attempted, and, unfortunately, although computation times decrease significantly when the first derivative coefficients are used, accuracy is also lost. We do not intend to pursue this procedure further, since it now seems clear that the whole (11-year-old) QUANDRY formulation itself can be greatly simplified by using quartic polynomials instead of analytic functions to expand the flux within a node.

It has been established by comparison with both experiment and more precise calculational models that the two-group diffusion theory underlying most nodal codes is capable of predicting the static behavior of light water reactors. Experimental verification for transient models is much more difficult--and impossible for many transients which must be analyzed for safety studies. For this reason we have been comparing (in one-dimension) the predictions of two-group, time-dependent diffusion theory with those of a multigroup, P-1 model. In particular, we have been investigating whether conventional flux-spectrum weighted two-group constants are adequate to describe transient behavior, or whether, instead, both the regular and adjoint flux must be used. So far, the use of the conventional procedure appears to provide acceptable accurate results. However, the relative accuracy of two-group results based on the various ways of obtaining the two-group cross sections does not conform with theoretical expectations, and we are continuing to study the problem.

Investigators: Professor A.F. Henry; K.W. Brooks, R.P. Jacqmin, M. Kim, P.W. Kao, K.R. Rempe, A.Z. Tanker, E. Tanker, F. Tarantino, and M.L. Zerkle

Support: MIT Energy Laboratory Utility Program; DOE; GA Technologies; Sandia National Laboratory

Related Academic Subjects:

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

Recent References:

Antonio F.V. Dias and A.F. Henry, "Evaluation of Systematically Derived Neutron Kinetics Models," Nuclear Simulation; International Nuclear Simulation Symposium and Mathematical Modelling Workshop, October 1987, Schliersee, Proceedings, edited by Moshe R. Haller, Springer-Verlag.

K.F. Hansen, E.V. Depiante, P.J. Laughton, J.E. Meyer, A.F. Henry, and L.H. Mweene, "Parity Simulation: An Electronic Approach to Simple Flow Systems," Computers in Mechanical Engineering, Vol. 5 No. 4, 25-33.

M. Kim and A. Henry, "Flux-Adjoint Weighted Few-Group Cross Sections Used for Reactor Transient Analysis," International Reactor Physics Conference, Jackson Hole, Wyoming, Sept. 18-22, 1988, Vol. II, p. 75.

K. Rempe, K. Smith (Studsvik), A. Henry (MIT), "Verification of the SIMULATE-3 Pin Power Distribution," Proc. 1985 Int. Reactor Physics Conf., Jackson Hole, Wyoming, Sept. 18-22, Vol. III, p. 31.

Pin-Wu Kao and A.F. Henry, "Supernodal Analysis of PWR Transients," American Nuclear Society Proceedings of the Topical Meeting on Advances in Nuclear Engineering Computation and Radiation Shielding, Santa Fe, New Mexico, April 9-13, 1989, Vol. 2, p. 63.

3.1.2.3 Fuel Management and Fuel Cycle

The level of activity in this area has decreased over the past several years because of declining student interest and faculty availability. However, subject 22.35 Nuclear Fuel Management, now on an every-other-year basis, was offered spring term 1989. In addition, a master's thesis was completed which made substantial progress toward development of an expert system for PWR core reload optimization. A monograph on the linear reactivity model of reactor core behavior, based in large part on earlier research and teaching efforts at MIT, will soon be published by the ANS.

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

Investigators: Professor M.J. Driscoll; G. Broadbent

Support: Internal

Related Academic Subjects:

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

Recent References:

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

G. Broadbent, "A Rule-based Approach to PWR Reload Pattern Development," S.M. Thesis, Nuclear Engineering Department, MIT, July 1989.

3.1.3 Reactor Engineering

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

3.1.3.1 Subjects of Instruction

A total of seventeen 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 US central station power reactors. Topics covered include: the elementary economic aspects of electric power generation; heat generation, transfer, and transport; radiation protection and safety analysis.

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

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

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

22.312 Engineering of Nuclear Reactors, covers engineering principles of nuclear reactors emphasizing applications in central station power reactors. Power plant thermodynamics; energy distribution and transport by conduction and convection of incompressible one- and two-phase fluid flow in reactor cores; 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 Heat Transfer, is a specialized course in the power reactor engineering curriculum offered in conjunction with the Mechanical Engineering Department. Topics treated include phase change in bulk stagnant systems, kinematics and dynamics of adiabatic two-phase flow, with boiling and/or evaporation, thermal and hydrodynamic stability of two-phase flows and associated topics such as condensation and atomization. Both water and liquid metal applications are considered under each topic where data exists.

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

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

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

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

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

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

3.1.3.2 Mixed Convection Flow Recirculation in LMFBR Rod Assemblies

This project is concerned with the development of thermal hydraulic methods for use in assuring the effectiveness of the passive decay heat removal in liquid metal cooled fast breeder reactors by natural convection. In particular, thermal hydraulics of rod assemblies in LMFBR cores under small core through-flow conditions where flow recirculations occur, is the current focus of this research. Onset of flow recirculation, recirculation flow patterns, associated flow conditions (as represented by Reynolds, Grashof, and Prandtl numbers) and a possibility of one dimensional modeling of flow recirculation effects are being addressed. Since the net coolant that flows through the reactor core is eventually established by global natural circulation within the reactor vessel during the passive decay heat removal process, coolant flows through rod assemblies of the core can then be viewed as the problem of mixed convection flows in vertical multi-rod channels.

Two types of flow recirculations are considered possible in rod assemblies. The first is recirculation induced by cooling through assembly walls. Buoyancy forces in the vicinity of the heated rods work in the direction opposite to the buoyancy forces acting in the neighborhood of the cooled walls where heat is transferred out to the cooler neighboring assemblies. These buoyancy effects, at low flow conditions, can give rise to flow separation from the main stream, resulting in internal flow recirculation along the cooled walls within the rod assemblies. The second is flow recirculation resulting from an interaction between cold coolant in the upper plenum and hot buoyant jet of coolant emerging from core assemblies (i.e., upper plenum cooling induced flow recirculation). The coolant from the upper plenum may penetrate down the core assemblies from the low heating side when imbalance between buoyancy induced flow due to heating from rod assemblies and core through-flow which limits the total net flow through the core occurs. The penetration depth of the upper plenum coolant into the rod assemblies depends upon the Grashof and Reynolds numbers as well as the temperature difference between the core exit and the upper plenum.

Three investigation approaches, experimental, numerical and analytical have been employed in a complementary fashion. Physical experiments involved water flow visualization and temperature measurement in a 4x4 rod square channel with a plan to extend to a 19 rod triangular array channel. A single rod cylindrical channel was also used to investigate for fundamental understanding of the phenomenon in the absence of complicated geometry as well as for studying the rod-wall spacing and power level effects. Flow visualization using fluorescein as a tracer have been undertaken for several power skew heating patterns. The onset of flow recirculation, its penetration depth, flow patterns and temperature fields have been recorded.

TEMPEST, a three-dimensional time-dependent finite difference computational fluid dynamics code developed at Battelle, was employed to simulate flow recirculation in a multi-rod channel. The purpose of the simulation is to study the Prandtl number effect. Since it is not always economically practical to simulate large, 3-dimensional problems it is thus desirable to minimize the number of simulated rods. For this purpose, a 2x2 rod channel represents the minimum configuration required to produce power skew effect.

For the results of the study of interassembly cooling induced flow recirculation, in general, it can be said that (1) a decrease in Prandtl number and/or an increase in power skew will accelerate the onset and increase the penetration depth of internal flow recirculation. (2) The weakening of power skew effect becomes pronounced as penetration depth (or Gr/Re) increases, resulting in the flattening of transverse temperature profile and the merging of penetration depths of different power skews. (3) The axial temperature develops a linear profile with increasing penetration depth (or Gr/Re).

Preliminary results of upper plenum cooling induced flow recirculation experiments indicate that the thermal mixing of the hot upflow of coolant and the cold downflow resulted in unstable and complicated temperature and flow fields. Research efforts are currently focused on this part of the problem.

Based on the physical insight obtained from our experimental and numerical investigations of vertical-rod experiments, an approximate model for internal recirculation incorporating effects of flow recirculation (i.e., linearization of axial temperature profile and flattening of transverse temperature profile) has been formulated. The goal is to achieve a correlating equation for the onset and penetration depth of flow recirculation which is capable of correctly predicting the experimental trend. A model for upper plenum cooling induced flow recirculation is being developed.

Investigators: Professor N.E. Todreas; W. Luangdilok and A.I. Barakat.

Support: Power Reactor and Nuclear Fuel Development Corporation of Japan.

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors

Recent References:

W. Luangdilok and N.E. Todreas, "Wall-Cooling-Induced Mixed-Convection Flow Recirculation in a Vertical Square-Array Multi-Rod Channel," to be presented at Fourth International Topical Meeting on Nuclear Reactor Thermal Hydraulics, October 10-13, 1989, Karlsruhe, FRG.

A.I. Barakat and N.E. Todreas, "Mixed Convection Buoyancy-Induced Backflow in a Vertical Single-Rod Channel Connected to an Upper Plenum," to be presented at Fourth International Topical Meeting on Nuclear Reactor Thermal Hydraulics, October 10-13, 1989, Karlsruhe, FRG.

3.1.3.3 Natural Circulation for Decay Heat Removal

Rejection of decay heat to ambient air by natural convection, to achieve inherent, passive safety, is now a well-established feature of virtually all advanced reactor designs. The department continues to pursue its long-standing research interest in this area, with recent emphasis on application to the MHTGR.

A computer program has been developed incorporating a k-ϵ turbulence model for calculation of buoyancy-driven flow in core cavity riser ducts. It is being used to study, and develop correlations for, heat transfer and pressure drop in the mixed convection regime.

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

Results to date show a decrease in Nu and increase in f relative to pure forced convection, in agreement with the limited and often contradictory literature on mixed convection.

In addition to work on the above specialized heat transfer topics, overall system optimization is also being addressed, including conduction from the depressurized reactor core to the reactor vessel, radiation to the riser ducts, and then internal convection to air.

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

Support: DOE via General Atomic, Bechtel, and ORNL

Related Academic Subjects:

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

Recent References:

M.J. Driscoll and N.E. Todreas, "Review of Design Requirements for the MHTGR Reactor Cavity Cooling System," October 1987.

M.J. Driscoll and N.E. Todreas, "Review of Development Plan for the MHTGR Reactor Cavity Cooling System," October 1987.

M.J. Driscoll, N.E. Todreas, and G. Fu, "Review of Design Methods for the MHTGR Reactor Cavity Cooling System," January 1988.

M.J. Driscoll, G. Fu, D.A. Bushko, N.E. Todreas, and A.R. Barakat, "An Assessment of Selected Thermal-Hydraulic Aspects of the MHTGR Reactor Cavity Cooling System," February 1988.

M.J. Driscoll, G. Fu, and N.E. Todreas, "Augmentation of Vessel to Riser Heat Transfer in the MHTGR RCCS," July 1988.

M.J. Driscoll, G. Fu, and N.E. Todreas, "Fluid Flow in the MHTGR RCCS," September 1988.

M.S. Boehle, "An Improved Method for the Computation of Passive Heat Removal for LMRs," S.M. Thesis, MIT Nucl. Eng. Dept., January 1987.

D. Bushko, "Passive Cooling of Nuclear Reactors," S.M. Thesis, MIT Nucl. Eng. Dept., May 1987.

Von B. Duran, "Design and Construction of a Mock-up to Study MHTGR Reactor Cavity Cooling System Riser Performance," S.B. Thesis, MIT Nucl. Eng. Dept., May 1988.

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

3.1.3.4 Parity Simulation of Nuclear Plant Dynamics

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

It is well-known that electric analogs to a variety of physical problems can be built. However, for most cases the electronic analog must have nonlinear characteristic. With the parity simulator approach it is quite easy to design integrated circuits with nonlinear behavior.

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

Progress has been made in the modeling of both fluid-flow and neutron-flow problems. Neutronics models have been testing for both point kinetics, and space-dependent, diffusion theory problems. In the fluids area models of single-phase and two-phase flows have been tested. Full simulations of both PWR and BWR plants have been achieved. Further efforts are concentrating upon advanced flow problems as well as improved models.

Investigators: Professors K.F. Hansen and J.E. Meyer; Dr. E. Depiante

Support: Department of Energy

Related Academic Subjects:

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

Recent References:

K.F. Hansen, E.V. Depiante, P.J. Laughton, J.E. Meyer, A.F. Henry, and L.H. Mweene, "Parity Simulation: An Electronic Approach to Simple Flow Systems," Comp. In. Mech. Eng., Vol. 5, No. 4, January 1987.

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

P.J. Laughton, "Parity Simulation Applied to Reactor Physics Nodal Theory Transient Analysis," Prof. 15th Annual Nuc. Sum. Symp., Canadian Nuclear Soc., May 1989.

3.1.3.5 Thermal Phenomena in Severe LWR Accidents

The initial two years of this research program were aimed at defining the cooling potential for a degraded LWR core. Subsequently, the focus has been on determining the containment thermal response to vessel melt-through, under severe accident conditions, and the fission product release potential during core-concrete interaction.

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

A semiempirical correlation was developed to describe the heat transfer at the horizontal core/concrete interface. The correlation was implemented in the CORCON-MOD 2 code of Sandia Laboratories, and used to analyze several experiments conducted both in the United States and Germany on fuel-concrete interaction. The modified CORCON was also used to assess the consequences of several accidents in various plants.

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

Investigators: Professor M. Kazimi; L.S. Kao

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 Heat Transfer

Recent References:

M. Lee and M.S. Kazimi, "Aspects of Severe Light Water Reactor Accident Analysis," EPRI NP-5403 (1987).

Lainsu Kao and M.S. Kazimi, "The Impact of Heat Transfer Models on Core/Concrete Interaction," Nuclear Technology, 78 (1987): 170-184.

M.S. Kazimi, "Recent Developments in Thermal-Hydraulics of Severe Accidents," Trans. Int'l Mtg. on Nuclear Power Plant Thermal Hydraulics and Operations, Vol. 1, Seoul, Korea, November 1988.

3.1.3.6 Accident Scenario Analysis in Risk Assessment

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

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

A deductive, digraph-oriented model has been developed and partially applied to the analysis of a loss of feedwater accident in a PWR. Due to combinatorial problems associated with this approach, continuing efforts are concentrating on an alternate approach, in which a dynamic event tree is constructed during the analysis.

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

Support: NRC

Related Academic Subjects:

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

Recent References:

K.R. Doremus, "Event Tree Linking Program: An Application of Prolog in Probabilistic Risk Assessment," S.M. Thesis, September 1987.

S. Nguyen, "Physical Dependencies in Accident Sequence Analysis," S.M. Thesis, May 1989.

3.1.3.7 Dynamic Human Error During Accident Sequences

A central feature of the dynamic response of the plant during an accident sequence is the behavior of the operating crew. This new project will develop models to treat the crew and will link these models to the accident sequence models being developed in the above project.

The crew models will extend current empirical models for treating individual operators to incorporate recent improvements in cognitive modeling. They will treat uncertainties in the operators' knowledge of the plant status, conflicting plant status indications, and the limited amount of resources available to perform required tasks. A simulation framework will be adopted to manage the interactions between the operators, and between the plant and the operators.

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

Related Academic Subjects:

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

3.1.3.8 Simulation Methods in Risk Assessment

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

A dynamic availability model has been developed using the SIMSCRIPT II.5 simulation language. This model can treat interactions between components governed by complex rules (e.g., those arising when repair resources are limited). The model can also accommodate the actions of control systems (these are often determined by the behavior of the continuous process variables being controlled).

Current research is directed at eliminating weaknesses in the simulation approach. These include the need to employ many simulation trials to treat the occurrence of rare events, and the lack of structural information in the results of a simulation analysis (which are needed to determine the major contributors to risk).

Investigators: Professor N. Siu; V. Dang

Related Academic Subjects:

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

Recent Publications:

D.L. Deoss, "A Simulation Model for Dynamic System Availability Analysis," S.M. Thesis, May 1989.

3.1.4 Nuclear Materials and Radiation Effects

The nuclear materials program has three major objectives: (1) to provide students in the Department with sufficient background in the principles of physical metallurgy and physical ceramics to incorporate a fuller consideration of reactor structural and fuel materials in their thesis programs; (2) to advance reactor materials technology in the areas of materials selection, component design, irradiation behavior modeling, 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.

3.1.4.1 Subjects of Instruction

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

22.070J Material for Nuclear Applications, is an introductory subject for students who are not specializing in nuclear materials. Topics covered include applications and selection of materials for use in nuclear applications, radiation damage, radiation effects and their effects on performance of materials in fission and fusion environments. The subject meets concurrently with 22.70J, but assignments differ.

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

22.71J Physical Metallurgy, 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 and subsequent courses are conducted jointly between the Department of Nuclear Engineering and the Department of Materials Science and Engineering.

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

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

3.1.4.2 Environmentally Assisted Cracking of Ni-Cr-Fe Alloys

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

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

Support: Electric Power Research Institute, Department of Energy

Related Academic Subjects:

22.71J Physical Metallurgy
3.54 Corrosion – The Environmental Degradation of Materials
3.39J Mechanical Behavior of Materials

Recent References:

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

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

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

M.J. Driscoll et al., "The MIT In-Pile Loops for Coolant Chemistry and Corrosion Studies," 1988 JAIF Int. Conf. on Water Chemistry in Nuclear Power Plants, April 19-22, 1988, Tokyo, Japan.

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

3.1.4.3 Modeling 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 Company to relate environmental factors to stress corrosion cracking susceptibility, including the effects of radiation.

Investigators: Professor R.G. Ballinger; Dr. A. Turnbull; M. Psaila-Dombrowski and J. Chun

Support: Electric Power Research Institute

Related Academic Subjects:

22.71J	Physical Metallurgy
3.54	Corrosion – The Environmental Degradation of Materials

Recent Reference:

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

3.1.4.4 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; M. Morra and F. Wong; Dr. I.S. Hwang

Support: Department of Energy

Related Academic Subjects:

22.71J	Physical Metallurgy
3.39J	Mechanical Behavior of Materials

Recent References:

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

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

M.M. Morra, "Alloy 908 – A New Low Coefficient of Thermal Expansion Alloys for Cryogenic Applications," S.M. Thesis, Materials Science and Engineering Department, MIT, June 1989.

M.M. Steeves et al., The US-DPC, "A Poloidal Coil Test Insert for the Japanese Demonstration Poloidal Coil Test Facility," 10th Int. Conf. on Magnet Technology, September 21-25, 1987, Boston, MA.

3.1.4.5 Irradiation Assisted Stress Corrosion Cracking

There is mounting evidence that the in-core radiation environment of light water power reactors can enhance the crack growth rate of core structural components. A basic understanding of this phenomenon is of importance in predicting the service performance of critical in-core components. Recently a proposal was funded for the research effort designed to develop a basic understanding of IASCC. This research program would include in-pile testing using the MITR-II. The proposal was requested by the Tokyo Electric Power Company (TEPCO).

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

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

Related Academic Subject:

22.71J Physical Metallurgy

Recent Reference:

Y. Komori, X. Mao, O.K. Harling, G.E. Kohse, R.G. Ballinger, and M.J. Driscoll, "Preliminary Design of the NRL IASCC In-Pile Test Rig," Report No. MITNRL-029, June 1988.

3.1.4.6 Radiative Corrosion Products in the Primary Coolant Systems of Light Water Power Reactors

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

Investigators: Professors O.K. Harling, M.J. Driscoll, D.D. Lanning, and R.G. Ballinger; Drs. J.A. Bernard and G. Kohse

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

Related Academic Subjects:

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

Recent References:

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

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

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

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

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

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

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

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

Support: Department of Energy, NORCUS

Related Academic Subjects:

22.71J	Physical Metallurgy
22.73J	Radiation Effects in Crystalline Solids
3.40J	Physical Metallurgy

3.1.4.8 Nuclear Chemical Engineering

Research in this area has been reinvigorated by activities associated with the design, installation, and operation of several in-pile loop facilities at the Nuclear Reactor Laboratory. In particular, loops capable of simulating reactor coolant conditions of both PWR and BWR systems are now operational, and in use for dose and corrosion reduction research sponsored by several US utility organizations, recently joined by a number of Japanese corporations.

The focus of the PWR coolant chemistry research is on optimization of pH control to minimize the transport and deposition of corrosion product radionuclides. While the primary strategy is to operate loops which are close physical analogs of a PWR core/steam generator tube flow cell, state-of-the-art computer models are also being employed, evaluated and improved.

BWR work is aimed at improving our understanding of coolant radiolysis chemistry-hydrogen peroxide formation in particular, because of its influence on electrochemical corrosion potential, and thus stress corrosion cracking. Again, experiments using an in-pile loop are the main thrust, but we are also making good use of prior and ongoing modeling work in our materials science program.

Investigators: Professors M.J. Driscoll, O.K. Harling, and R.G. Ballinger; Drs. G.E. Kohse and M. Ames; R. Sanchez, J. Outwater, C.-B. Lee, E. Cabello, J. Baeza, A. Esteves, and V. Mason

Support: Utility organizations (EPRI, ESSERCO, MIT-EUP) via NRL

Related Academic Subjects:

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

Recent References:

C. Oliveira, "Design and Proof-of-Principle Testing of an In-Pile Loop to Simulate BWR Coolant Chemistry," N.E. Thesis, Nuclear Engineering Department, MIT, December 1987.

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

E.D. Cabello, "Development of an Apparatus for the Determination of the Soret Coefficient for Cobalt Ions in High Temperature Water," S.B. Thesis, Nuclear Engineering Department, MIT, May 1988.

M.J. Driscoll, O.K. Harling, G.E. Kohse, and R.G. Ballinger, "The MIT In-Pile Loops for Coolant Chemistry and Corrosion Studies," in Proceedings of the 1988 JAIF International Conference on Water Chemistry in Nuclear Power Plants, Tokyo, April 19-22, 1988.

3.1.5 Quantum Thermodynamics

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

3.1.5.1 Subjects of Instruction

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

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

22.572J Quantum Thermodynamics, presents a nonstatistical unified quantum theory of mechanics and thermodynamics for all systems, including a single particle, and all states, including nonequilibrium, and an equation of motion for reversible and irreversible processes. Self-contained review of necessary background. Applications to fermious, bosons, black-body radiation, electrons in metals, crystals, rate processes, and relaxation phenomena.

3.1.5.2 Foundations of Quantum Thermodynamics

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

In June 1989, Professors Gyftopoulos and Gian Paolo Beretta submitted to their publisher the manuscript of a textbook on "Thermodynamics: Foundations and Applications."

Investigator: Professor E.P. Gyftopoulos

Support: None

Related Academic Subjects:

22.571J General Thermodynamics
22.572J Quantum Thermodynamics

Recent References:

E.P. Gyftopoulos and W.J. DiBartola, "Energy Conservation and Productivity Improvements in Steel Plants," Proceedings US-USSR Symposium on Energy Conservation, Moscow, USSR, June 6-12, 1985.

E.P. Gyftopoulos and G.P. Beretta, "What is the Second Law," Proceedings, IV International Symposium on Second Law Analysis of Thermal Systems, Rome, Italy (1987).

E.P. Gyftopoulos, "Energy," Lincoln Homework Encyclopedia, 1988 Edition.

E.P. Gyftopoulos, "Cogeneration-Resource Recovery," Proceedings European Conference on Development of Energy Conservation Technologies, Athens, Greece, pp. 217-223 (1988).

E.P. Gyftopoulos, "Temperature: a Matter of Degrees," Letter to the Editor, Physics Today, pp. 148-149, September (1988).

D. von Winje, K.F. Hansen, E. Beckjord, E.P. Gyftopoulos, M.W. Golay, and R.K. Lester, "Ursachen unterschiedlicher Verfügbarkeiten von Leichtwasserreaktoren in ausgewählten Industrieländern," VGB Kraftswerkstechnik 68, 82, pp. 1227-1232, December (1988).

K. Hansen, D. Winje, E. Beckjord, E.P. Gyftopoulos, M. Golay, and R. Lester, "Making Nuclear Power Work: Lessons from Around the World," Technology Review, pp. 30-40, February (1989).

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

E.P. Gyftopoulos, "The Temperature of a System with One Degree of Freedom," International Symposium on Thermodynamic Analysis and Improvement of Energy Systems," Beijing, China, June (1989).

3.2 Plasmas and Controlled Fusion

3.2.1 Theoretical Plasma Physics

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

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

3.2.1.1 Subjects of Instruction

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

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

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

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

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

22.602 Fusion Energy II discusses the basic engineering physics and technology of current fusion experiments and controlled thermonuclear reactors. Topics include operation of tokamaks, mirrors, alternate concepts; systems analysis and design of power reactors, ignition experiments, hybrid reactors; neutronics, blanket design, magnet design, first wall, materials and activation, heating technology, tritium handling, safety and environment.

22.611J Introduction to Plasma Physics I is an introduction to plasma phenomena relevant to energy generation by controlled thermonuclear fusion and to astrophysics. Coulomb collisions and transport processes. Motion of charged 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; Vlasov plasma model; electron plasma waves and Landau damping; ion-acoustic waves; streaming instabilities.

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

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

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

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

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

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

22.67 <u>Principles of Plasma Diagnostics</u> 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 <u>Plasma Laboratory</u> introduces the advanced experimental techniques needed for research in plasma physics and useful in experimental atomic and nuclear physics. Laboratory work on vacuum systems, plasma generation and diagnostics, physics of ionized gases, ion sources and beam optics, cryogenics, magnetic field generation, and other topics of current interest; brief lectures and literature references to elucidate the physical basis of the laboratory work.

3.2.1.2 <u>Theory of Magnetically Confined Fusion Plasmas</u>

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

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

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

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

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

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

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

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

Support: US Department of Energy

Related Academic Subjects:

22.601 Fusion Energy I
22.602 Fusion Energy II
22.611J Introduction to Plasma Physics I
22.612J Introduction to Plasma Physics II
22.615J MHD Theory of Magnetic Fusion Systems I
22.616 MHD Theory of Magnetic Fusion Systems II
22.64J Plasma Kinetic Theory
22.66 Plasma Transport Phenomena

3.2.1.3 Space Plasma Physics Theory

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

Digital Logic for Fluid Dynamics

This project is concerned with the development of algorithms in logic that can simulate realistic fluid dynamics. Such a "reduction of hydrodynamics to logic" has a strong philosophical motivation, of course, but its main purpose in this project is for the practical application of fluid dynamics simulation on the computer. It offers the promise of providing algorithms of sufficient simplicity that massively parallel computer architectures could be implemented to solve them in practical situations. This could open the door to the kind of massive parallelism that substantial improvements in fluid dynamics computing will require. The class of theories we develop are written in Boolean algebra--the language of the microchip--and offer the hope of being directly implemented at the hardware level without all the extremely complex layers of software and numerical analysis that present floating point computations require.

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

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

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

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

Investigators: Professor K. Molvig; Dr. G. Vichniac

Support: Office of Naval Research

Related Academic Subjects:

22.601	Fusion Energy I
22.602	Fusion Energy II
22.611J	Introduction to Plasma Physics I
22.612J	Introduction to Plasma Physics II
22.615J	MHD Theory of Magnetic Fusion Systems I
22.616	MHD Theory of Magnetic Fusion Systems II
22.64J	Plasma Kinetic Theory
22.66	Plasma Transport Phenomena

3.2.2 Experimental Plasma Physics and Fusion System Technology

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

3.2.2.1 Subjects of Instruction

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

3.2.2.2 Experimental Plasma Physics

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

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

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

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

Smaller scale experiments are also conducted both within the Plasma Fusion Center and outside. Nuclear Engineering students are actively involved in ongoing experiments involving RF heating and current drive on MIT's Versator II tokamak. In addition, collaborations have recently taken students to the Text tokamak and to fundamental plasma physics experiments at UCLA.

Investigators: Professor I.H. Hutchinson; Drs. D.B. Montgomery and R.F. Post; T. Hsu, R. Kirkwood, C. Petty, C. Tsui, K. Wenzel, and C.K. Li

Support: US Department of Energy

Related Academic Subjects:

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

Recent References:

I.H. Hutchinson, "Requirements for Ohmic Ignition," J. Fusion Energy 6, 257 (1987).

R.K. Kirkwood, I.H. Hutchinson, S.C. Luckhardt, and J.P. Squire, "Measurement of Superthermal Electrons in Tokamaks via Electron Cyclotron Transmission," to be published in Nuclear Fusion.

K.S. Chung, I.H. Hutchinson, B. LaBombard, and R.W. Conn, "Plasma Flow Measurements along the Presheath of a Magnetized Plasma," to be published in Physics Fluids B.

3.2.2.3 Fusion Reactor System Safety Studies

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

1) Magnet Safety Studies

The analysis of failure consequences is needed in the performance of a risk and reliability analysis of magnet systems. The consequences of two groups of electrical faults which originate in the poloidal field (PF) coil system (shorts between coil terminals and faults with constant applied voltage) have been investigated using a simplified model of the Compact Ignition Tokamak. It was found that shorts do not pose large risks while under selected scenarios with constant applied voltage the out-of-plane forces at the inner corner of the toroidal field (TF) magnets were found to increase substantially. For all scenarios, the type of plasma disruption had modest impact on the force distributions for the OF and TF magnets.

2) Lithium Fire Kinetics

A series of experiments has been conducted to characterize the kinetics of lithium reactions with mixtures of oxygen, nitrogen and steam. Lithium reaction rates with the various gas mixtures were determined as functions of the lithium temperature and the gas composition. In each experiment, gas of a desired composition was passed over lithium preheated to a specific temperature (between 400 and 900°C). It was found that the oxygen inhibited the nitrogen reaction rate by reacting much more quickly and keeping the nitrogen from the available lithium. Tests with steam and nitrogen indicate that the lithium-nitrogen reaction is catalyzed by the presence of steam and that little elemental hydrogen is generated.

The LITFIRE code was modified and used to model lithium chemical reactions with steam-air mixtures in situations representative of accidental spills in fusion reactors. New water pool nodes were added to the primary and secondary cells representing the reactor and its building. An iterative energy balance routine was developed to determine the temperature of the cell gas; heat transfer to structures was modified to include the effect of water condensation and the cell gas emissivity calculation was changed to account for the presence of polar water vapor molecules. Calculations were performed describing a spill on the building floor as well as a spill within the plasma chamber. Humidity and steam injection were also represented. The results indicated that the primary effect of the steam was to raise the emissivity of the cell gas, and thus the gas temperature and pressure, while reducing somewhat the temperatures of both the lithium combustion zone above the pool and the lithium pool itself.

3) Thermal Margin in Blankets

Activation and thermal safety analyses for experimental and power reactors were performed. The effects of a strong neutron absorber, B_4C, on activation and temperature response of experimental reactors to Loss-of-Cooling Accidents were investigated. Operational neutron fluxes, radioactivities of elements and thermal transients were calculated using the codes ONEDANT, REAC and THIOD, respectively.

The inclusion of a small amount of B_4C in the steel blanket of an experimental reactor reduces its activation and the post LOCA temperature escalation significantly. Neither the inclusion of an excessive amount of B nor ^{10}B enrichment in the first walls of an experimental reactor bring much advantage. The employment of a 2 cm graphite tile liner before the first wall helps to limit the post LOCA escalation of first wall temperature.

The impact of natural convection on the temperature response to a LOFA was analyzed, using the assumption that the secondary cooling cycle remains available during the transient. It was found that helium is a poor natural convection medium. In liquid metal cooled blankets, the impact was found to depend heavily on the post-accident behavior of the magnetic field. If the magnetic field remains at its operational value, then only $Li_{17}Pb_{83}$ experiences sufficient natural convection to have an impact on the temperature response. Natural convection in liquid lithium is suppressed due to the high MHD pressure drop. If the magnetic field experiences rapid reduction, such as two orders of magnitude in 30 minutes, then the natural convection impact is substantial. In both liquid lithium and $Li_{17}Pb_{83}$ cooled systems, the temperature decreases rapidly and levels out at a quasi-steady state value which is well below the temperature limits. For this reason, it is important to design super-conducting magnets such that they can experience a rapid field reduction.

Plasma overpower and continuation transients were also analyzed. In a plasma overpower transient, the plasma heat flux could increase well above the nominal level, with no corresponding increase in the cooling rate. In this case, there appears to be a threshold heat flux. Above this heat flux, the first wall will likely fail almost immediately. Below the threshold heat flux, the first wall will survive for some time. A plasma continuation transient occurs when cooling is lost but the plasma continues to burn. This can cause first wall failure in a matter of seconds. The heat transfer pathway from the first wall to the rest of the blanket has a large impact on the failure time. Both the overpower and continuation transients indicate the need for an automatic (or passive) plasma shut-off mechanism.

Investigators: Professors M.S. Kazimi and J. Meyer; Dr. S. Brereton; D. Hanchar, D. Lo, J. Massidda, S. Barnett, M. Zimmerman, and Y. Parlatan

Support: US Department of Energy, and EG&G Idaho

Related Academic Subjects:

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

Recent References

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

J.E. Massidda and M.S. Kazimi, "Aspects of Decay Heat Behavior in Fusion Reactor Blankets," Eighth Topical Meeting on the Technology of Fusion Energy, Salt Lake City, Utah, October 9-13, 1988.

D.S. Barnett, T.K. Gill, and M.S. Kazimi, "Lithium-Mixed Gas Reactions," Eighth Topical Meeting on the Technology of Fusion Energy, Salt Lake City, Utah, October 9-13, 1988.

D.S. Barnett and M.S. Kazimi, "The Consequences of Lithium Fires in the Presence of Steam," Eighth Topical Meeting on the Technology of Fusion Energy, Salt Lake City, Utah, October 9-13, 1988.

M. Zimmermann, M.S. Kazimi, et al, "On the Consequences of Electrical Failures of PF Magnet Systems for Fusion Reactors," Eighth Topical Meeting on the Technology of Fusion Energy, Salt Lake City, Utah, October 9-13, 1988.

S.J. Brereton, J.E. Massidda, and M.S. Kazimi, "Safety Comparison of Fusion Fuel Cycles," Eighth Topical Meeting on the Technology of Fusion Energy, Salt Lake City, Utah, October 9-13, 1988.

M.S. Kazimi, J.E. Massidda, and M. Oshima, "Thermal Limits for Passive Safety of Fusion Reactors," Eighth Topical Meeting on the Technology of Fusion Energy, Salt Lake City, Utah, October 9-13, 1988.

3.2.2.4 Plasma Engineering and Technology

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

1) Compact Ignition Tokamak (CIT) Design

There is active participation in a number of aspects of the design of the CIT, the next major tokamak planned in the US fusion program. The objective of this device is to obtain self-heated deuterium-tritium plasma operation, a milestone that is analogous to the achievement of the self-sustained fission reaction by Fermi and co-workers. It will use high-field, high performance copper plate magnets. The national CIT project draws heavily on the ignition experiments, concepts, and engineering approaches originated by the Plasma Engineering Group, particularly the Long Pulse Ignition Test Experiment (LITE) concept. Members of the group are currently working on the CIT project in the areas of magnet design, heating, and burn control. Concepts for obtaining a higher performance/cost ratio are also being developed, with particular emphasis on very strong ohmic heating and use of high aspect ratios.

2) Systems Studies and Superconductor Technology

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

3) Diagnostic Development

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

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

Support: US Department of Energy

Related Subjects:

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

3.3 Radiation Science and Technology

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

3.3.1 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.

3.3.1.1 Subjects of Instruction

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

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

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

22.113 <u>Nuclear and Atomic Collision Phenomena</u>, principles and applications of quantum theory of nuclear and charged particle collision-sections. Detailed study of partial wave and phase shift analysis, time-dependent perturbation theory, and Born approximation. Optical model description of nuclear reactions. Atomic stopping power. Thermal neutron inelastic scattering in condensed matter.

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

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

This new course will be offered in the spring term of 1990 by Professors S. H. Chen, D. Litster (Physics) and D. Blanckschtein (Chem. Eng.).

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

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

Subject 22.111 is taken by practically all the graduate students in the Department. Most of the undergraduates take 22.09 and many will take 22.02. All the doctoral students in Condensed Matter Sciences will take 22.113, 22.51, 22.53, and 22.59.

3.3.1.2 Neutron Spectrometry and Molecular Dynamics in Solids and Fluids

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

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

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

Investigators: Professor S.H. Chen; Drs. G. Briganti and P. LoNostra

Support: National Science Foundation

Related Academic Subjects:

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

Recent References:

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

W.B. Nelligan, D.J. LePoire, C.K. Loong, T.O. Brun, and S.H. Chen, "Molecular Spectroscopy of n-Butane by Incoherent Inelastic Neutron Scattering," Nucl. Inst. and Meth. in Phys. Research, A254, 563 (1987).

K. Toukan, M.A. Ricci, S.H. Chen, C.K. Loong, D.L. Price, and J. Teixeira, "Neutron Scattering Measurements of Wave-Vector Dependent Hydrogen Density of States in Liquid Water," Phys. Rev. A37, 2580 (1988).

K.F. Bradley, S.H. Chen, T.O. Brun, R. Kleb, W.A. Loomis, and J.M. Newsam, "The Design and Performance of QENS, A Medium Resolution, Inverted Geometry TOF Quasi-elastic and Inelastic Spectrometer at IPNS," Nuclear Inst. and Meth. A270, 78 (1988).

S.H. Chen, "Quasi-Elastic and Inelastic Neutron Scattering and Molecular Dynamics of Water at Supercooled Temperature," invited lectures given at NATO Advanced Study Institute on Hydrogen-Bonded Liquids, April 1989, Cargese, France. To appear as a vol. in Plenum Press.

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

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

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

Support: National Science Foundation

Related Academic Subject:

22.51 Interactions of Radiation with Matter

Recent References:

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J. Rouch, A. Safouane, P. Tartaglia, and S.H. Chen, "Static and Dynamic Light Scattering Studies of Water-in-Oil Microemulsions in the Critical Region. Evidence of the Cross Over Effect," J. Chem. Phys. 90, 3756 (1989).

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

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

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

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

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

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

Support: National Science Foundation

Related Academic Subject:

22.51 Interactions of Radiation with Matter

Recent References:

E.Y. Sheu, C.F. Wu, and S.H. Chen, "Effects of Ion Sizes on the Aggregation and Surface Charge of Ionic Micelles in 1-1 Electrolyte Solutions," J. Phys. Chem. 90, 4179 (1986).

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S.H. Chen, E.Y. Sheu, J. Kalus, and H. Hoffmann, "SANS Investigation of Correlations in Charged Macromolecular and Supramolecular Solutions", J. Appl. Cryst. 21, 751 (1988).

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

3.3.1.5 Atomistic Simulation Studies of Materials Properties and Behavior

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

Atomistic simulation has no difficulty in dealing with processes that are highly nonlinear, inhomogeneous, or nonequilibrium. They are therefore particularly effective for treating problems that are not amenable to analytical studies. As supercomputers become increasingly more powerful and available, the scope and significance of simulation studies will grow correspondingly.

Current problems under investigation fall into three main areas: structural and dynamical properties of interfacial systems such as grain boundary solids and free surfaces, fracture and mechanical properties of crack-tip systems, and phase transitions such as melting, vitrification (liquid to glass), and amorphization (crystal to glass). A number of these studies involve close collaborations with external colleagues at research laboratories. These interactions have proved to be very beneficial, not only in gaining access to scientific expertise and computational facilities not available at the Institute, but also in giving the students valuable exposure to different types of research environments.

<u>Investigators</u>: Professor S. Yip; K. Cheung; Drs. Tue Nguyen, D. Wolf, J.F. Lutsko, and S.R. Phillpot (Argonne)

<u>Support</u>: Argonne National Laboratory, IBM Watson Research Center, DOE Fellowship (1984-88), NSF Fellowship (1985-88)

<u>Related Academic Subject</u>:

22.53 Statistical Processes and Atomistic Simulations

<u>Recent References</u>:

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

This project is concerned with the study of transport and fluctuation phenomena in simple fluids which undergo a liquid-glass transition under rapid cooling or compression, and the study of point defect migration and clustering in crystals which undergo a transition to amorphous structures under irradiation. Molecular dynamics simulation is employed to investigate the atomic-scale behavior of density and current correlations in metastable fluids beyond the freezing density; it is also used to follow the structural relaxation of crystal lattices into which self-interstitials have been introduced and to determine the mechanism of amorphization.

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

Support: National Science Foundation, Argonne National Laboratory

Related Academic Subjects:

22.53 Statistical Processes and Atomistic Simulations
22.73J Radiation Effects in Crystalline Solids

Recent References:

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

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

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

S. Yip, "Comments on the Self-Consistent Model-Coupling Approximation," Journal of Statistical Physics, in press.

3.3.1.7 Structural Relaxation in Glassy Polymers

This project is part of a University Research Initiative Program on the study of mechanical properties of structural polymers with Professor A.S. Argon (Mechanical Engineering) as the Principal Investigator and other Co-Investigators consisting of Professors R.E. Cohen and U.W. Suter (Chemical Engineering), and D.M. Parks (Mechanical Engineering). The objective is to use molecular dynamics to study the glass transition in a polymeric system and to investigate the fundamental molecular processes pertaining to the phenomenon of ageing.

Investigators: Professor S. Yip; M. Sylvester

Support: Office of Naval Research/Defense Advanced Research Agency

Related Academic Subject:

22.53 Statistical Processes and Atomistic Simulations

Recent References:

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

D. Deng, A.S. Argon, and S. Yip, "Topological Features of Structural Relaxations in a Two-Dimensional Model Atomic Glass - II, " ibid.

D. Deng, A.S. Argon, and S. Yip, "Kinetics of Structural Relaxations in a Two-Dimensional Model Atomic Glass - III," ibid.

D. Deng, A.S. Argon, and S. Yip, "Simulation of Plastic Deformation in a Two-Dimensional Atomic Glass by Molecular Dynamics - IV," ibid.

M.F. Sylvester, S. Yip, and A.S. Argon, "Molecular Dynamics Simulation of Atactic Poly(propylene): Structural Differences Between the Liquid and Glass State," American Chemical Society Polymer Preprints 30 (1989), in press.

3.3.1.8 Interfacial Properties of Semiconductor Materials

This project is part of an MIT-IBM Joint Studies Program. The primary purpose of the project is to apply the techniques of molecular dynamics and Monte Carlo simulation to study the structure, energetics, and mechanical behavior of surfaces of silicon using empirical interatomic potential functions, and to address the problems of atom aggregation and cluster nucleation in the early stages of epitaxial growth. Of current interest is the question of stability and stress relaxations of single and double step surfaces on Si(100).

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

Support: IBM Watson Research Center

Related Academic Subject:

22.53 Statistical Processes and Atomistic Simulation

3.3.1.9 Molecular Dynamics Study of Icing on Cables and Structures

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

Investigators: Professor S. Yip; N. Sonwalker

Support: National Science Foundation, Electric Power Research Institute

Related Academic Subject:

22.53 Statistical Processes and Atomistic Simulations

3.3.2 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.

3.3.2.1 Subjects of Instruction

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

22.04 Radiation Effects and Uses, 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. The new undergraduate subject 22.055 meets with graduate subject 22.55J, but assignments differ.

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

22.57J <u>Radiation Biophysics</u>, 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. The new undergraduate subject 22.057 meets with graduate subject 22.57J, but assignments differ.

3.3.2.2 <u>Boron Neutron Capture Therapy for Brain Cancer</u>

A highly malignant type of brain cancer, glioblastoma, is fatal for 5000-6000 US residents each year. Conventional modalities of treatment are not effective in treating this cancer. Recently a major project leading to clinical trials has been funded. The approach is to use neutron capture therapy at the MIT research reactor to selectively destroy the malignant cells in high grade astrocytomas. Initially ten patients will be treated. If results are positive, expanded clinical trials will be initiated. Current efforts are focused on preclinical studies and on the development of an epithermal beam at MITR-II.

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

<u>Support</u>: US Department of Energy

<u>Related Academic Subjects</u>:

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

<u>Recent References</u>:

R.G. Zamenhof, S. Clement, K. Lin, C. Lui, D. Ziegelmiller, and O.K. Harling, "Monte Carlo Treatment Planning and High-resolution Alpha-track Autoradiography for Neutron Capture Therapy," Strahlenther. Onkol. 165, No. 2/3 (1989), 188-192.

O.K. Harling, S.D. Clement, J.R. Choi, J.A. Bernard, and R.G. Zamenhof, "Neutron Beams for Neutron Capture Therapy at the MIT Research Reactor," Strahlenther. Onkol. 165, No. 2/3 (1989), 90-92.

R.G. Zamenhof, H. Madoc-Jones, O.K. Harling, and J.A. Bernard, Jr., "A Multidisciplinary Program Leading to a Clinical Trial of Neutron Capture Therapy at Tufts-New England Medical Center and the Massachusetts Institute of Technology," Strahlenther. Onkol. 165, No. 2/3 (1989), 254-257.

3.3.2.3 Track ETCH and Autoradiograph Techniques for Application to Boron Neutron Capture Therapy

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

Investigators: Professors G.L. Brownell and J. Yanch; T. Nguyen

Support: National Institutes of Health

Related Academic Subject:

22.57J Radiation Biophysics

3.3.2.4 Collaborative Projects with Massachusetts General Hospital (MGH)

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

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

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

Investigator: Professor G.L. Brownell

Support: National Institutes of Health; US Department of Energy

Related Academic Subjects:

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

Recent References:

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

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

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

H. Kuzuka, D.R. Elmaleh, G.J. Boudreaux, H.W. Strauss, R.H. Ackerman, and G.L. Brownell, "N-[11C-methyl]Chlorophentermine and N,N-[11C-dimethyl]Chlorophentermine as Brain Blood-flow Agents for Positron Emission Tomography," J. Nucl. Med. 27, pp. 532-537, 1986.

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

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

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

C.A. Burnham, D. Kaufman, D.A. Chesler, C.W. Stearns, and G.L. Brownell, "Cylindrical PET Detector Design," IEEE Trans. Nucl. Sci., NS-35(1), pp. 675-679, 1988.

C.W. Stearns, C.A. Burnham, D.A. Chesler, and G.L. Brownell, "Simulation Studies for Cylindrical Positron Tomography," IEEE NS-35(1), pp. 708-711, 1988.

C.W. Stearns, D.A. Chesler, and G.L. Brownell: "Three-dimensional Image Reconstruction in the Fourier Domain," IEEE NS-34(1), pp. 374-378, February 1987.

E. Livni, J.P. Spellman, J.A. Correia, N.M. Alpert, G.L. Brownell, H.W. Strauss, and D.R. Elmaleh, "[C-11]MPTP: A Potential Tracer for Parkinson's Disease Research in Laboratory Animals," J. Nucl. Med. 27(10), pp. 1600-1603, 1986.

3.3.3 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.

3.3.3.1 Subjects of Instruction

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

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

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

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

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

22.55J 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 radio-pharmaceuticals. Principles of nuclear medicine. Requires a comprehensive term paper and presentation.

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

22.59 Principles of Nuclear Radiation Measurement and Protection, combines lectures, demonstrations, and experiments. Covers effects of radiation on persons, control of radiation exposure within applicable standards, theory and use of α, β, γ, and n detectors and spectrometers, use of isotopes, radiation shielding and dosimetry. Includes demonstrations and experiments using the MIT research reactor, accelerators, and power reactors. Assignments for graduate and undergraduate students will differ. Students will have choices in the experiments they perform.

3.4 Energy Economics and Policy

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

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

3.4.1 Subjects of Instruction

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

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

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

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

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

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

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

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

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

3.4.2 US Industrial Productivity

During the past two years, a major study of US industrial performance has been carried out by the MIT Commission on Industrial Productivity. The study, which involved faculty and students from 13 MIT departments including nuclear engineering, sought to identify the causes of recent weaknesses in US productive performance relative to its own earlier performance as well as the recent achievements of other major industrialized nations. Based on its research on eight major manufacturing industries in the US, Europe, and Japan, the Commission identified and analyzed several pervasive weaknesses in US industry and recommended actions to overcome these weaknesses by industry, government, and the educational system.

Investigators: Various; Professor R.K. Lester was Executive Director

Support: Sloan Foundation; Hewlett Foundation

Recent References:

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

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

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

3.4.3 Nuclear-Powered Submarines in Non-Nuclear Weapons States

During the past two years, three non-nuclear weapons states, Brazil, India, and Canada, have indicated an interest in acquiring nuclear-powered--but not nuclear-armed--submarines (SSN). Indeed, in February 1988, India acquired an SSN from the Soviet Union via a lease arrangement. Previously, the only countries that had SSNs were the five nuclear-weapons states. These actions raise the following issues: (1) What are the geopolitical implications of these actions; in particular, what is their impact on the international non-proliferation regime? (2) To what extent does the proliferation impact depend on the specifics of submarine-reactor technology, in particular, on the degree of enrichment of the uranium fuel?

Research on these issues was started in September 1987. In March 1989, an international conference on the subject of SSNs in non-nuclear weapons states was held at MIT with 40 participants from the US, Canada, France, Brazil, Ireland, and India. The proceedings of the conference as well as a book will be published in 1990.

Investigators: Dr. M. Miller; Professor D. Lanning; T. Ippolito and M. Morris (Political Science)

Support: Plowshares Foundation; Carnegie Corporation; NED

3.4.4 Nuclear Proliferation in the Middle East

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

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

A study of the subject was started in September 1988.

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

Support: American Academy of Arts and Sciences; a proposal for additional funding has been submitted to the Rockefeller Brothers Fund and the Carnegie Corporation

Reference:

A. Cohen and M. Miller, "Facing the Unavoidable: Israel's Nuclear Monopoly Revisited," Journal of Strategic Studies, August 1989.

3.4.5 Verification and Safeguards in Superpower Arms Control

Recently there has been increasing interest in the verification of treaties between the US and the Soviet Union on banning or restricting the production of nuclear weapons launchers or even the nuclear weapons materials themselves. A major issue in these discussions is the relevance of the safeguards procedures developed by the International Atomic Energy Agency (IAEA) to detect the diversion of nuclear materials in peaceful use in non-nuclear weapons states to the superpower verification problem.

We have studied these issues in two specific situations: (1) the detection of nuclear weapons; (2) limitations on the production of tritium.

Investigators: Dr. M. Miller; W. Stern

References:

M. Miller, "Tritium Verification and Safeguards," in *The Tritium Factor*, a workshop co-sponsored by the Nuclear Control Institute and the American Academy of Arts and Sciences, December 1988.

M. Miller et al., "Detecting Nuclear Weapons," *Science and Global Security* (to be published).

3.4.6 Nuclear Waste Management Technology

The prospects worldwide for greater acceptance of nuclear power are closely linked to the successful development and deployment of systems for the disposal of high-level nuclear waste. Constraints on facility availability limit the extent of departmental involvement in this area, but a modest level of work continues, in recognition of its importance.

In spring term 1988, the student design team in subject 22.33 Nuclear Engineering Design addressed the task of designing a HLW disposal system centered around a repository at the DOE-designated Yucca Mountain, Nevada, site.

Graduate theses were completed on two topics of current interest: the consequences of a further delay in US repository construction, and the compatibility of advanced reactor (MHTGR and LMR/IFR) fuel cycles with a repository system optimized for the once-through LWR fuel cycle.

Work has recently been initiated to assess the viability and benefits of actinide burning using the Integrated Fast Reactor (IFR) concept developed by ANL for disposal of actinides produced in thermal as well as fast reactors.

Investigators: Professors M.J. Driscoll and R.K. Lester; Dr. M. Miller; K. Yuracko, M. Siegel, W. Holloway, P. Morgan, and S. Vance

Support: Internal, and DOE Waste Management Fellowships

Related Academic Subjects:

22.35	Nuclear Fuel Management
22.77	Nuclear Waste Management
22.341	Nuclear Energy Economics and Policy Analysis

Recent References:

MITNE-281, "Design of a High-level Waste Repository System for the United States," Department of Nuclear Engineering, MIT, May 1988.

M. J. Siegel, "Economic Ramifications of a Delay in the National High-level Waste Repository System," Nuclear Engineering Thesis, Department of Nuclear Engineering, MIT, May 1989.

W. R. Holloway, "An Assessment of High-level Radioactive Waste Disposal for Advanced Reactor Fuel Cycles," S.M. Thesis, Department of Nuclear Engineering, MIT, May 1989.

S. A. Vance, "The Ramifications of a Delay in the National High-level Waste Repository Program," S.M. Thesis, Department of Nuclear Engineering, MIT, May 1988.

4. CURRICULUM

4.1 Degree Programs

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

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

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

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

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

4.2 Fields of Study

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

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

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

Fields 1-8 are appropriate for candidates for the doctor's degree. Doctoral candidates taking the General Examination required for that degree have the option of being examined in any one of these eight fields.

4.3 Subjects of Instruction

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

Undergraduate Subjects

22.U.R.	Undergraduate Research Opportunities Program
22.002	Management in Engineering
22.003	Nuclear War: Threat and Avoidance
22.006	Computer Models of Physical and Engineering Systems
22.011	Seminar in Nuclear Engineering
22.012	Seminar in Fusion and Plasma Physics
22.013	Applications of Radiation in Science, Technology, and Medicine
22.02	Introduction to Applied Nuclear Physics
22.021	Nuclear Reactor Physics
22.03	Engineering Design of Nuclear Power Systems
22.031	Engineering of Nuclear Reactors
22.033	Nuclear Systems Design Project
22.04	Radiation Effects and Uses
22.055	Biological and Medical Applications of Radiation and Radioisotopes
22.056	Principles of Medical Imaging
22.057	Radiation Biophysics
22.061	Fusion Energy I
22.062	Fusion Energy II
22.069	Undergraduate Plasma Laboratory
22.070J	Materials for Nuclear Applications
22.08	Energy
22.084	Inventions and Patents
22.088J	Human Factors in Design
22.09	Principles of Nuclear Radiation Measurement and Protection
22.091	Special Topics in Nuclear Engineering
22.092	Engineering Internship

Graduate Subjects

Nuclear Physics

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

Nuclear Reactor Physics

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

Nuclear Reactor Engineering

22.311	Energy Engineering Principles
22.312	Engineering of Nuclear Reactors
22.313	Advanced Engineering of Nuclear Reactors
22.314J	Structural Mechanics in Nuclear Power Technology
22.32	Nuclear Power Reactors
22.33	Nuclear Engineering Design
22.341	Nuclear Energy Economics and Policy Analysis
22.35	Nuclear Fuel Management
22.36J	Two-Phase Flow and 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
22.572J	Quantum Thermodynamics

<u>Numerical and Mathematical Methods</u>

22.42	Numerical Methods in Engineering Analysis
22.43	Advanced Numerical Methods in Engineering Analysis
22.44	Modeling and Simulation

<u>Radiation Interactions and Applications</u>

22.51	Interactions of Radiation with Matter
22.52J	Statistical Thermodynamics of Complex Liquids
22.53	Statistical Processes and Atomistic Simulations
22.55J	Biological and Medical Applications of Radiation and Radioisotopes
22.56J	Principles of Medical Imaging
22.561J	Magnetic Resonance – Analytic, Biochemical, and Imaging Techniques
22.57J	Radiation Biophysics
22.59	Principles of Nuclear Radiation Measurement and Protection

<u>Plasma and Controlled Fusion</u>

22.601	Fusion Energy I
22.602	Fusion Energy II
22.611J	Introduction to Plasma Physics I
22.612J	Introduction to Plasma Physics II
22.615J	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
22.66	Plasma Transport Phenomena
22.67	Principles of Plasma Diagnostics
22.69	Plasma Laboratory

<u>Nuclear Materials</u>

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

<u>General</u>

22.81	Energy Assessment
22.82	Engineering Risk-Benefit Analysis
22.821	Engineering Systems Analysis
22.841	Nuclear Weapons and Arms Control: Technology and Policy Issues
22.86	Entrepreneurship
22.901-4	Special Problems in Nuclear Engineering
22.911	Seminar in Nuclear Engineering (Fall)

22.912	Seminar in Nuclear Engineering (Spring)
22.913	Graduate Seminar in Energy Assessment (Fall)
22.914	Graduate Seminar in Energy Assessment (Spring)
22.92	Advanced Engineering Internship
22.93	Teaching Experience in Nuclear Engineering

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

Civil Engineering

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

Mechanical Engineering

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

Materials Science and Engineering

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

Electrical Engineering and Computer Science

6.013	Electromagnetic Fields and Energy
6.683	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-Energy Plasmas I
8.642	Physics of High-Energy Plasmas II

Chemical Engineering

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

Ocean Engineering

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

Economics

14.272	Industrial Organization II

Management

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

Mathematics

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

4.4 Independent Activities Period

The January Independent Activities Period was an extremely busy period for faculty, staff, and students. The department sponsored 10 official activities, including seminars (e.g., Professor Sow-Hsin Chen's "What is Interesting About Microemulsions," Professor Mujid Kazimi's "Fusion Technology Today and Tomorrow," Professor David Lanning's "Nuclear Engineering in the Future," Professor Neil Todreas' "MHTGR Thermal Hydraulics"), workshops (Professor Norman Rasmussen's "Wise Astute Guesses," Professor Nathan Siu's "But Will It Work?"), and field trips (e.g., a trip to the Pilgrim Nuclear Plant). The latter were organized by the MIT Student Chapter of the American Nuclear Society. Unofficial activities (not listed with the IAP Office) included a discussion of the Twin Paradox (Professor Allan Henry) and a computer workshop (Rachel Morton and Anne Hudson). By and large, the activities were well attended and judged to be successful by their organizers.

4.5 Undergraduate Research Opportunities Program

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

4.6 Changes in Nuclear Engineering Subjects

Since our last Activities Report, dated August 1987, the Department has introduced seven new subjects of instruction. Listed below are the new subjects, as well as those subjects that have undergone a change.

A. Subjects Introduced Since Last Report

22.055	Biological and Medical Applications of Radiation and Radioisotopes
22.056	Principles of Medical Imaging
22.057	Radiation Biophysics
22.44	Modeling and Simulation
22.52J	Statistical Thermodynamics of Complex Liquids
22.53	Statistical Processes and Atomistic Simulations
22.843J	Technology, Productivity, and Industrial Competition

B. Subject with Revised Content

22.36J	Two Phase Flow and Heat Transfer

C. Subjects with New Titles

22.51	Interactions of Radiation with Matter
22.571J	General Thermodynamics
22.71J	Physical Metallurgy

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

22.05	Introduction to Engineering Economics
22.071J	Physical Metallurgy Principles for Engineers
22.085	Introduction to Technology & Law
22.41	Numerical Methods of Radiation Transport
22.65J	Advanced Topics in Plasma Kinetic Theory
22.87J	Cases and Issues in Engineering Management

4.7 Undergraduate Program

4.7.1 Description of the Undergraduate Program

The undergraduate program in nuclear engineering provides engineering and science education related to the peaceful applications of nuclear processes. Three types of nuclear process applications are emphasized in the program's "tracks," or options, for undergraduate study: fission, fusion, and radiological sciences.

In the fission track, the processes are those related to the production of electrical power derived from the fission of heavy isotopes. The fusion track focuses on eventual power production from the fusion of light isotopes. In particular, technology topics are covered for understanding systems for plasma physics experiments in the short term and for power production in the long term. The radiological sciences track relates to medical applications of nuclear processes. These applications include biomedical imaging for diagnosis, and radiation capture therapy for medical treatments.

The objective of the nuclear engineering program is accomplished through a curriculum under which a student completes general MIT requirements and a departmental program. The departmental program includes background subjects (science and mathematics); engineering principles subjects (five subjects in fundamentals); nuclear engineering specialty subjects (laboratory, applied physics, and design/systems); and an S.B. thesis project. In this manner, the student is prepared for immediate employment at the S.B. level in the nuclear industry, for further graduate level training in nuclear engineering, or for entry into medical school.

4.7.2 Reviews and Revisions of the Undergraduate Program

During spring term 1988, we completed an extensive review of the Nuclear Engineering Department (NED) undergraduate program. The three-track structure of the program was retained (FI - fission; FU - fusion; and RS - Radiological Sciences). Major changes were adopted for the RS-track:

- switching to biology from physics as a background subject;
- defining a mostly new list of engineering principle subjects judged to be more suitable for the RS-track; and
- converting three previous NED graduate subjects to mixed undergraduate/graduate subjects and using these as design and system requirements.

The changes to FI and FU were largely evolutionary and included:

- increasing the emphasis on reactor engineering and decreasing nuclear physics content in subject 22.03 (engineering design of nuclear power systems); and
- providing an engineering principle elective (one from a list of three) to give some awareness that there are many "principles" topics that could or should be studied in the student's future (and yet must be omitted when the engineering principles list is restricted to five subjects by other demands of the program).

Other changes to the program are fairly minor. These include rule changes (adopted by MIT) regarding HASS (humanities, arts, and social sciences) selection and credit counting. Another new MIT breadth rule requires each student to enroll in a science distribution subject that is neither required nor taught by the student's department. Finally, NED reduced the number of options automatically available to the student in selecting some engineering principle subjects (e.g., thermodynamics). We had found that almost all students selected from a smaller subset anyway and that we could monitor changes made by other departments more easily.

During spring term 1989, we began preparation for an upcoming accreditation evaluation of our undergraduate nuclear engineering program. The evaluation will be performed by the Accreditation Board for Engineering and Technology (ABET) and will parallel evaluations of other programs in the MIT School of Engineering. An ABET team will visit MIT during fall term 1989. After the previous ABET visit in fall term 1983, our nuclear engineering program was accredited for six years. We have completed the first major step in the reaccreditation process by preparing a "self-study questionnaire for review of engineering programs."

4.7.3 Subjects of Instruction

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

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

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

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

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

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

22.03 Engineering Design of Nuclear Power Systems, introduces nuclear engineering as applied to power plant design. Basic principles of nuclear physics, reactor physics, and environmental health physics; engineering and heat transfer principles. Description of various reactor types for both standard and advanced concepts (e.g., LWR, HTGR, and LMR). Emphasizes reliability and reactor safety methods for improving design and operation of future reactors.

22.031 Engineering of Nuclear Reactors, engineering principles of nuclear reactors, emphasizing power reactors. Power plant thermodynamics, reactor heat generation and removal (single-phase as well as two-phase coolant flow and heat transfer), and structural mechanics. Engineering considerations in reactor design. Meets with 22.312, but examinations differ.

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

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

22.055 Biological and Medical Applications of Radiation and Radioisotopes, principles of radiation production and interactions. Radiation dosimetry, emphasizing 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. An advanced undergraduate subject that meets with graduate subject 22.55J. Same content but assignments differ.

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

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

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

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

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

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

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

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

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

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

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

4.8 Engineering Internship Program

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

The student is paid by the company for the work; however, it is intended that the assignments be valid learning experiences and not only a way to make money. The program provides for completing an S.M. thesis as part of the final work assignment.

A total of six students--two graduate and four undergraduate--are now in the program. Companies which have placed students from the Nuclear Engineering Department are Brookhaven National Laboratory, Commonwealth Edison, and EG&G National Laboratory.

4.9 Undergraduate Seminar Program

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

5. RESEARCH FACILITIES

5.1 MIT Reactor

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

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

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

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

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

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

Researchers at the NRL have received financial support from DOE, EPRI, NSF, NIH and MIT.

5.2 Computing Facilities

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

Recent additions to the equipment in the two computer rooms include both Macintosh systems and 386 generation computers. The MicroVAX II systems have been upgraded to the VAX III level. Additional terminals and larger, faster mass storage devices have been added.

The Project Athena workstations in our facility in 24-023A have served the computer needs of undergraduates enrolled in nuclear engineering courses. These VAX/UNIX systems will soon be available to graduate students as well, offering all students access to the Institute-wide network.

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

5.3 Nuclear Engineering Department Teaching Laboratories

The Nuclear Engineering Department teaching laboratories are specially equipped rooms located in Buildings NW12-133 and NW13-133. The NW12-133 (22.09/59 Principles of Nuclear Radiation Measurement and Protection) laboratory combines lectures, demonstrations, and experiments. The course covers effects of radiation on persons; control of radiation exposure within applicable standards; theory and use of α, β, γ, and η detectors and spectrometers; use of isotopes, radiation shielding, and dosimetry. Demonstrations and experiments using the MIT research reactor, accelerators, and power reactors are also included.

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

6. DEPARTMENT PERSONNEL

6.1 Faculty

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

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

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

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

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

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

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

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

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

Kent F. Hansen
Professor of Nuclear Engineering; Associate Director, Energy Laboratory; S.B. '53, Sc.D. '59 (nuclear engineering) MIT; Nuclear energy policy and management; nuclear plant operations and simulation.

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

Allan F. Henry
Professor of Nuclear Engineering; B.S. '45, M.S. '47, Ph.D. '50 (physics) Yale; Reactor physics; kinetics and design methods.

Ian Hutchinson
Professor of Nuclear Engineering; Head, Toroidal Confinement Division, PFC; B.A. '72 Cambridge University; Ph.D. '76 (plasma physics) Australian National University; Experimental plasma physics; controlled fusion.

Irving Kaplan
Professor 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.

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
Associate Professor of Nuclear Engineering; B.S. '74 Imperial College University of London; Ph.D. '79 (nuclear engineering) MIT; Nuclear power economics and policy analysis; nuclear waste disposal.

Lawrence M. Lidsky
Professor of Nuclear Engineering; B.E.P. '58 Cornell; Ph.D. '62 (nuclear engineering) MIT; Advanced fission and fusion reactor system designs.

Eric W. McFarland
Assistant Professor of Nuclear Engineering; B.S. '80, M.S. '82 University of California, Berkeley; Ph.D. '87 (medical engineering) MIT; M.D. '88 Harvard; Nuclear medical imaging; industrial applications of imaging technology; neutron therapy; nuclear magnetic resonance, imaging, and spectrosocpy.

John E. Meyer

Professor of Nuclear Engineering; B.S. '53, M.S. '53, Ph.D. '55 (mechanical engineering) Carnegie Institute of Technology; Structural mechanics; heat transfer and fluid flow.

Kim Molvig

Associate Professor of Nuclear Engineering; B.S. '70 Cornell; Ph.D. '75 (physics) University of California; Theoretical plasma physics.

Norman C. Rasmussen

McAfee Professor of Engineering; Professor of Nuclear Engineering; A.B. '50 Gettysburg; Ph.D. '56 (physics) MIT; Reactor safety; reliability analysis.

Kenneth C. Russell

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

Nathan O. Siu

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

Neil E. Todreas

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

Jacquelyn C. Yanch

Assistant Professor of Nuclear Engineering and Whitaker College; B.S. '81 (psychology), B.S. '83 (health and radiation physics), M.S. '85 (health and radiation physics) McMaster University; Ph.D. '88 (physics) University of London; Nuclear medical imaging; computational modelling in both therapy and image restoration; radiation health physics; neutron dosimetry.

Sidney Yip

Professor of Nuclear Engineering; B.S. '58, M.S. '59, Ph.D. '62 (nuclear engineering) University of Michigan; Atomistic simulations; condensed matter sciences; statistical mechanics; neutron scattering.

6.2 Complete Listing of Nuclear Engineering Department Personnel (as of August 1989)

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

Associate Professors
R.G. Ballinger (joint w/MS&E)
R.K. Lester
K. Molvig

Assistant Professors
E. McFarland
N.O. Siu
J. Yanch (joint w/Whitaker)

Senior Lecturer
F.X. Masse*

Senior Research Scientists
T.H. Dupree (joint w/Physics and Professor Emeritus)
M.M. Miller (joint w/CIS)

Principal Research Scientist
R. Lanza

Research Engineer
P. Stahle

Research Staff
R.M. Morton (Mgr., Computer Facilities)

Administrative Officer
J.B. deVries Gwinn

Administrative Staff
C.M. Egan (Graduate Office Administrator)

Support Staff
L. Arduino
P. Cornelio
A. Hudson
E. Kehoe
E. Ledgister
M. Levine
D. Lewis
L. Miltner
E. Parmelee
G. Rook
L. Sparks
L. Suter

Visiting Scientists
A. Turnbull
P. Lo Nostro

Research Affiliates
R. Christensen
J. Lutsko
V. Manno
B. Rosen
A. Schor
K. Smith
D. Trent
W.E. Vesely
L. Wolf

*Mr. Masse holds the primary appointment of Radiation Protection Officer at the Medical Department and the Bates Linear Accelerator Center.

6.2.1 Complete listing of jointly held faculty and academic research staff appointments in the NED, the loci of which are other departments, labs, and/or centers

Name	Appointment Title	Locus
D. Bruce Montgomery	Associate Director, PFC Senior Research Engineer, joint PFC/NED	PFC
D.R. Cohn	Head, Fusion Systems and Technical Division, PFC Senior Research Scientist, joint PFC/NED	PFC
J.E.C. Williams	Head, Magnet Technology Division, FBNML Senior Research Engineer, joint FBNML/NED	FBNML
K.C. Russell	Professor, Materials Science and Engineering, joint w/NED	MS&E
D.J. Sigmar	Group Leader, Theoretical Analysis Group, Toroidal Confinement Division, PFC Senior Research Scientist, joint PFC/NED	PFC

6.3 Complete List of Graduate Student Staff (as of Spring 1989)

Teaching Assistants

Broadbent, Gregory
Cheema, Mahmood
Cubukcu, Erol
Dobrzeniecki, Andrew
Duraski, Robert
Guimaraes, Alex
Hechanova, Tony
Ippolito, Tom
Iqbal, Asjad
Kim, Colin
Lui, Christiana
Nguyen, Son
Palmer, Matthew
Parlatan, Yuksel
Siegel, Matt
Taiwo, Ademola
Wang, Ling
Zhou, Xiaolin

Research Assistants

Acosta, Cris
Barakat, Abdel
Barnett, David
Bates, Jason
Betti, Riccardo
Bieri, Robert
Boerigter, Stephen
Brooks, Kenneth
Cabello, Ernesto
Chaniotakis, Emmanouil
Cheung, Kin
Choi, Richard
Chu, Tak Sum
Chun, John
Chung, Kyu-Sun
Crotinger, James
Dehbi, Abdelouahab
Eland, Bernice
Fox, Brian
Fricke, Stanley
Fu, Gang
Gormley, Robert
Grimm, Terry
Gung, Chen-Yu
Guo, Xuan Hui
Hakkarainen, Pekka
Han, Jian-Chiu
He, Weiguo
Herbelot, Olivier
Hiltz, Thomas
Hogan, Patrick

Research Assistants (cont'd)

Jacqmin, Robert
Khan, Arslan
Kim, Son Hwi
Kiryaman, Tugrulbey
Kupfer, Kenneth
Kurz, Christian
Kwok, Kwan
Lapp, Christopher
Lau, Eddy
Li, Chjikang
Liao, Chungpin
Luangdilok, Wison
Machuzak, John
Martin, John
McKinstry, Robert
McLoughlin, James
McMahon, Michael
Michael, David
Moore, Gregory
Neuder, Michelle
Nguyen, Tien
Offutt, Martin
Oshima, Marie
Outwater, John
Panych, Lawrence
Pendergast, Ken
Peng, Scott
Petty, Craig
Poon, Tze
Psaila-Dombrowski, Maureen
Reese, Timothy
Rhee, David
Sanchez, Rene
Siddique, Mansoor
Solares-Hernandez, Guido
Stewart, William
Tanker, Ediz
Teixeira, Chris
Tsui, Chi-Wa
Urbahn, John
Wang, Dan
Wang, Jinghan
Wang, Pei-Wen
Wei, Jiann
Wenzel, Kevin
Wong, Frank
Wu, Chuan-Fu
Zerkle, Michael
Zhang, James
Zolfaghari, Ali

7. DEPARTMENTAL STATISTICS (Summary)

Academic Year Sept-June	September Registration: Under-graduate	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	-
52 - 53	none	in	nuclear				none			2	4
53 - 54	-	8	-	8	-	4	-	-	4	2	5
54 - 55	-	20	-	20	-	13	-	-	13	2	5
55 - 56	-	46	-	46	-	10	-	-	10	3	6
56 - 57	-	74	-	74	-	32	-	-	32	5	7
57 - 58	-	93	1	94	-	31	-	2	33	6	8
58 - 59	-	95	6	101	-	44	-	7	51	8	12
59 - 60	-	102	6	108	-	32	-	5	37	10	14
60 - 61	-	112	10	122	-	25	1	7	33	10	16
61 - 62	-	118	8	126	-	34	-	11	45	13	17
62 - 63	-	109	8	117	-	27	1	12	40	15	20
63 - 64	-	103	10	113	-	20	2	13	35	15	21
64 - 65	-	124	6	130	-	24	3	14	41	16	24
65 - 66	-	125	6	131	-	30	3	15	48	16	25
66 - 67	-	122	6	128	-	28	11	22	61	18	26
67 - 68	-	132	4	136	-	27	2	13	42	17	27
68 - 69	-	127	3	130	-	35	6	14	55	18	28
69 - 70	-	128	-	128	-	31	8	22	61	20	28
70 - 71	-	111	3	114	-	27	4	14	45	19	37
71 - 72	-	117	1	118	-	20	2	19	41	20	35
72 - 73	-	115	1	116	-	29	5	14	48	18	42
73 - 74	-	127	2	129	-	32	12	8	52	19	49
74 - 75	-	138	7	145	-	38	4	7	49	19	52
75 - 76	20	182	2	204	-	39	8	24	71	22	58
76 - 77	33	188	2	223	2	37	10	23	72	24	61
77 - 78	47	170	3	220	11	57	18	20	106	23	63
78 - 79	41	172	1	214	11	40	10	15	76	19	58
79 - 80	39	170	1	210	11	40	8	19	78	21	55
80 - 81	35	154	2	191	10	34	7	20	71	24	62
81 - 82	37	154	1	192	6	25	3	19	53	23	64
82 - 83	33	164	0	197	12	28	4	15	59	24	67
83 - 84	27	164	3	194	9	36	11	29	85	26	70
84 - 85	18	162	0	180	8	27	2	18	55	24	71
85 - 86	25	148	0	173	9	28	3	30	70	24	58
86 - 87	20	150	1	171	6	32	3	20	61	25	66
87 - 88	22	148	0	170	3	29	5	13	50	25	85
88 - 89	28	150	1	179	6	29	3	13	51	23	84
				TOTALS	104	1074	159	497	1834		

8. STUDENTS

Chapter 8 presents statistical information about the 148 full-time graduate students registered in the Department during the spring term 1989. Table 8.1 catalogues the background of these graduate students according to their profession and country. It also contains a listing of the colleges attended by our domestic students prior to their graduate admission.

As noted in our last Activities Report, a large percentage of our graduate students enter the Department with a nuclear engineering background. This is followed by physics and electrical engineering majors.

The distribution of schools from which our domestic students are drawn is very widespread. Approximately 16% of our domestic graduates entered the Department with degrees from MIT. Our international student population represents 40% of our total graduate enrollment for the spring term 1989. This number has not changed since the last report.

Table 8.2 summarizes the various sources of financial support available for the spring term 1989. With assistance from the nuclear industry and other organizations, we have been able to maintain our level of support as in previous years.

The distribution of activities of our graduates is given in Table 8.3. The breakdown among the categories of National Laboratories, Teaching, and Industry has changed very little since our last Activities Report. A larger percentage of our recent graduates are pursuing further study. Figure 8.1 summarizes the distribution of types of first employment of our graduate students through June 1989.

Table 8.1

Background of Graduate Students Registered

in Nuclear Engineering Department (Spring 1989)

By Profession (148)

Aero & Astro (1)
Aerospace Engineering (1)
Applied Mathematics (1)
Applied Physics (1)
Basic Science (1)
Biology (2)
Biophysics (1)
Chemical Engineering (4)
Electrical Engineering (15)
Electronics (1)
Engineering Physics (1)
Engineering Science (2)
Geological Engineering (1)
Marine Engineering (1)
Materials Science (1)
Mathematics (3)
Mechanical Engineering (8)
Mechanics (1)
Nuclear Engineering (74)
Physics (27)
Systems Engineering (1)

By College (US citizens only) (90)

Air Force Institute of Technology (1)
Boston University (1)
California State Polytechnic University (1)
Carnegie-Mellon (1)
Colby (1)
Columbia (1)
Cornell (4)
Georgia Institute of Technology (3)
Georgia Southern College (1)
Harvard (2)
Iowa State University (1)
Kansas State University (3)
Michigan Technological University (1)
MIT (14)
North Carolina State (1)
North Park College (2)
Northeastern (2)
Penn State (1)
Princeton (1)
Purdue (2)
RPI (1)
Rutgers (1)
SUNY (1)
Texas A&M (1)
Tufts (1)
University of Arizona (2)
University of California (9)
University of Cincinnati (1)
University of Connecticut (1)
University of Florida (2)
University of Illinois (5)
University of Lowell (1)
University of Maryland (2)
University of Michigan (2)
University of Minnesota (1)
University of Missouri (1)
University of Tennessee (3)
University of Texas (2)
University of Virginia (1)
University of Utah (1)
University of Wisconsin (1)
UCLA (1)
USMA (1)
USMMA (1)
USNA (2)
Wheaton (1)

Table 8.1 (continued)

By Country (148)

Algeria (1)
Austria (1)
Brazil (1)
Canada (4)
Chile (1)
Egypt (1)
France (3)
Guatemala (1)
Iran (1)
Italy (2)
Japan (1)
Korea (3)
Nigeria (1)
Pakistan (2)
People's Republic of China (8)
Philippines (1)
Republic of China (15)
Saudi Arabia (1)
Thailand (1)
Turkey (8)
United Kingdom (1)
United States of America (90)

Table 8.2

Sources of Financial Support
(as of Spring Term 1989)

Research Assistantship (81)
Teaching Assistantship (18)
DOE Radioactive Waste Management Fellowship (3)
DOE Nuclear Science and Engineering Fellowship (4)
DOE Magnetic Fusion Energy Technology Fellowship (3)
Pickard, Lowe & Garrick (PLG) Fellowship (1)
Sherman Knapp Fellowship (1)
NASA Fellowship (1)
Theos Thompson Fellowship (1)
Manson Benedict Fellowship (1)
TRW Fellowship (1)
Argonne National Lab Fellowship (1)
INPO - Nuclear Engineering (1)
Materials Processing Center Fellowship (1)
Wolfe Fellowship (1)
SURDNA (1)
IPA Agreement (1)
Stone & Webster Fellowship (1)
U.S. Army (3)
U.S. Navy (4)
Government of Chile (1)
Government of Korea (2)
Government of Brazil (1)
Government of the Republic of China (3)
Government of Saudi Arabia (1)
Government of Turkey (4)
Self-supported (7)

Table 8.3

Activities of Nuclear Engineering Department Graduate Students

(Place of first employment--information current as of June 1989)

US Industry and Research (445) (28.1%)

Apollo Computer
Aerodyne Research Inc.
Aerojet Nuclear
Air Research Mfg. Co.
Allis Chalmers (2)
American Electric Power
Amer. Science and Eng.
APDA (2)
Assoc. Planning Res.
Atomics Int. (10)
AT&T Bell Labs (2)
Avco (6)

Babcock & Wilcox (8)
Battelle Columbus
Battelle Northwest (12)
Bechtel (5)
Bendix
Berkeley Research Associates
Bettis (4)
Booz, Allen & Hamilton
Boston Edison (2)
Burns & Roe (3)

California Oil
Colonial Management Associates
Combustion Eng. (21)
Commonwealth Edison (16)
Computer Processing
Conn. Mutual Life Ins.
Consolidated Edison (4)
Consultant
Consumers Power
Cornell University (research)
Creare Research & Development

Detroit Power Co.
Direct Energy Con. Lab.
Douglas United Nucl. (2)
Draper Lab
Duke Power & Light (2)
Dyntech R/D Co.

Ebasco (2)
Edgerton, Germ. & Grier
EDS Nuclear
EG&G (8)
Energy Awareness
EPM, Inc. (4)
EPRI
Exxon Research & Eng.

Fauske & Associates, Inc.

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

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

IBM (4)
Industrial Tech. Services Inc.
Inst. for Defense Analysis (2)
Internuclear Co.
Isotopes, Inc.

Jackson & Moreland
Jet Propulsion Lab

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

Table 8.3 (continued)

Management & Tech. Cons.
Martin-Marietta (3)
Mass. General Hospital (7)
Maxson Electric
McDonnell-Douglas
McKinsey & Co. (2)
Medisys
MIT (research) (28)
Mobil Oil
Monsanto
MPR Associates (3)

National Nuclear Corp. (2)
National Academy of Eng.
New England Nuclear Corp.
New England Power Service Co. (2)
New York Law Firm
North American Rockwell (2)
Northeast Utilities Serv. (4)
Northern Research & Eng. (3)
Nortronics
Nuclear Fuel Service (2)
Nuclear Mater. & Equipment
Nuclear Products
Nuclear Utility Services (4)
NUS Corporation (2)
NUTECH Engineers

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

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

Sanders Corp.
Science Applications (7)
Scientific Data Systems
Siemens Medical Systems
Sloan Kettering Mem. Hospital
Smithsonian Astrophys. Obs.
Southern Calif. Edison (4)
Spire Corp.
Stanford Research Institute
S.M. Stoller Assoc.
Stone & Webster (15)
Systems Sci. & Eng.
Systems Control

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

Union Carbide
United Aircraft (3)
United Eng. & Constr. (2)
United Nuclear (5)
U. of California (research) (3)
U. of Maryland (research)
U. of Texas (research)
U. of Wisconsin (research) (2)

Vacuum Industries

Wastechem
Watkins-Johnson
Westinghouse (32)
Wisconsin Electric

Yale (research) (2)
Yankee Atomic (19)

National Laboratories (105) (6.6%)

Argonne (18)
Brookhaven (7)
Knolls Atomic Power (19)
Lawrence Livermore (8)
Lawrence Radiation (5)
Los Alamos (16)
Oak Ridge (18)
Sandia (9)
Savannah River (5)

Table 8.3 (continued)

Further Study (277) (17.5%)

MIT (237)
Other (40)

US Government (226) (14.3%)

Atomic Energy Commission (22)
Air Force (17)
Army (89)
Army Nuc. Def. Lab.
Army Research Lab. (2)
Ballistic Research Lab
CIA (2)
Coast Guard
Dept. of Commerce
Dept. of Energy
Energy Res. & Dev. Admin. (5)
Environmental Prot. Agency (2)
NASA
National Bureau of Standards
Naval Research Lab
Navy (71)
Nuclear Regulatory Commission (5)
Peace Corps
Picatinny Arsenal
Dept. of Public Health

Teaching (69) (4.4%)

American Univ. (Washington, D.C.)
Brooklyn College (CCNY)
Calif. State (Long Beach)
Carnegie-Mellon University
Case Institute
Catholic University of America
Cornell
El Rancho High School
Georgia Institute of Technology
Howard University
Iowa State
Kansas State
Lehigh
Lowell Tech (4)
Loyola University
Mass. Maritime Academy
Michigan State University
MIT (13)
Northeastern University (2)
Northwest Nazarene
Pennsylvania State
Princeton
Purdue
Radford College
Rensselaer Polytech.
Swarthmore
Texas A & M (2)
US Military Academy
University of British Columbia
University of California (9)
University of Florida (2)
University of So. Florida
University of Illinois (3)
University of Kentucky
University of Missouri (2)
University of New Hampshire
University of Texas
University of Washington
University of Wisconsin (2)

Foreign (265) (16.7%)

Algeria (4)
Argentina (8)
Belgium (10)
Brazil (30)
Canada (15)
Chile (14)
Columbia, S.A. (2)
England (2)
France (27)
Germany (5)
Greece (6)
India (13)
Indonesia
Iran (26)
Israel (4)
Italy (5)
Japan (18)
Jordan
Korea (12)

Table 8.3 (continued)

Libya (1)
Malaysia (2)
Mexico
Morocco
Nigeria
Norway
Pakistan (4)
People's Republic of China
Philippines
Poland
Republic of China (17)
Saudi Arabia
Spain (14)
Switzerland (7)
Turkey (4)
Venezuela (5)

<u>Not Reported (197) (12.4%)</u>

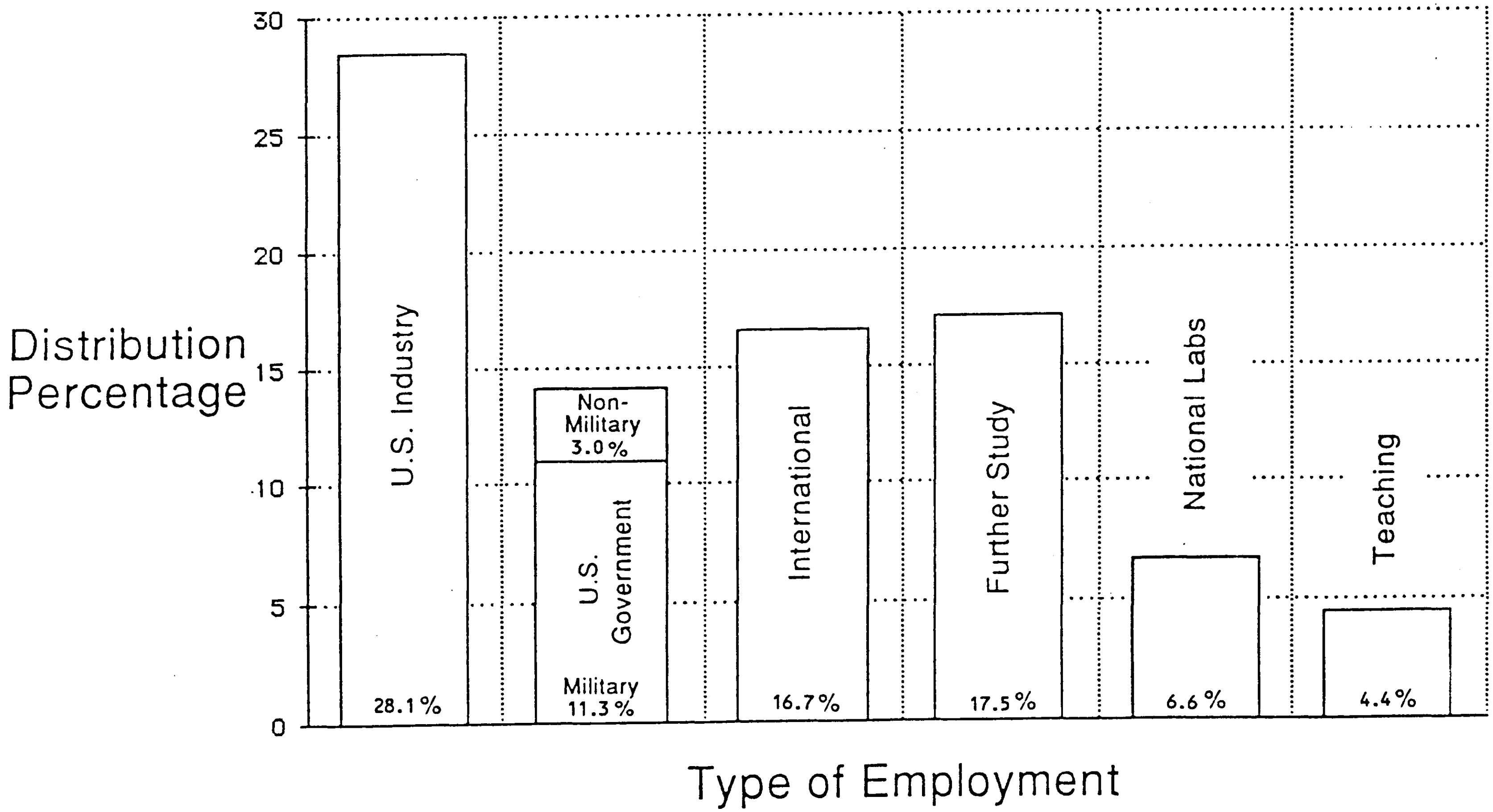
TOTAL 1584*

*Records from early years are incomplete

Figure 8.1

Distribution of First Place of Employment of Nuclear Engineering Graduates*

(as of June 1989)



* Excludes 197 (12.4%) Students Not Reporting

9. LIST OF GRADUATE THESES (SEPTEMBER 1987 TO JUNE 1989)

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

J.I. Choi, "Non-linear Digital Computer Control for the Steam Generator System in a Pressurized Water Reactor Plant," Ph.D. Thesis.

V.B. Dimitrijevic, "A Methodology for Incorporating Component Aging in System Reliability Calculations," Ph.D. Thesis.

K.R. Doremus III, "Event Tree Linking: An Application in PRA Using Artificial Intelligence," S.M. Thesis.

K. Elmediouri, "Development and Evaluation of Algorithms for PWR Fuel Assembly Shuffling," N.E./S.M. Thesis.

M.A. Islam, "Effect of Self Attenuation on the Shape of Venticular Time Activity Curves," S.M. Thesis.

T.S. Mogstad, "Stability Theory of Plasma Clouds About Large Space Vehicles," S.M. Thesis.

A.M. Morillon, "Modelling of Radionuclide Transport in a Simulated PWR Environment," S.M. Thesis.

E.E. Sasson, "Fluid Flow and Stratification in BWR Containment Cooling," S.M. Thesis.

D.C. Zraket, "Testing the Predictive Value of the One-Dimensional Transport Equation With a Diffuse Light Approximation in Predicting Light Flux in Tissue," S.M. Thesis.

The following theses were submitted to the Department of Nuclear Engineering in February 1988:

S.E. Cooper, "Uncertainty and Importance Analyses of the Reliabilities of Systems Experiencing Aging," Ph.D. Thesis.

R.L. Coxe, Jr., "Electric Utility Capacity Planning With Modular Generating Technologies," Ph.D. Thesis.

A.A. Dehbi, "A Two-Region Model for the Analysis of Steam Injectors," S.M. Thesis.

M.R. Helmick, "Vapor Condensation on a Turbulent Liquid Interface for Application in Low-Gravity Environments," S.M. Thesis.

H. Hsieh, "Defect-Induced Crystal-to-Amorphous Transition in an Atomistic Simulation Model," Ph.D. Thesis.

J.W. Keffer, "Passive Cooling of a Sealed BWR Containment," S.M. Thesis.

S.H. Lau, "Predictive Information as an Aid to Human Operators for Reactor Power Control," S.M. Thesis.

P.J. Laughton, "Parity Simulation Applied to Reactor Physics Nodal Theory Transient Analysis," Ph.D. Thesis.

J.E. Massidda, "Thermal Design Considerations for Passive Safety of Fusion Reactors," Ph.D. Thesis.

G.J. Moore, "Localized in Vivo 31P-NMR Spectroscopy for Clinical Applications," S.M. Thesis.

S.G. McInall, "Atomspheric Transport of Radionuclides Due to the Accident at the Chernobyl Unit 4 Nuclear Power Station," B.S./S.M. Thesis.

C.R. Lopes de Oliveira, "Design and Proof-of-Principle Testing of an In-Pile Loop to Simulate BWR Coolant Chemistry," N.E./S.M. Thesis.

S.E. Plomgren, "Alignment of Digitized Ocular Images for Planning Proton Radiation Therapy," S.M. Thesis.

C. Schmidt, "Economic Impact of the Three Mile Island Accident: A Case Study Analysis," Ph.D. Thesis.

O.P. Srinivasan, "Information Technology in Development – Implications for the Energy Sector in Less Developed Countries (LCD's)," S.M. Thesis.

T.L. Sowdon, "Prediction of the Response of Survey Instruments and Thermoluminescent Dosimeters to Beta Radiation Fields and the Measurement of Skin Dose," S.M. Thesis.

J.A. Vergara Aimone, "Low Cycle Fatigue of Alloy 718 in Cryogenic Environment," S.M. Thesis.

C.F. Wu, "Small Angle Neutron and X-Ray Scattering Study of Protein and Polymer Solutions," Ph.D. Thesis.

The following theses were submitted to the Department of Nuclear Engineering in June 1988:

A.I. Barakat, "Mixed Convection Plenum-Channel Interactions in a Vertical Heated Channel Connected to Upper and Lower Plena," S.M. Thesis.

E.V. Depiante, "Parity Simulation of Light Water Reactor Thermal Hydraulics," Ph.D. Thesis.

B.J. Eland, "Quantitative Lactate Imaging with Nuclear Magnetic Resonance," S.M. Thesis.

S.P. Hakkarainen, "Equilibrium and Stability Studies of Strongly Shaped Tokamaks," Ph.D. Thesis.

S.W. Haney, "Methods for the Design and Optimization of Shaped Tokamaks," Ph.D. Thesis.

I. Kato, "Use of Probabilistic Risk Assessment in Nuclear Power System Design Refinement," S.M. Thesis.

M.H. Kim, "The Use of Bilinearly Weighted Cross Sections for Few-Group Transient Analysis," Ph.D. Thesis.

N.S. Lizzo, "Prompt Gamma Activation Analysis of Boron 10 in Blood and Dosimetric Measurements Associated with Boron Neutron Capture Therapy," N.E./S.M. Thesis.

J.H. Musk, "The Scattering of Gamma Radiation from Hydrogeneous Media," S.M. Thesis.

J. Myczkowski, "Lattice Gas Hydrodynamics," N.E./S.M. Thesis.

T.W. Seubert, "Modular Shipbuilding and its Relevance to Construction of Nuclear Power Plants," S.M. Thesis.

G.R. Solares-Hernandez, "An Automated Computer Controlled Counting System for Radionuclide Analysis of Corrosion Products in LWR Coolant System," N.E./S.M. Thesis.

T.L. Turnipseed, "Public Utility Commission Structure and Decision Making," S.M. Thesis.

S.A. Vance, "The Ramifications of a Delay in the National High-Level Waste Repository Program," S.M. Thesis.

M.G. Woodruff, "Information Policy and Radiation Reporting During the Chernobyl and Three Mile Island Nuclear Accidents," S.M. Thesis.

The following theses were submitted to the Department of Nuclear Engineering in September 1988:

D. Chien, "Quantitative Magnetic Resonance Imaging of Proton Self-Diffusion and Microcirculation," Ph.D. Thesis.

Y. Chou, "Avoiding Steam Bubble Collapse Induced Water Hammer in Piping Systems," Ph.D. Thesis.

P.A. Donis, "Lattice Gas Hydrodynamics with Galilean Invariance," S.M. Thesis.

J.A. Izatt, "Ablation of Hard Biological Tissue Using Pulsed Hydrogen Fluoride Laser Radiation," S.M. Thesis.

P.W. Kao, "Application of Supernodal Methods to Transient Analysis," Ph.D. Thesis.

D.N. Kennedy, "Multiple Quantum Nuclear Magnetic Resonance Imaging," Ph.D. Thesis.

R.H. Miller, "Triggering and Termination of Whistler Emissions," Ph.D. Thesis.

D.Y.H. Rhee, "Ray Tracing for Millimeter/Submillimeter Wave Plasma Diagnostics," S.M. Thesis.

S.A. Simonson, "Modeling of Radiation Effects on Nuclear Waste Package Materials," Ph.D. Thesis.

The following theses were submitted to the Department of Nuclear Engineering in February 1989:

J.L. Baeza, "Refinement of an In-Pile Loop Design for BWR Chemistry Studies," S.M. Thesis.

S.T. Boerigter, "Optimization of Life Prediction Using Uncertain Data," S.M. Thesis.

E.L.L. Cabral, "Real-Time Three Dimensional Thermal-Hydraulic Model and Non-Linear Controller for Large PWR Cores," Ph.D. Thesis.

R.M. Gates, "Interaction of Hydrogen with Microstructures of Nickel-Based Alloys," S.M. Thesis.

A. Iqbal, "Measurement of Microdistribution of Radiolabelled Substances & Dosimetric Implications," S.M. Thesis.

K.S. Kwok, "Experimental Implementation of the MIT-SNL Period Generated Minimum Time Control Laws," S.M./S.B-2 Thesis.

C. Liao, "Ionospheric Plasma Modifications Caused by the Lightning Induced Electromagnetic Effects," S.M. Thesis.

C.A. Lobo, "Filling Strategies for Avoiding Water Hammer in Steam Filled Pipes," N.E./S.M. Thesis.

T. Nguyen, "Molecular Dynamics Study of Thermal Disorder in a Bicrystal Model," Ph.D. Thesis.

J.C. O'Shaughnessy, "Carbon Dioxide: An Evaluation of its Effectiveness as a Cover Gas in the Graphite Reflector of MITR-II," S.M. Thesis.

D.R. Rivas, "Thermal Plasma Instabilities Driven by Electrojet or Cross-Field Electric Currents in the Ionosphere," S.M. Thesis.

W.M. Stern, "Nuclear Weapons Material Control: Verification of Tritium Production Limitations," S.M. Thesis.

D. Wong, "Quantum Theory of Nonlinear Fiber Interferometer," S.M. Thesis.

M.L. Zerkle, "Reactivity Estimation Using Delayed Neutron Precursor Smoothing," S.M. Thesis.

M. Zimmermann, "Failure Modes and Effects Analysis of Fusion Magnet Systems," S.M. Thesis.

The following theses were submitted to the Department of Nuclear Engineering in June 1989:

A.A. Bednarczyk, "Nuclear Electric Magnetohydrodynamic Propulsion for Submarines," S.M. Thesis.

D.S. Barnett, "The Chemical Kinetics of the Reactions of Lithium with Steam-Air Mixtures," Ph.D. Thesis.

K.W. Brooks, "Application of the Point Synthesis Method to the Analytic, Nodal, Two-Group, Multidimensional Neutron Diffusion Equation," S.M. Thesis.

K.S. Chung, "Ion Collection by Probing Objects in Flowing Plasma," Ph.D. Thesis.

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