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ACTIVITIES IN NUCLEAR ENGINEERING AT MIT

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Prepared by the Staff of the
Nuclear Engineering Department
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I. INTRODUCTION

This report has been prepared by the personnel of the Nuclear Engineering Department at M.I.T. to provide a summary and guide to the Department's educational, research, and other activities. Information is presented on the Department's facilities, faculty, personnel, and students. The 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.

In the last two years there have been several factors which have reduced the projected demands for electricity. The Arab oil embargo and the fixing of oil prices by the OPEC countries have nearly tripled the cost of imported oil into the United States. Despite this, the United States has continued to grow and in several recent months imports rates have exceeded domestic production for the first time. During the period (1974-75) the United States economy has experienced a recession combined with a period of rapid inflation. One effect of the recession and increased costs has been that the historic growth rates in electric demand have leveled off for the last two years, mostly due to reduced industrial demand. In 1976, with the United State's economy recovering from the recession, initial indications are that electrical demands are increasing again. However, it is too early to tell whether these rates of growth will return to the historic rates of 6 to 7% per year. The reduction in projected demand has led to the cancelling or delaying of many power plant projects. Nuclear plants have been particularly hard hit because their capital investiment is larger than coal-fired plants. Very few new orders for domestic nuclear plants have been received for the last two years. In the rest of the world, particularly Europe and Japan where there is little coal available, nuclear orders have continued at a fairly high level. There seems little doubt that nuclear power will have to be an important part of the electrical generating capacity of most of the industrialized countries for the rest of this century. By that time, it is possible, but by no means assured, that geothermal, solar, and fusion may have reached the stage of development where they can begin to make contributions. Nevertheless, it must be recognized that at least for the next few decades coal and nuclear power must continue to be the prime sources of any increased electrical demand. In fact, the United States government has ordered that no new oil or gas-fired plants be built.

Today, there are 60 operating nuclear power stations; in 1976 they are expected to produce nearly 10% of the nation's electricity. In New England about 25% of all electricity is produced by nuclear plants. During 1976 the nuclear electric supply of the Chicago area reached 50%. Thus, although nuclear power growth has slowed in the last two years there seems little doubt that fission reactors will provide an increasing fraction of the electricity of the United States, Western Europe and Japan for the rest of this century.

By the turn of the century it is believed that domestic supplies of high grade uranium will be diminishing and the need for the breeder reactor, which uses uranium about 60 times more efficiently, will develop. This concept, which has already been demonstrated in France and Russia, offers great promise, for it uses U-238, the 99.3% abundant isotope of uranium, as fuel. To illustrate the importance of the breeder one only has to realize that the U-238 already mined and available in the tails from the diffusion plants represents more energy than the entire coal reserves of the United States. Thus, a successful breeder reactor program offers an electric supply with almost unlimited fuel supply.

A second possibility for future electric supply is the use of fusion reactions such as those which provide energy from the sun. The fusion program has the potential of deriving energy from the heavy hydrogen that occurs naturally in water. If successful, the oceans could become an unlimited supply of fuel. However, the engineering problems yet to be solved are extremely difficult. There seems little question that successful fusion will require the solution of the most difficult engineering problems that man has yet faced.

The Department of Nuclear Engineering conducts teaching and research in both the fusion and fission areas. In fission both the problems of present day fission reactors as well as future generation reactors are being investigated. Every attempt is made to provide the student with courses and research opportunities that will prepare him or her with the basic education needed to pursue a career in a growing and evolving industry.

Despite the fall-off in nuclear orders in the last two years, the demand for trained nuclear engineers continues to grow. The best projections available indicate that about 1,500 S.B. graduates and 500 to 800 advanced degree (S.M. and Ph.D.) graduates per year will be needed to support the nuclear industry. These numbers do not include the needs of the growing R&D programs in fusion. Today, the total United States supply of S.B. graduates is about 500 and the number of advanced Nuclear Engineering degrees being awarded is about 550. Currently the short-falls are made up by hiring engineers from other disciplines who have some nuclear courses. Because the demands are not expected to decrease for the next decade, it seems likely that there will continue to be a shortage of trained nuclear engineers for some time.

Student recognition of the need for trained nuclear engineers, at all levels, is apparent in the application statistics in our department. Table 1 shows the trend in applications versus time.

Table 1

Application for Admission
to M.I.T. Nuclear Engineering Department

Academic Year	1972/73	85
	1973/74	102
	1974/75	103
	1975/76	149
	1976/77	129

Table 2

Enrollment in M.I.T. Nuclear Engineering Department

1971/72	117
1972/73	113
1973/74	127
1974/75	139
1975/76	200*
1976/77	230 (estimate)

*includes special Iranian program and new Undergraduate program.

The size of our graduate enrollment is now limited by the availability of financial aid and faculty, rather than by the availability of qualified applicants.

The aid available to students has increased rather dramatically in the past years. In 1972/73 the Department had a sponsored research volume of $545,000. In 1973/74 the research volume was $734,000, while for 1974/75 the volume was $1,200,000. During the 1975/76 year the research volume reached $1,600,000. For 1975/76 we have 50 research assistants, which is a reflection of the "student-intensive" nature of the research within the Department. By virtue of the increased research support we have been able to increase our enrollment. There are indications that Federal support for graduate students particularly in the crucial area of energy, will increase in the future. Thus, we anticipate further modest increases in the graduate student body size.

The recognition of the importance of nuclear power as an alternative to fossil fuels has been made by foreign governments. We have been in discussions with representatives of the governments, or national utilities, of Brazil, the Republic of China, Iran, and Spain concerning their sending students to M.I.T. for training. These discussions have been initiated at the request of the foreign governments, and have already led to placement of 9 students from Brazil in the Department. In the fall of 1975 the Department initiated a special training program with Iran. In this program 22 Iranian students were admitted to a special two-year M.S. program. The Iranian government provided the additional support needed to cover the additional needs of this program. In the fall of 1976, 15 more students will enter this program.

The manpower needs clearly reflect the need for S.B. students in Nuclear Engineering. As a result, the Department introduced an undergraduate program in 1975. The first sophomore class in this program numbered 22. It is expected that in two more years the program will have between 60 and 80 undergraduates. The program has been able to use resources from several other Departments of the Institute. As a result, a minimum increased demand was placed upon the Department's resources. This program is described in Section 4.8.

In Section 2 of this report there is a discussion of developments within the Department since February 1975. Section 3 is a detailed discussion of our research and educational activities. Section 4 presents a discussion of our curriculum, including the S.B. program. Section 5 discusses the facilities of the Department as well as those available to the Department. 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, is a listing of theses completed since our last report.

2. SUMMARY OF DEVELOPMENTS SINCE FEBRUARY 1975

This section is a summary and discussion of developments within the Department since our previous report. The summary includes academic programs, research programs, special summer activities, the Department's contribution to the Institute-at-large, and recent honors to the faculty.

An important modification to our curriculum has been the introduction of an undergraduate program. The first year we had a total of 22 undergraduates. We anticipate another 20 students to register for the fall 1976 term, bringing our current undergraduate program up to between 40 and 45 students.

A major part of the requirements for this program consists of subjects already offered by other Institute departments. By using these available Institute resources, the program was introduced with little increase in the size of the Department faculty. Thus, only a limited number of new undergraduate nuclear engineering subjects were added to the program. The projections indicate that, when the undergraduate class reaches full enrollment in two more years, the program will involve about 60 to 70 students. A complete description of the undergraduate program may be found in Section 4.8.

In September 1975 a program was begun for the training of students from Iran. The program duration is to be for two years for two classes, each of approximately 25 students. Because of the number of students involved and the additional facilities needed, the program could only be established as a special program and not part of the regular on-going curriculum A full description of the Iranian Program is given in Section 4.7.

The academic program of the Department continues to undergo revision and updating. The growth of the fusion technology area, with strong support from ERDA, has brought the fusion and fission options closer together. This program addresses the difficult engineering problems that must be solved before fusion can become practical. The Department's expertise in nuclear materials, and in heat transfer and fluid flow gained in fission-oriented programs, has been of great benefit in attacking these practical fusion problems. In addition to fusion technology, the Department continues to have a strong plasma physics program. Professor James Woo offered a new course, Engineering Principles for Fusion Reactors (22.63) in the spring semester, 1976. This course is an introductory subject for advanced undergraduate and graduate students without previous background in principles and practices of systems relevant to controlled fusion. Another new subject to be taught by Professor L. Scaturro in the spring 1977 semester will cover fusion processes and their potential for energy production. This subject, Preparation for Plasma Physics (22.07) is one of the new subjects added to the curriculum as a result of the new undergraduate program.

Professor David D. Lanning has introduced a new subject, 22.001, Seminar in Nuclear Engineering. This subject was offered for the first time in the fall semester of 1975 and was attended by over 40 students. The new undergraduate subject is an introductory discussion of the basic phenomena of fission and fusion power and related aspects of reactor design.

Professor Gordon L. Brownell and Drs. Brian Murray and Donald Hnatowich revised the content of subjects relating to nuclear medicine. The new subjects are better integrated with the M.I.T. Health Sciences and Technology (HST) program. Relative to these revisions, a new subject will be offered in the fall 1975 semester, 22.56J, Biological and Medical Applications of Radiation and Radioisotpes II.

Two new subjects were offered by Professor Elias Gyftopoulos. These subjects present the foundations of classical thermodynamics following a newly developed approach.

Professor Norman C. Rasmussen offered a new subject in Reliability Analysis Methods (22.83) which covers the principles of the methods of reliability analysis including fault trees, decision trees and reliability block diagrams.

Professor Sow-Hsin Chen is introducing a new subject, Introductory Nuclear Measurements Laboratory, in the fall 1976 semester. The subject will include basic principles of interaction of nuclear radiation with matter.

Section 4.6 gives complete descriptions of new and revised subjects offered by the Department during the past 18 months.

The Department continues to offer a number of very popular special summer programs attended by a wide spectrum of professional people involved in nuclear engineering. The 310 registrants in Nuclear Engineering Special Summer Programs in 1975 accounted for 19 percent of the 1,635 registrants in all M.I.T. Special Summer Programs. Of the 1,809 registrants participating in M.I.T. Summer Programs in 1976, 432 were enrolled in Nuclear Engineering Special Programs, representing 24% of the total M.I.T. enrollment. Both the 1975 and 1976 enrollment exceeded that of any other Institute department.

These programs have proved to be a valuable method of establishing contacts between the Department and the various parts of the nuclear industry. The Nuclear Engineering Department offered seven such programs in 1976. The largest of these was a three-week program (22.94s, 22.95s, 22.96s) Nuclear Power Reactor Safety, under the direction of Professors Norman C. Rasmussen, Neil E. Todreas, and Arden L. Bement. Professor Gordon L. Brownell directed a very successful new summer program, 22.85s, Principles of Computerized Axial Tomography. This program had the second highest attendance of all programs in the Institute, reflecting the growing interest and research in computerized axial tomography (CAT) scanning. Dr. R. E. Zimmerman of the Harvard Medical School, with Professor G. L. Brownell and Dr. Brian Murray, directed the program 22.83, Principles of Nuclear Medicine. Professor Kent F. Hansen directed a two-week program on Nuclear Fuel and Power Management (22.98s, 22.99s). This program provides utility managers and practicing nuclear engineers with a rigorous and complete survey of the technical and economic methods available for analysis of the management of nuclear fuel. A new two-week program in fusion technology was introduced this summer, Principles of Controlled Fusion (22.80s) and Technology for Fusion Reactors (22.81s). This successful program was under the joint direction of Professors Lawrence M. Lidsky, Peter A. Politzer, David J. Rose and James T. Woo. The program offered a comprehensive and up-to-date review of both the principles and technology for controlled fusion. Professor David Rose also participated in the joint direction of 22.92s, Energy for Energy Decision-Makers, with Professor Ernest G. Cravalho of the M.I.T. Mechanical Engineering Department.

The M.I.T. Research Reactor was shut down on May 24, 1974 to begin the core modification to increase the neutron levels available to experimenters on the beam port by a factor of about 2.5. The MITR-II went critical again on August 10, 1975. The modification was directed by Professor David D. Lanning. Professor Otto K. Harling was appointed to the new position of Director of the M.I.T. Nuclear Reactor Laboratory on July 1, 1976. Mr. Lincoln Clark, Jr. continues to have responsibility for reactor operations in the new position of Director of Reactor Operations. This will mark the last year that the reactor will be the responsibility of the Department of Nuclear Engineering. After a careful review, it has been decided to designate the reactor as an Institute Laboratory and place it under the supervision of the Vice President for Research. One of the principal reasons for this change has been to make the reactor a more broadly-based Institute facility with the aim of increasing its research program. The modification of the MITR-II is discussed in detail in Section 3.5.

This year the research volume of the Department reached a new high of $1.6 million. Details of all research, both new and continuing, are given in Section 3. Below are listed only new projects with their sponsor and faculty participants.

(1) Finite Element and Flux Expansion - Electric Power Research Institute - Professor A. Henry

(2) Thermal Reactor Physics - Energy Research and Development Administration - Professors M. Driscoll, D. Lanning, D. Rose, and L. Wolf

(3) Rod-Drop Accident Analysis - Commonwealth Edison Company - Professor K. Hansen

(4) Hydrogen Economy Energy and Transmission Storage Technology - Energy Laboratory - Professor M. Golay

(5) Radioactive Corrosion Products in the Primary Coolant Systems of Light Water Power Reactors - Energy Research and Development Administration - Professors O. Harling, D. Lanning, R. Latanision, G. Yukic, Dr. W. Hinkle

(6) Surface Effects in Fusion Reactors - Energy Research and Development Administration - Professors O. Harling and J. Woo

(7) Bulk Irradiation Damage Studies to Simulate CTR Effects - MIT Energy Laboratory - Professors O. Harling and K. Russell

(8) Thermal Neutron Scattering Studies of Dense Gases - National Science Foundation - Professors S.H. Chen, S. Yip, and Dr. P.K. Tseng

(9) The Development of Radiation Synovectomy in Arthritis - National Institutes of Health - Dr. D. Hnatowich

(10) In Vitro Activation Analysis - National Institutes of Health - Dr. D. Hnatowich

(11) The Development of the Osmium-Iridium Radionuclide Generator - National Institutes of Health - Drs. D. Hnatowich and S. Kulprathipanja

(12) High Resolution Lyman-α Spectrometer - Energy Research and Development Administration - Profs. L. Lidsky and P. Politzer

(13) Energy Flux Measurements in Alcator - Energy Research and Development Administration - Profs. L. Lidsky, and P. Politzer

(14) Trapped Particle Instabilities - Energy Research and Development Administration - Profs. L. Lidsky, P. Politzer and L. Scaturro

(15) Experimental and Theoretical Studies of Radiation Damage - Energy Research and Development Administration - Profs. B. Mikic, O. Harling and K. Russell

(16) High Aspect Ratio Toroidal Reactors -EBT - Energy Research and Development Administration - Profs. P. Politzer and L. Lidsky

(17) Reactor Safety and Environmental Studies - Energy Research and Development Administration - Profs. N. C. Rasmussen and D. Rose

(18) Fusion Plasma Modelling and Reactor Synthesis - Energy Research and Development Administration - Prof. J. T. Woo

(19) Theoretical Determination of Local Temperature Fields in LMFBR Fuel Rod Bundles - Energy Research and Development Administration - Prof. L. Wolf

(20) Three Dimensional Transient Analysis Computer Code MEKIN Sensitivities Studies - Professors D. Lanning, L. Wolf, A. Henry, K. Hansen, and N. Todreas

In addition to these new projects, a number of well-established programs continue. A complete description of both the new and continuing programs can be found in Section 3.

Financial support for the Department's students has increased as a result of the high level of sponsored research. From a low of slightly over $0.5 million in 1972-73, the volume increased to $1.4 million in 1974-75, and this year reached nearly $1.6 million. These funds helped support the research of nearly 50 graduate students. The Department continues to benefit from more than a dozen traineeships from the Energy Research and Development Administration and a modest number of fellowships from other sources.

Department of Nuclear Engineering faculty continue to be active outside the Department, in both M.I.T. non-departmental activities and a variety of activities outside M.I.T. for professional societies and government agencies. Professor David Rose is a member of the steering committee of the National Academy of Sciences Committee on Nuclear and Alternative Energy Systems. This study, started in 1975 and presently scheduled to terminate in July 1977, has been undertaken by the National Academy of Sciences. The study addresses the broad question of Nuclear Power - Compared to What? from several points of view: technologies, demands, risk assessments, economic costs (and benefits), all as functions of time, out to approximately the year AD 2010. The Steering Committee has held a series of public hearings, set up four panels and presently is studying the merits and demerits of many energy alternatives, and plans to issue a preliminary report about 1 January 1977. Professor Rose continues to serve as an advisor to the Office of Science and Technology Assessment on matters concerning Federal energy budgets. He served as a member of the Organizing Committee for the AAAS Workshop on Adapting Science to Social Needs. The World Council of Churches continues to use him as a participant in their study on energy. This year he completed service on the Massachusetts Governor's Advisory Committee on Nuclear Energy. In addition to this, he has given numerous talks on energy options, including two appearances before Congressional committees. Professor Hansen was chosen by the Dean of Engineering to chair the newly-formed Committee on Engineering Education of the School of Engineering. This important committee is studying ways of improving the efficiency and effectiveness of engineering education at M.I.T. Professor Chen, while on a one-term sabbatical leave, was invited to give lectures at a number of leading laboratories of Western Europe on his internationally-renowned work on neutron and light scattering. He also spent part of this time as a Visiting Scientist at the Argonne National Laboratory. Professor Sidney Yip continued work on the computer simulation of molecular dynamics in fluids and solids at the Theoretical Physics Division of Lawrence Livermore Laboratory during the summer of 1975 and 1976. Professor Allan Henry continues his work as a member of the Advisory Committee on Reactor Physics for ERDA, and also as a member of the editorial advisory board of Nuclear Science and Engineering. Professor Michael Driscoll was on sabbatical leave during the past year. He remained on campus to pursue his ongoing research interests and to promote a new research project under the M.I.T. Energy Laboratory's ERDA-funded block grant. Professor Driscoll continues to serve on the M.I.T. and Boston Edison Pilgrim Unit I Reactor Safety Committees. He is also on the Lowell University Nuclear Engineering Department Visiting Committee. He has been elected vice chairman/chairman elect of the Reactor Physics Division of the ANS for 1976/1977.

Professor Neil E. Todreas continues as chairman of the American Society of Mechanical Engineers Heat Transfer Division's Committee on Nucleonics. Professor Elias Gyftopoulos directed a study for the National Science Foundation on government incentives for energy-conserving technologies in the paper and steel industries. He participated as a member of an M.I.T. team helping Spain in the establishment of a Spanish Institute of Industry. He accepted the invitation of his homeland to help them formulate their national energy program, in the role of Chairman of the National Energy Council of Greece. He also serves as a member of the Energy Task Force of the Commission on Socio-Technical Systems of the National Academy of Sciences. Professor Michael Golay was elected Vice Chairman of the Northeastern Section of the American Nuclear Society and a member of the American Nuclear Society Standards Committee, and Secretary of the Environmental Science Division. Professor John E. Meyer developed further the instruction in the area of structures and has been coordinating this program closely with other engineering departments, particularly the Department of Civil Engineering. He served as a Faculty Coordinator member of the Operating Committee of the M.I.T. Energy Laboratory starting December 1975. He has recently been elected Secretary of the Mathematics and Computations Division of the American Nuclear Society for a term from June 1976 to June 1977. Professor Sigmar was chosen as one of five United States delegates to the official US-USSR Scientific Exchange Program to visit the Kurchatov Institute for Plasma Physics, Moscow, April 1976. He also served on the U.S. Energy Research and Development "Panel on High Beta Theory", to help assess the current level of research in this area and to recommend future funding policies. Professor Irving Kaplan serves as Secretary to the M.I.T. Faculty. Professor Rasmussen continued his service on the Defense Science Board. He also serves as a member of the Review Committee for the Components Technology Division, Argonne National Laboratory. His work as director of the Reactor Safety Study (WASH-1400) for the U.S. Nuclear Regulatory Commission concluded with the issuance of the final report in October 1975. He has continued to give talks in the United States and in foreign countries to explain the results of the study.

The Department was particularly pleased that President Ford asked two of its faculty to serve on the Presidential Advisory Committee charged with helping to develop areas of work for the new Office of Science and Technology Policy. Professor Benedict was appointed to the Advisory Group on Anticipated Advances in Science and Technology, and Professor Rasmussen was appointed to the Advisory Group on Contributions of Technology to Economic Strength.

There have been a number of personnel changes in the Department during the past year. The Department was fortunate to obtain the services of Dr. John E. Meyer in August 1975. Professor Meyer will lead the Department activities in structures. Dr. Lothar Wolf, who was here as a Visiting Professor from the Technical University of Berlin (1974-75), has been appointed Associate Professor. He will continue to assist the Department in the fission reactor engineering area. Dr. Owen Deutsch has joined the Department as Assistant Professor and will assist in research and teaching in the area of nuclear physics. Dr. Louis Scaturro joined the faculty in June 1976. Dr. Scaturro is working closely with Professors Lidsky and Politzer and other members of the fusion area in experimental plasma physics and fusion technology. Dr. Otto K. Harling joined the staff as Senior Research Scientist and Visiting Professor to take on his responsibilities as Director of the M.I.T. Reactor Laboratory. Professor Lawrence M. Lidsky was promoted to Professor this year. In September 1976, Dr. Mujid Kazimi joined the Department as Assistant Professor. Professor Kazimi will strengthen the Department's program in fission engineering. Dr. James Woo spent the year here as Visiting Associate Professor. Dr. William E. Vesely of the NRC, appointed a Research Affiliate, contributes work in the reliability area. Dr. P.K. Tseng of the Taiwan University has been working with our neutron molecular spectroscopy project as a Visiting Scientist since last November. Professor Edward A. Mason continued his leave of absence as a Commissioner of the U.S. Nuclear Regulatory Commission. Professor Arden L. Bement started a two-year leave of absence to take on the job of Director of the Materials Research Program of the Defense Advanced Research Projects Agency. In his absence, Professor Lidsky will assume responsibility for the ERDA-sponsored Fusion Technology Program. Professor Dieter J. Sigmar will start a two-year leave of absence this September as a Senior Scientist in the Thermonuclear Division of the Oak Ridge National Laboratory to work on the Tokamak project of that laboratory.

Several of the Department faculty were recognized with honors. Professor Benedict received the National Medal of

Science and the Founders Award of the National Academy of Engineering. Professor Chen was elected a Fellow of the American Physical Society. Professor Driscoll was awarded the Outstanding Teacher Award of the Nuclear Engineering Division of the American Society for Engineering Education. He also received the Outstanding Nuclear Engineering Teacher Award from the American Nuclear Society student chapter and M.I.T. graduate study council for 1975. Professor Todreas received the Outstanding Teacher Award of the M.I.T. Student Chapter of the American Nuclear Society for 1976. Professor Rasmussen received the American Nuclear Society Special Award and the Distinguished Achievement Award of the Health Physics Society. As the result of a national competition, one of our outstanding graduate students, Mr. Glenn E. Lucas, won the Joseph Warren Barker Fellowship in Engineering, given by the Research Corporation of New York.

3. RESEARCH AND EDUCATIONAL ACTIVITIES

3.1 Reactor Physics

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

3.1.1 Subjects of Instruction

The basic subjects of instruction in reactor physics are offered in a three-semester sequence:

22.211, Nuclear Reactor Physics I, which 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, which deals with problems relating to the operation of nuclear reactors at power including few group and multigroup 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, which considers current methods for predicting neutron behavior in complex geometrical and material configurations, the transport equation and methods for solving it, systematic derivation of group diffusion theory, and homogenization, synthesis, finite element and response matrix techniques applied to reactor analysis.

Most students in the Department take at least the first two courses, and those whose special interests lie in the general area of nuclear reactor physics also take 22.213.

22.22, Nuclear Reactor Kinetics, deals with the dynamic behavior of neutrons in a reactor. Point kinetic formalisms, the physical significance of parameters appearing in point kinetics equations and analysis of methods for measuring ratios of these parameters are discussed. Also covered are methods for analyzing the dynamic behavior of neutrons when time and space are not separable: the direct finite space time difference approach, nodal methods, the application of orthogonal and non-orthogonal nodes, flux synthesis schemes, and problems in analysis of spatial xenontransients and reactor power transients involving feedback.

22.28, Introductory Nuclear Measurements Laboratory, which deals with the basic principles of interaction of nuclear radiation with matter. Statistical methods of data analysis; introduction to electronics in nuclear instrumentations; counting experiments using Geiger Müller counter, gas-filled proportional counter, scintillation and semiconductor detectors. Applications to experimental radiation physics, neutron physics, health physics and reactor technology.

22.29, Nuclear Measurements Laboratory, covers the experimental aspects of nuclear reactor physics and deals with the principles underlying instrumental methods for detection and energy determination of gamma rays, neutrons and charged particles. A number of laboratory experiments deal with various types of detectors, nuclear electronics, subcritical assembly measurements, gamma attenuation and pulse neutron techniques.

22.35, Nuclear Fuel Management, serves to bring together those aspects of nuclear reactor physics, engineering and numerical methods of solution which are required to characterize the space-time history of nuclear fuel and the effects on fuel cost.

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

22.42, Numerical Methods of Reactor Analysis is a subject in numerical and mathematical methods which deals with analytic and numerical methods useful in solving problems in reactor physics.

3.1.2 Reactor Theory

Much of the theoretical work on reactor physics carried out in the Department applies equally well to fast and to thermal reactors. This is true of the kinetics activities in Section 3.1.5. Another area being developed, at present for thermal reactors but potentially applicable to fast systems, is that of nuclear fuel management. Activities in this area are discussed in Section 3.2.4. Work on the purely thermal reactor problem of fuel element design for plutonium recycle studies is reported in Section 3.2.5.

Certain investigations, which when completed will be applicable to both fast and thermal reactors are being developed and tested first for thermal reactors since a thermal reactor offers more of a challenge to the approximation being investigated and since meaningful testing can then be done more cheaply using only a one or two energy group model. Studies of this nature include:

a) An investigation of systematic methods for determining equivalent homogeneous few group diffusion theory parameters: It has been found that the standard flux weighting procedure can lead to significant errors in the values of the homogenized parameters, and these errors then lead to corresponding errors in the predicted power shape throughout a reactor.. We have developed an alternative method for finding equivalent homogeneous parameters. The method is based upon finding parameters which reproduce the response matrices of regions being homogenized. Numerical tests show that the predicted power distribution throughout the reactor is improved in accuracy when the new parameters are used. We are currently refining the method further.

b) The response matrix technique for predicting reactor criticality and flux distributions: The response matrix technique has been tested for a two-dimensional cut of a pressurized water reactor controlled with large cross-shaped rods. The technique was used to do a depletion history of a slice of the core, and results were compared with a detailed fine mesh finite difference solution (used as the numerical standard) and with results of the usual design technique based on the use of homogenized group parameters to represent the fuel assemblies along with their associated control rods. The response technique seems to be about as accurate as the conventional depletion method based on the use of homogenized constants.

Since the method shows promise of being cheaper than the conventional scheme, we are continuing to refine it. Specifically, we are studying methods for extending it to three dimensions.

c) Cell stitching techniques: For several years we have been investigating a cell stitching technique, the basic idea of which is to represent the overall detailed flux shape throughout a reactor as a series of cell solutions for the subassemblies or clusters (wherein control rods, poison lumps and structural regions are represented explicitly) joined together by a smoothly varying, finite element type of flux shape. The scheme has now been successfully tested for a two-dimensional, two-group model of a reactor composed of subassemblies controlled by cross-shaped rods. The cell stitching is considerably cheaper than a full finite difference solution of the flux shape throughout the reactor. However, it is more expensive than a coarse-mesh nodal computation of the power distribution throughout a reactor. Because of this we do not intend to develop the cell stitching technique further at the present time.

d) Collocation Methods: During the past year we completed a study of a collocation method for determining the critical flux-shape and eigenvalue of a reactor. In this method the flux is expanded in finite element functions and that expansion is required to obey the defining equations at particular points (rather than in an element-weighted integral sense). The resultant equations are simpler to solve than the corresponding finite element equations. However our studies show that unless the collocation points are chosen with great care, unacceptable errors arise.

e) Albedo Boundary Conditions: During the past year a method was devised for representing the effects of a reflector surrounding a reactor by imposing a boundary condition at the core-reflector interface. When this boundary condition is applied, the flux in the reflector need not be computed. A saving of about 40% in running time is thereby obtained. The general theory of this method has been worked out and it turns out that for PWRs having a metal shroud between the core and the reflector, the boundary condition can be greatly simplified. In fact for a test case involving a large shrouded PWR, the flux shapes and eigenvalues of the core having an explicitly represented reflector and the core having a reflector represented by a boundary condition are essentially identical. We are continuing with the further development and testing of this method.

f) Block depletion techniques: Most methods for speeding up reactor computations (nodal methods, response matrix methods, cell stitching methods) become extremely complicated if the subassemblies within the reactor are depleted non-uniformly. Hence it is important that the so-called "block depletion" method, in which the average flux throughout an assembly is used to deplete the isotopes within that assembly, be applicable to these schemes. In addition, the block depletion method is used as a standard procedure with current reactor design methods. With the importance of the block procedure in mind, we have begun a study of its accuracy and of ways of improving that accuracy.

All of these developments are aimed at increasing the speed and accuracy with which predictions of neutron behavior within a reactor can be made. They will thus be applicable to standard design studies and (because of their greater speed) of considerable use for fuel management analysis. The long-range aim of the studies, however, is for application to space-dependent kinetics problems. Here the long running time of the standard finite difference technique makes it almost mandatory that more efficient methods for solving the group diffusion equations be found.

Investigators: Professor A.F. Henry; Messrs. P. Kalambokas, Y. Lukic, J. Mason, A. Perez, R. Quintana, B. Worley, S. Yang.

Support: USERDA (approximately $40,000/year); EPRI (approximately $20,000/year).

Related Academic Subjects

22.211 Nuclear Reactor Physics I
22.212 Nuclear Reactor Physics II
22.213 Nuclear Reactor Kinetics
22.41 Mathematical Methods of Reactor Analysis
22.42 Numerical Methods of Reactor Analysis
22.43 Advanced Methods of Reactor Analysis

Recent References

S. Yang, A.F. Henry, "Finite Element Synthesis Method", COO-2262-5, MITNE-171, May 1975.

J.H. Mason, A.F. Henry, "Collocation Methods for Solution of the Static Neutron Diffusion Equation", COO-2262-11, MITNE-180, November 1975.

B.A. Worley, A.F. Henry, "Determination of Equivalent Diffusion Theory Parameters", EPRI-305, August 1975.

P.C. Kalambokas, A.F. Henry, "The Replacement of Reflectors by Albedo-Type Boundary Conditions", MITNE-183, November 1975.

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S. Yang, A.F. Henry, Nucl. Sci. and Engr. Vol. 59, p 63 (1976).

J.G. Kollas, A.F. Henry, Nucl. Sci. and Engr. Vol. 60, p. 464, (1976).

3.1.3 Fast Reactor Physics Analysis

Research into the neutronics and photonics of the blanket region of fast breeder reactors has been underway at M.I.T. for over seven years now. For the first five years work was centered around experimental mockups in the Blanket Test Facility at the MIT Reactor. The prolonged reactor shutdown which began in May 1974 has led to an emphasis on analytical and numerical studies in the interim. However, experimental work has been carried out on the development of a readout device for interrogating the radiophotoluminescent response of thermoluminescent detectors. This will greatly facilitate gamma heating measurements in the future.

Recent work has been concerned with correlation of the economic and burnup characteristics of fast reactor blankets. Substantial progress has been achieved on simple models which permit rapid estimation of optimum blanket irradiation schedules as a function of the economic environment. Another major area studied has been the use of internal blankets in fast reactor cores -- an area pioneered at MIT and currently being given serious consideration both in France and in the U.S.

The blanket research program is in the first year of a projected three-year extension of its ERDA contract.

Investigators: Professors M.J. Driscoll, D.D. Lanning; Engineering Assistant A.T. Supple; Computer Operations Assistant R. Morton; Students J.I. Shin, A. Salhi, O.K. Kodiroglu, M.S. Kalra, S.S. Wu, M. Ketabi, D. Bruyer, R.A. Morneau, R.A. Pinnock, D.C. Aldrich, C.A. Chambers, J. Pasztor, S. Keyvan, D. Wargo

Support: U.S. Energy Research Development Administration (approximately $100,000 in FY 1977)

Related Academic Subjects:

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

Recent References:

M.S. Kalra, "Gamma Heating in Fast Reactors", Ph.D. thesis, MIT Nuclear Engineering Department, February 1976

R.A. Pinnock, "Parfait Blanket Configurations for Fast Breeder Reactors", S.M. Thesis, MIT Nuclear Engineering Department, June 1975.

C.A. Chambers, "Design of a Graphite Reflector Assembly for an LMFBR", S.M. Thesis, MIT Nuclear Engineering Department, August 1975

M. Ketabi, "The Breeding-Economic Performance of Fast Reactor Blankets", S.M. Thesis, MIT Nuclear Engineering Department, May 1975

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R.A. Morneau, "Improved Radiophotoluminescence Technique for Gamma Heating Dosimetry", S.M. Thesis, MIT Nuclear Engineering Department, September 1975.

S.S. Wu, "Experimental Verification of Breeding Performance in Fast Reactor Blankets", Nuclear Engineers Thesis, MIT Nuclear Engineering Department, June 1976.

D.C. Aldrich, "Parfait Blanket Systems Employing Mixed Progeny Fuels", S.M. Thesis, MIT Nuclear Engineering Department, June 1976.

A. Tagishi, *et al*. "The Effect of Reactor Size on the Breeding Economics of LMFBR Blankets", Ph.D. thesis, MIT Nuclear Engineering Department, Also, COO-2250-13, MITNE-168, February 1975.

M.S. Kalra and M.J. Driscoll, "Gamma Heating in LMFBR Media", COO-2250-18, MITNE-179, February 1976.

A. Tagishi and M.J. Driscoll, "The Effect of Core Size on Fast Reactor Blanket Performance", TANSAO, 21, June 1975.

M.J. Driscoll, ed. "LMFBR Blanket Physics Project Progress Report Number 6", COO-2250-21, MITNE-185, June 30, 1975.

O.K. Kadiroglu, *et al*. "Uranium Self-Shielding in Fast Reactor Blankets", Ph.D. thesis, MIT Nuclear Engineering Department; Also, COO-2250-17, MITNE-178, March 1976.

M. Ketabi and M.J. Driscoll, "The Breeding Economics of Fast Reactor Blankets", Trans. Am. Nucl. Soc. 22, Nov. 1975.

J.I. Shin and M.J. Driscoll, "Generalized Fissile Buildup Histories for FBR Blankets", Trans. Am. Nucl. Soc. Vol. 23, June 1976.

G.J. Brown and M.J. Driscoll, "Evaluation of LMFBR Blanket Configurations", Trans. Am. Nucl. Soc., Vol. 23, June 1976.

M.J. Driscoll, G.A. Ducat, R.A. Pinnock and D.C. Aldrich, "Safety and Breeding-Related Aspects of Fast Reactor Cores Having Internal Blankets" to be published in the *Proceedings of the International Meeting on Fast Reactor Safety and Related Physics*, Oct. 1976.

3.1.4 Thermal Reactor Physics

A project was initiated in June 1976 under the MIT Energy Laboratory's ERDA block-grant funding to determine whether significant reductions in LWR uranium ore consumption are possible by means of technological improvements such as thorium utilization. Changes in other core design parameters such as the ratio of lattice pitch to fuel rod diameter are also being investigated using state-of-the-art computer methods.

Systems analysis studies are being carried out to determine whether symbiotic fuel utilization strategies involving LWR's and LMFBR's can be of use in the next several decades during which both subsystems must undergo rapid growth. Constraints and advantages of the ex-reactor sectors of the thorium fuel cycle are also being evaluated.

This work is in the first year of a projected three-year program.

Investigators: Professors M.J. Driscoll, D.D. Lanning, D.J. Rose, L. Wolf, W. Hinkle; Computer Operations Assistant R. Morton; Students K. Garel, F. Abtahi, A. Salehi, B. Atefi, F. Correa, G. Andrade, O. Da Silva, H. Khan

Support: U.S. Energy Research Development Administration ad MIT Energy Laboratory (approximately $82,000 per FY)

Related Academic Subjects:

22.211	Nuclear Reactor Physics I
22.212	Nuclear Reactor Physics II
22.213	Nuclear Reactor Physics III
22.313	Advanced Engineering of Nuclear Reactors
22.35	Nuclear Fuel Management

3.1.5 Reactor Kinetics

The Department has had an active research program in the area of reactor kinetics for approximately nine years. The work has been sponsored by the USAEC (now USERDA). The type of transient conditions for which the work has been directed include both fast transients, such as are characteristic of reactor safety analysis, as well as slow transients, such as depletion effects and xenon oscillations. The physical model considered has been that of the multigroup diffusion theory model with space-dependence of varying complexity. Usually the space-dependence has been incorporated in the form of regionwise, homogeneous, few-group parameters. Nonlinear effects have been included in the studies for depletion and xenon oscillations.

The problems are of such complexity that direct solutions are impossible and numerical methods have been developed as part of the project. The work has progressed from one-dimensional finite-difference codes through three dimensional finite-difference codes. A variety of methods for temporal integration have been developed and used in industry for certain large-scale benchmark transient codes. In particular, a spinoff project from this work was a very large project developed for EPRI and reported under Section 3.1.7.

The work for the past year has concentrated on various forms of alternating-direction methods for integration of the time-dependent, finite-difference equations. These alternating-direction methods have included a variety of methods, including the so-called checkerboard scheme. As part of these developments the use of a nonlinear exponential transformation called a "frequency transformation" has been developed. We have looked at a variety of procedures for selecting the frequency and the particular form of the equations to be integrated.

In order to look at alternative temporal integrations, we have investigated various uses of the finite element method applied to the time-dependent problem. This work is continuing. We have also looked at applications of methods to reduce the number of spatial unknowns by use of the finite element method for space-dependence, and other schemes including the response matrix method for time-dependent problems. Preliminary testing indicates that for the same accuracy they are about an order of magnitude faster than conventional finite difference or finite element methods. Work in this vein is continuing on the project.

There are often time ranges during space-dependent neutron kinetics problems when the shape of the neutron flux changes little. A so-called point kinetics model is adequate for describing the transient within such ranges. Accordingly we have been investigating methods for switching back and forth from the (expensive) space-time description of a transient to the corresponding point kinetics description.

One final study in the area of reactor kinetics relates to the problem of measuring the degree of shutdown resulting from the insertion of control rods in a power reactor that has operated for some period of time. The background neutron level due to γ-n reaction in such a reactor is significant, and period measurements of reactivity must be run at a relatively high power level - so high, in fact, that temperature feedback effects may prevent attainment of an asymptotic period. We are examining the problem theoretically using a one-dimensional computer model.

<u>Investigators</u>: Professors K. F. Hansen and A. F. Henry. Messrs. C. Almeida, R. Chen, J. Hendricks, M. Todosow, B Worley, R. Sims, A. Shober, E. Fujita, S. Grill.

<u>Support</u>: USERDA (approximately $80,000 per year). EPRI (approximately $65,000 per year). Combustion Engineering (approximately $15,000 per year).

Related Academic Subjects

22.211, 22.212, 22.213 Nuclear Reactor Physics I, II, III
22.22 Nuclear Reactor Kinetics
22.41 Mathematical Methods of Reactor Analysis
22.42 Numerical Methods of Reactor Analysis
22.43 Advanced Methods of Reactor Analysis

Recent References

F. A. Kautz and L. O. Deppe, "CHD! A Two-Dimensional Multigroup, Rectangular Geometry, Cubic Hermite, Finite Element Diffusion Code", USAEC Report COO-2262-10, (June 1975).

John S. Hendricks, "Finite Difference Solution of the True Dependent Neutron Group Diffusion Equations", PhD Thesis, MIT Nuclear Engineering Department (August 1975).

Antonio C. M. Alvim, "Finite Difference Techniques for Solving Multidimensional Kinetics", PhD Thesis, MIT Nuclear Engineering Department (January 1976).

David A. Botelho, "Multidimensional Finite Element Code", PhD Thesis, MIT Nuclear Engineering Department (January 1976).

C. Almeida, "Use of Response Matrix Technique in Nuclear Reactor Kinetics", USAEC Report COO-2262-9, (October 1975).

3.1.6 Reactor Physics Constants for Safety Analysis

The Department has been carrying out research projects with the support of the MIT Energy Laboratory on investigation of the representation of transients in nuclear reactors. In particular, the research was directed toward representing control rod motions during transients. The simplest possibility would be to represent the control rod as a time-varying thermal absorption which is the principal effect of the control rod. However, the motion of the control rod does change the local spectrum and hence, changes all of the few-group constants. This research investigated whether the spectrum effect was sufficiently important that the control rod motion had to be represented by time-varying few-group parameters. The results suggested that the control rod motion could not be represented as simply a change in thermal absorption, but that the spectrum effect was very important. Thus, it appears that the transient effects in reactors cannot be well represented without taking into account shifts in the local spectrum.

Investigators: Professor K. F. Hansen, Mr. J. Olmos

Support: MIT Energy Laboratory Electric Power Program (approximately $20,000 per year).

Recent Reference:

J. Olmos and K. F. Hansen, "Light-Water Reactor Physics Parameters for Transient Analysis", MIT Energy Laboratory Report MIT-EL75-022 (June 1975).

3.1.7 Reactor Safety Codes

The analysis of transients in nuclear reactors is very complex and requires the use of very sophisticated computer programs to describe the sequence of events. The simulation is usually done with computer codes that represent the reactor core, the primary coolant system, the secondary coolant system, and various safety systems. The core simulation is needed to describe the energy production during the course of the transients. It is not possible to incorporate all of the details of the behavior of the system external to the core. The current state-of-the-art is to use a very conservative estimate of the time-dependent power shape in the core when the overall system dynamics are modeled.

We have been conducting a research project aimed at development of a computer code to represent the details of the neutronics and thermal hydraulics in a three-dimensional few-group model during reactor transients. This has led to a production code called MEKIN (for MIT-EPRI Kinetics). The code will be useful for analysis of fast transients in reactor cores, including such events as rod-drop accidents, rod-ejection accidents, anticipated transients without scram, and others. Approval has recently been received for the continuation of sensitivity studies of the MEKIN code when applied to transient analysis.

Investigators: Professors M. Golay, K.F. Hansen, A.F. Henry, N.E. Todreas, D. Lanning, and L. Wolf, Dr. J.W. Steward, Messrs. R. Bowring, J. Bartsis, A. Shober and R. Sims

Support: EPRI (approximately $230,000 per year)

Related Academic Subjects

22.213	Nuclear Reactor Physics III
22.22	Nuclear Reactor Kinetics
22.313	Advanced Engineering of Nuclear Reactors
22.36	Two-Phase Flow and Boiling Heat Transfer
22.42	Numerical Methods of Reactor Analysis

3.1.8 Rod-Drop Accident Analysis

The MEKIN code described in the previous section is useful for describing reactor transients including the rod-drop accident in the boiling water reactor. With support from the Commonwealth Edison Company, we have undertaken a project to analyze a rod-drop accident in a boiling water reactor. In particular, the work consisted of developing appropriate two-group homogenized constants for representing the reactor core at standby, zero-power condition. In addition, the representation of the rod-drop required determination of the time-dependent, few-group parameters.

The MEKIN code was then used to calculate the power excursion following such a rod-drop, including the effects of thermal-hydraulic feedback. The results have suggested that the previously used models have not adequately represented the effect of decay heat following the end of the transient. Thus, we predict higher fuel temperatures than the point kinetics models and others that have been used. However the results to date have been based on a limited number of computing calculations and much further work remains to be done. Nevertheless, the work has demonstrated both the importance and usefulness of the MEKIN code for analyzing space dependent transients in reactor cores.

Investigators: Professor K. F. Hansen and Mr. J. Valente.

Support: Commonwealth Edison Company (approximately $50,000 per year).

Related Academic Subjects

22.213 Nuclear Reactor Physics III
22.22 Nuclear Reactor Kinetics
22.313 Advanced Engineering of Nuclear Reactors
22.36 Numerical Methods of Reactor Analysis

Recent Publication: John Valente, "Multidimensional Modeling of the Rod-Drop Accident", Nuclear Engineers Thesis, M.I.T. Nuclear Engineering Department, April 1976.

3.2 Reactor Engineering

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

3.2.1 Subjects of Instruction

A total of fourteen subjects of instruction are offered under the category of reactor engineering by the Department, including a new course 22.43, Numerical Methods in Reactor Engineering Analysis. This subject will be offered in the spring of 1977 by Professor Sidney Yip. The following paragraphs present a description of all of the subjects in reactor engineering.

22.03, Engineering of Nuclear Power Reactor Systems, an undergraduate offering for students interested in a minor program in Nuclear Engineering. It applies engineering fundamentals to analyze the system design of current U.S. central station power reactors. Topics covered include: the elementary economic aspects of electric power generation; heat generation, transfer, and transport; radiation protection and safety analysis.

22.311, Engineering Principles for Nuclear Engineers, 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, transport phenomena and structural mechanics, with examples of applications to nuclear power systems.

22.313, Advanced Engineering of Nuclear Reactors, is intended for students specializing in reactor engineering. Emphasis is placed on analytic techniques for steady state and accident analysis on central station and advanced power reactors. Topics treated include thermal design methods, core reliability analysis, engineering analysis of transients and loss-of-coolant accidents, liquid metal heat transfer and fluid flow, and mechanical design and analysis.

22.314, Structural Mechanics in Nuclear Power Technology. has two main purposes. First, it provides an introduction to pertinent structural mechanics techniques for nuclear engineering students. Second, it permits a student from another department who is familiar with structural mechanics to learn how his knowledge may be applied to nuclear power technology. Two sets of tutorial lectures are used to supplement the main series of lectures, one set in structural mechanics for the former group of students, another set in nuclear reactor fundamentals for the latter group.

The main series of lectures covers components and structures in nuclear power plant systems including: their functional purposes; mechanical, thermal and radiation operating conditions; design requirements; design criteria and limits. Other topics include unique problems in the analysis of stress and strain, deformation, stability, shake down and limit load of typical power reactor components and structural systems. Internal loading during operational and accident conditions, and external loading from seismic and aircraft impact are considered.

22.32, Nuclear Power Reactors, is a 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 the thermal 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 Reactor Design, is a project-oriented subject for second-year graduate students in which they carry out a fairly complete system design and analysis of a specific nuclear power plant. By this means the students are given the opportunity to assemble what they have learned elsewhere about reactor physics, engineering principles, properties of materials and economics to accomplish desired objectives. The necessity for making trade-off decisions among conflicting requirements is stressed. During the past year, for example, the design project focused upon the feasibility of a nuclear-powered total energy system for the greater Boston area. The analyses included power plant siting, economics, power plant safety and environmental problems, LOCA-related risk analysis, and air pollution alleviation, among other topics.

22.34, Economics of Nuclear Power, first presents the principles of engineering economics, including current and capitalized costs, depreciation, treatment of income taxes, rates of return and the time value of money. The structure of the electric power industry is described briefly, and the roles appropriate to conventional thermal generating stations, hydro-electric and pumped storage installations and nuclear power plants are taken up. The capital, operating and fuel cost information on different reactor types is presented. Uranium and plutonium requirements of converter and breeder reactors are described in relation to uranium resources. The economics of uranium enrichment and other steps in the nuclear fuel cycle are treated. Likely growth patterns for the nuclear power industry are developed.

22.35, Nuclear Fuel Management, is a subject developed to prepare students for work in the area of nuclear fuel economics and management. The subject deals with the physical methods and computer codes which have been developed for predicting changes in isotopic concentrations during irradiation of nuclear fuels. In addition, the important topics of reactivity changes, power density distribution changes, and constraints are also considered. Additional topics discussed in the subject include problems of utility power system management for systems containing nuclear plants, optimization methods, and economic factors in nuclear fuel managment.

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

22.37, Environmental Impact of Nuclear Power, deals with the assessment of the effects of modern nuclear power plants, including radioactive pollution, and radioactive waste disposal. Special attention is paid to reactor safety and the risks to society of nuclear accidents. Possible future improvements are considered and comparisons are made with other power generation methods including solar and fusion power.

22.39, Nuclear Reactor Operations and Safety, deals with the principles of operating power and research reactors in a safe and effective manner. Practical experience is provided through demonstrations and experiments with the MIT Reactor. Other topics taken up include operating experience with power reactors; control and instrumentation; criticality and startup considerations; and refueling. All topics are combined with reactor safety. Past accident experience is discussed with emphasis on safety lessons learned. The reactor licensing procedures are reviewed with consideration of safety analysis reports, technical specifications and other NRC licensing regulations.

22.43, Numerical Methods in Reactor Engineering Analysis is a new subject in which numerical methods used in the analysis of nuclear reactor engineering problems are studied. Topics include finite difference and finite element formulations in solution of heat conduction, fluid dynamics, structural component design, and transient system analysis problems.

22.83, Reliability Analysis Methods, includes a discussion of analytic methods for reliability analysis such as fault tree and decision tree methods. Procedures for creation of particular reliability block diagrams for physical systems will be considered. Applications to safety analyses of light water reactor systems will be incorporated into the syllabus.

In addition to regular courses, the Department has offered each year for the past nine years special summer programs 22.94s, 22.95s, and 22.96s, a three part course on Nuclear Power Reactor Safety. The programs are concerned with safety aspects of both thermal and fast power reactors and take up such topics as reactor materials, reactor core characteristics, reactor transients, heat removal under normal and emergency conditions, reactor containment, fission product release, waste disposal, safety analysis, and the licensing procedure. Lectures are given by authorities from universities, the national laboratories, equipment manufacturers, and the NRC Division of Licensing and Regulation. In addition, speakers from the United Kingdom and France lecture on the safety philosophies of the fast reactor programs in those countries. Individuals from many electric power companies, industrial concerns, universities and government agencies, both U.S. and foreign participate in these programs. The variety of topics discussed and points of view represented provide an excellent opportunity for advancing understanding of the goals of reactor safety and are a useful contribution to the development of nuclear power. These summer programs are under the direction of Professors Rasmussen, Todreas and Bement.

A special summer program, 22.98s, 22.99s, Nuclear Fuel and Power Management is also offered by the Department. The program presents a summary of the technical and economic aspects of all steps in the nuclear fuel cycle. In addition, engineering factors such as behavior of materials, radioactive waste disposal, and environmental effects of the nuclear fuel cycle are considered. Techniques and results for the analysis of in-core fuel management of light water reactors are considered in great detail. In addition to class discussions, there are workshops for participants to learn to use the present generation nuclear codes. Matters pertaining to power systems management are also considered, along with models and methods for the analysis of such systems. The program is under the direction of Professor Kent F. Hansen. Scientists, engineers, and managers from electric utilities, reactor vendors, government agencies, and universities have participated in the fuel and power system management program.

3.2.2 Reactor Thermal Analysis

The Department's program in reactor thermal analysis is focused on research in the following areas:

1) coolant and energy mixing in rod bundles,
2) fluid dynamic modeling of forced-buoyant flows in reactor vessel plenums,
3) theoretical determination of local temperature fields in LMFBR fuel rod bundles,
4) thermal design of fusion reactor blankets.

(1) Coolant and Energy Mixing in Rod Bundles

An experimental and analytical program has been continued under ERDA sponsorship on investigation of coolant and energy mixing in fast reactor rod bundles. Significant contributions to understanding performance of fuel, blanket and poison rod bundles are possible through detailed theoretical and experimental study of flow structure and energy transfer in rod arrays. The elements of this program are:

(1) Analysis and experimental water testing in wire-wrapped 61 pin hexagonal bundles to determine gross mixing between subchannels by salt tracer methods and peripheral subchannel velocities by a laser Doppler velocimeter system.

Analysis: The principal analytic task being undertaken was the development of a model for coolant temperature distribution within wire-wrapped LMFBR bundles. Existing methods of thermal analysis of a wire-wrapped rod bundle of a Liquid Metal Fast Breeder Reactor are based on the principle of subchannel analysis. The more versatile of these models solve the coupled momentum energy equations and therefore require long running times and large storage. Our goal was to develop a simplified but equally accurate procedure by solving only the energy equation using an input velocity field. The model developed is similar in principle to the one which has long been successfully used in chemical engineering for heat and mass transfer in fixed beds of packed solids. By dividing the bundle into two predominant regions and applying the model of a porous body to a LMFBR assembly, a simple procedure for calculating temperature distributions in LMFBR fuel and blanket assemblies has evolved. The results obtained from this analysis were found to predict available data with as good a precision as do the more complex analyses. Correlations for the two empirical constants of this model were obtained as functions of geometric parameters based on an extensive analysis of existing data.

The LMFBR fuel assemblies operate in forced convection (negligible natural convection) under steady-state conditions whereas the blanket assemblies may operate in forced or mixed convection (combined forced and free convection). Two different formulations of equations, corresponding to these two convection regimes, were developed using the same basic model. The calculation procedure for assemblies in forced convection (called ENERGY I) is considerably simpler than that (ENERGY II, ENERGY III) in mixed convection, where buoyancy effects become important. Therefore it is desirable to use ENERGY I for forced convection (although ENERGY II, III can also be used in forced convection, the computational times are fifteen-fold greater). In order to determine when buoyancy effects become important, a new criterion was developed. Given the power, the power skew, the operating and geometric characteristic of the bundle, the critical modified Grashof Number Gr_c^* predicts when buoyance effects become important.

The above methods are applicable to assemblies with adiabatic boundary conditions. Since considerable interassembly heat transfer occurs in LMFBR cores, the model discussed above (ENERGY I) was extended to include interassembly heat transfer. The procedure developed was the code SUPERENERGY. Using this code analytic techniques utilizing a set of normalized assembly maps derived from the code, we studied the effect of including various concentric rings of coupled assemblies on the temperature prediction of the central assembly under Clinch River Breeder Reactor conditions. Insignificant perturbation were found from the inclusion of second ring assemblies and important perturbation from the inclusion of first ring assemblies. Several other analytic studies were undertaken to either investigate the validity of the ENERGY I model or to extend its application. These include:

a) Comparison of the ENERGY I code to the Karlsruhle MISTRAL II code --

The comparison of ENERGY I and MISTRAL II shows their predictions are fairly comparable, except for the case of large bundles (217 pins). This result is advantageous for ENERGY I, which is a much smaller and simpler program than MISTRAL II and can therefore be run at much lower cost. The analyzed 217 pins case probably does not correspond to any real set of experimental data and therefore its results should perhaps not be taken into account. However, the noticed discrepancy can perhaps be explained by a bundle size effect. Two simple relationships have been derived, relating the sets of input parameters needed by the two codes. If further investigations confirm their reliability, it will be possible to take advantage of all the results obtained with the bundles previously analyzed by MISTRAL II and get directly ENERGY I's best prediction by simply converting the set of parameters.

b) Application of ENERGY I to Analysis of Gridded Bundles

The analysis of Karlsruhe data for gridded bundles, proves that the temperature profile can be accurately predicted at one axial level by adjusting a single parameter. The validity of the exponential decrease behind a grid could not be checked, so that investigation is still required to determine whether or not the temperature profile can be predicted everywhere by this model.

c) Prediction of the ORNL 5C (Half-Wire Gap) Bundle Results

The results obtained within ORNL 5C Bundle show a strong independence of a variation of ε^*, (one of the two empirical constants in ENERGY) especially in the inner region. Very different values of ε^* can yield about equivalent predictions and speaking of a real best fit is sometimes questionable. The criterion chosen to determine this best fit has been the ability to predict well the 50% over-powered corner (this is the most sensitive region to change of ε^*). This choice leads to very small values of ε^* and C (the second empirical constant) far below the range of recommendation for bundles having a full sized gap.

With these parameters, ENERGY I is able to predict fairly well the temperature distribution, when a uniform velocity profile is assumed across the bundle. These results are very comparable to the predictions given by other methods; in addition, these methods show the same inaccuracy as ENERGY I, in predicting the temprature in the gap region.

d) Investigation of 11:1 Scale Model results to determine axial bundle length required for attainment of equilibrium ε^*

The 11:1 Scale Model Clinch River Subassembly experiment shows that the values of ε^*, which should be used to match the local concentrations immediately downstream of the injector, oscillate strongly before attaining their equilibrium value.

This equilibrium value is reached first in the region where the sweep cross flow directs the injected tracer; in addition, attainment of this equilibrium value requires at least a fourth of helical pitch, in the subchannels adjacent to the injection point. Assuming that the mixing process is not directional requires implicitly that the flow is deviated in all directions; therefore it is possible that the mixing length for achieving the equilibrium value of ε^* may not be smaller than a full helical pitch.

Experiments: Preliminary experiments have been conducted in both fuel and blanket geometry bundles using salt tracers to measure gross mixing between subchannels and using the installed flow injector and pressure taps to measure static pressure distributions. The fuel geometries tested have P/D = 1.25 and wire leads of 6 and 12 inches. The blanket geometry investigated has P/D = 1.065 and wire lead of 4 inches. Both salt tracer tests resulted in relatively poor salt balances for the lower Reynolds number tests in the laminar region. The difficulty is believed due to so-called striping effect reflecting the tendancy of the salt to follow the wire and not thoroughly mix within the subchannel. The conductivity probes used were located in the mid-subchannel region and therefore could measure a nonrepresentative concentration. This difficulty is being eliminated by installation of flow separators at bundle exits which will isolate and mix the subchannel flow prior to concentration measurements. The flow separators are being designed to insure that their presence does not alter the normal flow distribution between subchannels.

Pressure measurements yielded axial and radial pressure drops. The radial pressure gradients within the bundle at any axial location are uniquely determined by the wire wrap pattern. Pressure measurements in the blanket bunle will be repeated to determine if any distortions were introduced by geometric distortions discovered upon bundle disassembly.

Laser doppler measurements were attempted in blanket bundle edge subchannels. This laser system works on the bundle edge subchannels. This laser system works on the principle of doppler shift in light scattered from microscopic particles added to the fluid passing through the bundle. Limitations and constraints not previously encountered in earlier LDA experiments in fuel wire wrapped bundles were discovered in this experiment and procedures for validating a doppler signal were developed. Weak but interpretable data could not be obtained. The explanation for this behavior is uncertain. It is believed that the geometric characteristics of the blanket bundle generates eddies of scale smaller than the measuring volume leading to signal degradation by turbulence broadening.

(2) Analysis and experimental water testing in small test section representing a simple array of subchannels. In these test sections wire-wrap or other means of pin mechanical support is not simulated. The investigations are aimed at providing a fundamental understanding of velocity and temperature fields in subchannels

typical of rod arrays. These experimental investigations will also make use of tracer techniques and the laser doppler system. Results obtained to date are on the turbulent velocity field of a typical interior subchannel.

A one-equation statistical model of turbulence was applied to compute the detailed description of velocity field (axial and secondary flows), the wall shear stress distribution and the friction factor of steady, fully-developed, turbulent flows with incompressible, temperature-independent fluid, flowing through triangular arrays of rods with different aspect ratios (P/D). Also, experimental measurements of the distributions of the axial velocity, turbulence kinetic energy and Reynolds stresses were performed using a laser Doppler anemomenter (LDA), operating in a "fringe" mode with forward scattering, in a simulated interior subchannel of a triangular rod array with P/D=1.123 and L/D_H=77. From the experimental results, a new mixing length distribution is proposed. Comparisons between the analytical results and the results of this experiment as well as other experimental data available in the literature were presented. The results are in good agreement.

Investigators: Professors N. Todreas, W. Rohsenow*, A. Sonin*, Messrs. A. Hanson, E. Khan, B. Chen, F. Carre, C. Oosterman, R. Anoba, P. Carajilescov

Support: U.S. Energy Research and Development Administration, ($148,000/year for coolant and energy mixing in rod bundles)

Related Academic Subjects:

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

Recent References:

P. Carajilescov, N.E. Todreas, "Experimental and Analytical Study of Axial Turbulent Flows in an Interior Subchannel of a Bare Rod Bundle," J. of Heat Transfer, 98, No. 2, 262-268, May 1976.

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "A Porous Body Model for Predicting Temperature Distribution in Wire-Wrapped Fuel Rod Assemblies," Nuclear Engineering and Design, 35 (1975) 1-12.

*Department of Mechanical Engineering

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "A Porous Body Model for Predicting Temperature Distribution in Wire-Wrapped Rod Assemblies Operating in Combined Forced and Free Convection," Nuclear Engineering and Design 35 (1975) 199-211.

B. Chen and N. Todreas, "Prediction of the Coolant Temperature Field in a Breeder Reactor Including Interassembly Heat Transfer," Nuclear Engineering and Design, 35 (1975) 423-440.

E. Khan, W. Rohsenow, A Sonin, N. Todreas, "A Porous Body Model for Predicting Temperature Distribution in Wire-Wrapped Fuel and Blanket Assemblies of a LMFBR," COO-2234-16TR, MIT, March 1975.

E. Khan, W.M. Rohsenow, A. Sonin, N. Todreas, "Input Parameters to the ENERGY Code (to be used with the ENERGY Code Manual) COO-2245-17TR, MIT, May 1975.

E. Khan, W.M. Rohsenow, A. Sonin, N. Todreas, "Manual for ENERGY Codes I, II, III," COO-2245-18TR, MIT, May 1975

P. Carajilescov and N. Todreas, "Experimental and Analytical Study of Axial Turbulent Flows in an Interior Subchannel of a Bare Rod Bundle," COO-2245-19TR.

B. Chen and N. Todreas, "Prediction of Coolant Temperature Field in a Breeder Reactor Including Interassembly Heat Transfer," COO-2245-20TR, MIT, May 1975.

F. Carre and N. Todreas, "Development of Input Data to Energy Code for Analysis of Reactor Fuel Bundles," COO-2245-21TR, MIT, May 1975.

R. Anoba and N. Todreas, "Coolant Mixing in LMFBR Rod Bundles and Outlet Plenum Mixing Transients," COO-2245-24TR, MIT, August 1975.

(2) Fluid Dynamic Modeling of Forced-Buoyant Flow in Reactor Vessel Plenums

Analytical and experimental work is being pursued with the goal of improving understanding of, and models for, behavior of turbulent mixing of buoyant plumes. The specific problem examined concerns development of models for plume mixing in the LMFBR outlet plenum. To do this the influence of different turbulence models upon predicted mixing patterns are being investigated. These results are to be compared to measured velocity and temperature fields, and measured velocity and temperature correlation functions, with the aim of developing an appropriate turbulence model for use in design calculations. In a broader sense this work permits an investigation into the nature of turbulent mixing in buoyant plumes, which has application in a wide range of practical problems.

A recent result of this effort is the development of a Mach-Zehnder Interferometer Temperature measuring system for use in observing very rapid (sub-millisecond time scale) turbulent fluid temperature fluctuations, without the requirement for a mechanical probe intruding into -- and disturbing -- the flow. This development provides a new fast-response temperature measuring capability, with potentially broad applications. In the outlet plenum work it will be used to provide direct measurements of statistical heat transport properties of the flow.

Investigators: Professor M.W. Golay and Mr. R. Bennett

Support: ERDA ($33,800)

Related Academic Subjects:

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

Recent References:

R.G. Bennett and M.W. Golay, "Development of an Optical Method for Measurement of Temperature Fluctuations in Turbulent Flows", Trans. Am. Nucl. Soc., 22, 581 (1975).

R.G. Bennett and M.W. Golay, "Interferometic Investigation of Turbulently Fluctuating Temperature in an LMFBR Outlet Plenum Geometry", Trans. Am. Soc., Mech. Engr., Winter Annual Meeting (1976).

R.G. Bennett and M.W. Golay, "Interferometric Investigation of Turbulently Fluctuating Temperature in an LMFBR Outlet Plenum Geometry", COO-2245-29TR, MIT (1976)

(3) Theoretical Determination of Local Temperature Fields in LMFBR Fuel Rod Bundles

Thermal stresses due to azimutal temperature gradients largely affect LMFBR fuel element and bundle integrity in the beginning of life state. Spacer design must be such that the overall bundle design can cope with the resulting strains and displacements especially in situations where large power scews exist throughout the bundle. This situation arises mainly at the core/blanket interface regions. Also, today's control rod design is mainly based on non-optimal, thus unfavorable, coolant channel layout which together with the operation in low-flow range situations creates severe temperature gradients around the structure of consideration which as a result tends to bow. Bowed control rod and bundle structures may lead to severe safety problems. Moreover, the fuel element clad must be designed under various neutronic, thermal-hydraulic and material constraints to meet its economical objectives. For instance, it has been estimated that a decrease of 10°C in operational temperature would allow the fuel element to operate for an additional 2500 hours. To cope with tomorrow's energy demands, it seems more than justified to look at local temperature fields.

Although much work has been devoted to overall bundle analysis on the basis of a lumped parameter approach in the United States, only little or no effort was made until now to predict local fluid temperature fields and 2-D and 3-D clad temperature fields as the result of a multiregion analysis. The same holds for experimental work in this field. Thus far, no attempts have been made to keep up with the development now underway in Europe.

This work will extend the work which is known in the literature as the VELASCO-type approach to more viable areas in the bundle, namely the corner and side channels.

Investigator: Professor L. Wolf

Support: ERDA ($20,000)

Related Academic Subjects:

22.312 Engineering of Nuclear Reactors
22.313 Advanced Engineering of Nuclear Reactors

(4) Thermal Design of Fusion Reactor Blankets

Initial work in this area was concentrated on assessing the blanket performance of several Tokamak reactors, including those designed by Princeton, Oak Ridge, Wisconsin and Brookhaven. A literature search was performed to obtain information pertaining to the methods and technologies used in the aforementioned reactor designs (especially in the areas of thermal analysis and MHD pumping requirements). Generally speaking, the tabulated design specifications of the reactors check out favorably with our calculations.

Although the design philosophies of the reactors are different and therefore result in quite different choices of key parameters, such as material, blanket flow channelling, operating limits, preliminary investigation shows: 1) all four reactors achieve generally accepted minimum breeding ratios (1.1 or greater) and, 2) with the proposed first wall loadings ranging from 0.7 to 2 mw/m^2, steady-state heat removal from the blanket is not beyond the capability of present heat transfer technology. For example, the proposed heat exchanger in the blanket of the Oak Ridge Reactor is designed to remove 140,000 BTU/hr. per sq. ft. which corresponds to a 0.69 mw/m^2 of first wall power loading. When compared to the ability of operating PWR to remove 350,000 BTU/hr per sq. ft. of heat transfer area, the reason for conclusion (2) is obvious.

Based on the above we conclude that the thermal design assessment should next focus on the inter-relationship of the key areas of blanket design - breeding ratio required, accessibility for maintenance, reasonable thermal efficiency, modest tritium inventory, reasonable operating life and the continued plant operation with failure of a portion of the blanket cooling system - and the heat removal technology. With the existing variety of approaches possible for heat removal, we believed that those approaches which enhance blanket design with respect to the above key areas should be identified and investigated. This effort culminated in evolution and exploration of a proposed solid breeder design, a concept in which the blanket was composed of fueled rods interspaced with graphite shims.

In the course of evaluating the thermal and hydraulic behavior of the design, a scheme to calculate one dimensional spatial energy generation rate, a coolant temperature model for the single stream counter flow breeder rod heat exchanger, a shim thermal model, a failed module temperature model, a graphite shield temperature model and a calculational scheme for pumping power were developed. The derivation of these models and methods as well as the thermal/hydraulic analysis of one postulated design point are presented. For a set of assumed material properties, geometry and coolant conductances, the thermal and hydraulic analysis further demonstrated the feasibility of the failure mode operation of the BRSR concept by easily meeting the temperature limits of normal and off-normal operation. The model for the coolant temperature revealed interesting thermal interactions between the peak coolant temperature and effective conductance between the flow passages, pointing out the important factor of insulation in the designing of the breeder rod heat exchanger.

In the course of evaluating the BRSR design, certain noteworthy characteristics pertinent to solid fusion blankets were also identified and serve as the basis for the continuing effort in which the overall potential of solid breeder blankets will be assessed.

Investigators: Professors N. Todreas, P. Griffith*, Messrs. S. Lefkowitz*, F. Chen*

Support: ERDA ($30,000/year for thermal design of fusion reactor blankets)

Recent References:

Franklin Chen, "Thermal and Hydraulic Considerations for the Designing of a Solid Tokomak Blanket", Sc.D thesis, MIT, May 1976.

Sheldon Lefkowitz, "Thermal Hydraulic Assessment of Recent Blanket Designs for Tokomak Fusion Reactors", M.S. thesis, February 1975

*Department of Mechanical Engineering

3.2.3 Nuclear Power Reactor Safety

During recent years increased public concern over nuclear power reactor safety has spotlighted issues such as emergency core cooling system capability and the effects of both chronic low level and large accidental radionuclide releases. This has reinforced the importance of maintaining an independent assessment and review capability, and has motivated continuance of the Department's long-standing in-house commitment to this otherwise largely unsupported academic research area despite a decline in overall available resources.

Faculty members have been quite active in the area of nuclear power reactor safety, in teaching, supervision of student research and in their consulting activities.

A) Professor N. C. Rasmussen has directed the recently completed NRC study on nuclear accident risks. The final report of the Reactor Safety Study (WASH-1400) was issued in October 1975. It has received worldwide attention. The study used probabilistic methods to estimate the risks to the public from reactor accidents from today's LWR's. It concluded that reactor accident risks are quite small in comparison with other risks that society accepts.

B) Professor M. W. Golay has continued service (since 1971) as an independent analyst in reviewing and advising corrections and improvements in the containment safety system analytical models and methods used by Stone and Webster Engineering Corporation in the design of LWR power stations.

C) Professor D. D. Lanning has continued service on the Safety Audit Committee for the Monticello Nuclear Generating Plant and has contacts with the Yankee Atomic Power Company with regard to safety-related studies. These contacts are of value in relating current information to student projects and education.

D) The Department has conducted for nine years a summer course in nuclear power reactor safety, drawing lecturers and students from all sections of the international atomic energy community.

F) A number of thesis projects have recently been completed or are underway:

1) Methodology for Estimating Consequences of Hypothetical Reactor Accident

The recently released Reactor Safety Study (WASH-1400) used a detailed and complicated computer code to estimate the consequences of hypothetical reactor accidents. This code is very expensive and time consuming to operate. The current work at M.I.T. is developing ways to reduce the complexity of these calculations. In principle, the method develops analytical functions for the risk curves. The functions have one or more parameters whose values are obtained from the WASH-1400 analysis. Once generated, these functions enable one to calculate changes in the risk curves as a function of such input parameters as population density, reactor safety systems, etc. After the verification with the WASH-1400 code these relations can be used to compare risks of various reactor designs and various reactor sites without the use of the long, expensive WASH-1400 code.

Investigators: Professor N. C. Rasmussen, Dr. W. Vesely*, Mr. Mitsuru Maekawa

*U.S. Nuclear Regulatory Commission

Support: U.S. Nuclear Regulatory Commission ($30,000)

Recent References:

M. Maekawa, "A Method for Risk Analysis of Nuclear Reactor Accidents", Ph.D. thesis, MIT, Department of Nuclear Engineering, July 1976.

2) Reliability Analysis of Gas Cooled Fast Reactor (GCFR)

As a possible alternative to the LMFBR, GCFR design studies are being carried out by General Atomic with modest support from ERDA. In order to better understand the possible failure modes of the GCFR design, an analysis of system failure modes has been carried out. This study used event tree logic similar to the WASH-1400 analysis to identify those kinds of system failures that were most likely to result in serious fuel damage. The study used rough probability estimates to establish dominate failure modes. No calculations of the consequences of failures were included. With considerable further development the work could form the basis for a WASH-1400 type analysis of the GCFR.

Investigators: Professors David D. Lanning, Norman, C. Rasmussen, Mr. Pascal DeLaquil

Support: General Atomic

Recent References:

P. DeLaquil, "An Accident Probability Analysis and Design Evaluation of the Gas-Cooled Fast Breeder Reactor Demonstration Plant", Ph.D. Thesis, MIT, Department of Nuclear Engineering, (1976).

3. Reliability Analysis of Reactor Systems with Random Failure Rates

The purposes of this research program are: (1) to develop a methodology for the evaluation of the dynamic availability of large reactor systems characterized by stochastic and statistically interdependent failure and repair rates; and (2) to apply this methodology to advanced reactor systems. Consideration of stochastic failure and repair rates is required either because our knowledge of these quantities for some components is incomplete or because the values of these quantitites may be inherently uncertain.

The steady-state reliability of a reactor for stochastic and statistically independent failure and repair rates can be evaluated by means of the event-tree and fault-tree methods, as was done in a recent safety study. When the failure and repair rates of the components of a reactor are not only stochastic but also statistically interdependent, these methods are not applicable, however, and other methods of logic must be developed. For such reactors we propose to investigate the applicability of the Markov-chain method.

The present work is developing the Markovian approach for application to advanced reactor systems particularly the LMFBR. The work is being jointly carried out with Brookhaven National Laboratory.

Investigators: Professor Elias Gyftopoulos, Mr. Ioannis Papazoglou.

Support: Brookhaven National Laboratory

4) Molten Fuel-Sodium Thermal Interaction in LMFBR's

This project was initiated under ERDA support to assist in determining the possibility and consequences of generation of high pressures and potentially destructive mechanical work due to thermal interaction between molten fuel and sodium. The work has continued to focus on predicting the mechanism for the onset of fragmentation of the molten fuel, since the fragmentation process may be a necessary condition for the destructive vapor explosion and is of interest in assessing the course of less intense scale-accidents. Our exploration of mechanisms has been in two areas:

A) Mechanisms responsible for fragmentation in molten metal droplet experiments. Here experimental work was continued in which small amounts of molten tin and bismuth were dropped into water to investigate the fragmentation of molten metals. The major parameter of the experimental program was the initial drop temperature but drop mass and drop material were also varied. The pressure signal of the interaction was recorded, high-speed motion pictures of the interaction were made, and the metallic debris was collected. Several important additions were made to the experimental apparatus previously used. Specifically they were a hotter furnace to allow a greater range of initial drop temperature, provision of an argon atmosphere and/or a vacuum during the melting and dropping of the metal sample to prevent excessive oxidation at high temperatures, and modification of the tape recorder to allow a longer time interval to be recorded.

The results obtained show well-defined patterns of pressure frequency and magnitude behavior. Application of the results to the acoustic cavitation theory of fragmentation shows that the pressure excursions within the molten tin are considerably less severe than was predicted. The likelihood that acoustic cavitation caused the observed fragmentation is therefore considerably diminished. Further comparison of results from air heating and vacuum heating tests strongly indicate that violet release of dissolved gas within the drop is also not responsible for the observed fragmentation. It is believed that the operative mechanism is related to disruption of the vapor film surrounding the hot drop which leads to direct contact of a portion of the drop surface and the liquid pool. The specific nature of the mechanism is not yet known and is under investigation in our program as well as other laboratories throughout the world.

B) Thermal Stress Initiated Fracture as a Fragmentation Mechanism

An analytic study was carried out to determine the applicability of the concept of thermal stress fragmentation to the UO_2/Sodium Fuel-Coolant Interaction. Major emphasis was put on the fracture mechanics approach to assessing whether or not the solidifying UO_2 would fracture under the thermally-induced stresses. It was found that the stress levels were sufficient to generate K_I values substantially in excess of the UO_2 fracture toughness, K_{IC}. Thus, rapid instantaneous propagation of inherent flaws is anticipated. Parametric studies in which the surface heat transfer boundary condition was varied did not alter this conclusion.

Extension of the thermal stress fracture concept to Al_2O_3 resulted in similar behavior. Subsequently, this material was selected as a good simulant for use in experimental studies of the mechanism. Additional studies led to the conclusion that thermal stress fracture was not an applicable mode of fragmentation inducement in ductile metal/water interactions.

It was concluded that thermal stress fragmentation is a feasible mode of fragmentation in the UO_2/sodium system. Based on this result, a second study was done to determine the minimum UO_2 particle size that could survive fragmentation induced by thermal stresses in a UO_2-Na Fuel Coolant Interaction (FCI). Solid and liquid UO_2 droplets were considered each with two possible interface contract conditions; perfect wetting by the sodium or a finite heat transfer coefficient. This analysis indicated that particles below the range of 50 microns in radius could survive a UO_2-Na fuel coolant interaction under the most severe temperature conditions without thermal stress fragmentation.

Environmental conditions of the fuel-coolant interaction were varied to determine the effects upon K_I and possible fragmentation. It was concluded that this analytic study seemed to verify the experimental observations of the range of the minimum particle size due to thermal stress fragmentation by FCI. However, the method used, when the results are viewed in light of the basic assumptions, indicates that the analysis is crude, at best, and can be viewed as only a rough order of magnitude analysis. The basic complexities in fracture mechanics make further investigation in this area interesting but not necessarily fruitful for the immediate future.

Further efforts in the thermal stress area are now directed at establishing minimum conditions necessary for this fragmentation mechanism to develop a specified destructive work potential. These conditions of final particle size, mixing time constant, fuel/sodium ratio are being established with the aid of the Cho-Wright parametric model. It is being shown that these conditions are far more restrictive than those being deduced from mechanistic analyses of LMFBR transients over power transients.

5) Methods for Thermal/Hydraulic Analysis of LWR Cores

The goal of this project is to provide publicly available tools, primarily computer codes, for the analysis of operational transients in LWR cores. The focus of the first year's effort was the development of a method for steady state PWR operation using publicly available computer codes. Such tools do not presently exist because vendor codes are proprietary and the well-known COBRA IIIC code must be used in a one-pass fashion, a technique whose bounds of validity have not previously been assessed.

In this effort the one-pass analysis approach was adopted and assessed. This assessment was done by comparing results for increasingly detailed core representations in the limit effectively simulating the standard vendor (THINC) cascade methods. This assessment was made possible by prior MIT refinements to the COBRA IIIC code leading to signficant reductions in running time for arrangements of 20 or more radial nodes. The refinements have been organized as the code COBRA IIIC/MIT.

The relative merits of the proposed simplified one-pass analysis versus the cascade method were assessed for various cases of interest under steady-state PWR operating conditions. It was concluded that the one-pass method did give results of equal or better validity than the cascade method. Based on this conclusion the optimum arrangement and size of fine (about the hot subchannel) and coarse (remainder of core) mesh zones for one-pass analysis were determined for core NDNBR analysis.

Future work will be directed at application of this simplified method for transient PWR operation and at developing techniques for BWR analysis.

Investigators: Professors N.E. Todreas, W.M. Rohsenow*, A.A. Sonin*, Messrs. G. Bjorkquist, G. Shiralkar*, R. Knapp, W. Lenz, M. Corradini, R. Bowring, E. Khan, C. Chiu, P. Moreno, J. Liu.

Support: ERDA $70,000/year for LMFBR Fuel Coolant Interaction work;
New England Electric System and Northeast Utilities Service Company as part of the Nuclear Reactor Safety Research Program under the MIT Energy Laboratory's Electric Power Program, $20,000/year for Thermal/Hydraulic Analysis of PWR Cores

Related Academic Subjects:

22.32 Nuclear Power Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer
22.39 Nuclear Reactor Operations and Safety

Recent References:

G.M. Bjorkquist, "An Experimental Investigation of the Fragmentation of Molten Metals in Water," S.M. Thesis, Nuclear Engineering Department, MIT, June 1975.

G. Shiralkar, "An Investigation of the Fragmentation of Molten Metals Dropped into Cold Water," S.M. Thesis, Mechanical Engineering Department, MIT, August 1976.

R. Knapp and N. Todreas, "Thermal Stress Initiated Fracture as a Fragmentation Mechanism in the UO-Sodium Fuel-Coolant Interaction," Nuclear Engineering and Design, 35, 1975, p 69-85.

M. Corradini, "Prediction of Minimum UO_2 Particle Size Based on Thermal Stress Initiated Fracture Model," COO-2871-4TR, August 1976.

*Department of Mechanical Engineering

G. Shiralkar, W.F. Lenz and M. Corradini, "Fuel Coolant Thermal Interaction Project UC 79", COO-2781-3TR, April 1976.

C. Chiu, "Two Dimentional Transport Coefficients for the PWR's Thermal/Hydraulic Analysis", S.M. Thesis, Nuclear Engineering Department, MIT, May 1976.

P. Moreno, "Thermal/Hydraulic Analysis Methods for PWR's", Nuclear Engineering Thesis, Nuclear Engineering Department, MIT, May 1976.

P. Moreno and R. Bowring, "COBRA IIIC/MIT Computer Code Manual,"

6) Flow Stability in BWR Coolant Channels During Transients

The stability of flow rates in parallel, heated boiling-water coolant channels during transients was investigated. This work was undertaken to investigate anticipated unstable flow behavior suggested by the nonlinear nature of the governing conservation equations. The approach utilized in this investigation was to develop the governing conservation equations of mass, momentum and energy from their most general forms into coupled relations applicable to an internally heat annulus operating at transient BWR conditions. The model was then extended to parallel annuli connected only by inlet and exit plenums and a digital computer program was written to examine the coupled transient behavior of these two flow channels. In analyzing three general classes of transients (reactivity insertions, loss of coolant pressure, and loss of coolant flow) no calculationally predicted instabilities were observed over a broad range of accident conditions and under severe transient conditions. However, it was observed that the qualitative behavior of the flow is strongly dependent upon the choice of empirical models for flow slip, pressure drop, and heat transfer rate.

Investigators: Professor M.W. Golay, Mr. A.E. Levin

Support: EPRI

Related Academic Subjects:

22.32 Nuclear Power Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer

Recent References:

A.E. Levin and M.W. Golay, "Simulation of Flow Behavior in BWR Coolant Channels During Transients", MEK-43, MIT (1975).

3.2.4 Nuclear Reactor and Energy System Design

Several research projects have been initiated or completed involving design aspects within the reactor engineering area. These are described below:

1) Nuclear-Powered Total Energy Analysis

A research effort directed toward analysis of the feasibility of total energy systems is currently in its third year of funding by the U.S. Army Corps of Engineers' Facilities Engineering Support Agency. In this work methods of satisfying all non-transportation energy demand for large (50,000 population) military installations are examined. In that demand schedules and energy consumer groups in such installations are quite similar to those ecountered in the civilian sector, the results and analytical methods of this work are generally applicable to a broad range of situations.

The most recent and most important product of this work is an analysis of the optimal total energy system (TES) for Ft. Bragg, North Carolina. In this analysis both HTGR-gas turbine (HTGR/GT) and coal gasification-gas turbine (CGGT) power station options are considered, as well as that of a hybrid combined coal-nuclear power station. The power station is used to provide electrical power via a Brayton-cycle power system, and thermal power in a high temperature water (HTW) thermal utility system. For each power station type the optimal (minimum TES cost-over-life) configuration is obtained by varying the thermal to electrical utility system load capacity. For each utility system configuration a year-long operational numerical simulation of consumer power demands, and of the dynamic response of the TES - including a large HTW storage reservoir-in meeting these demands is performed using a computer program (named TDIST), which was developed in this project for that purpose. This simulation provides estimates of the required power station thermal and electrical capacities, HTW storage reservoir capacity, annual fuel consumption, and TES capital costs.

In the Ft. Bragg analysis it is found that the minimal present-worth (in 1985) configuration CGGT-powered TES occurs at a thermal/electrical utility system capacity ratio of 70%, and that this option is approximately 30% less expensive than the minimal present worth HTGR/GT-powered TES (occurring at a thermal/electrical ratio value of 76%). In previous work the foundations of the Ft. Bragg analysis were laid with efforts investigating the costs and feasibility of small capacity HTGR power plants, hydrogen storage options, environmental impacts and safety risks of coal and nuclear power plants, coal gasification technology, and gas turbine technology. The results of these efforts are presented in a series of reports, listed at the end of this discussion.

The other important component of the currently-available analytical capability is the computer code TDIST, which consists of two parts.

1. The consumer demand section, in which space conditioning, electrical, illumination and hot water service energy requests are calculated for as many as twenty consumer categories, and

2. The thermal utility simulation section, in which the dynamics behavior of the thermal utility system is simulated over a 24-hour period.

This work is continuing currently in its third year of funding, with the focus of effort being upon extension and further improvement of TDIST, and upon analyzing Fts. Hood and Knox.

Investigators: Professors M. Golay, M. Driscoll, D. Lanning, N. Rasmussen, Messrs. F. Best, W. Boyd, M. Doyle, S. Goldman, M. McRobbie, L. Metcalfe, A. Ribeiro, J. Shin, J. Stetkar, M. Tyson and G. Was; and a total of 25 members of subject 22.33, Nuclear Reactor Design during Fall 1974 and Spring 1976.

Support: U.S. Army, Facilities Engineering Support Agency ($72,000/year for the HTGR Total Energy System Design).

Related Academic Subjects:

22.33	Nuclear Reactor Design
22.312	Engineering of Nuclear Reactors
22.212	Nuclear Reactor Physics
22.34	Economics of Nuclear Power
22.35	Nuclear Fuel Management
22.37	Environmental Impact of Nuclear Power

Recent References:

L. Metcalfe and M.J. Driscoll, Final Report: Economic Assessment of Nuclear and Fossil-Fired Energy Systems for DoD Installations, U.S. Army Corps of Engineers,-FESA-RT-2002 (1975)

M. Doyle, M.W. Golay, and N.C. Rasmussen, Final Report: Comparison of Environmental Impacts of Coal and Nuclear Systems for Military Applications and Consequences of Reactor Accidents, U.S. Army Corps of Engineers-FESA-RT-2001 (1975)

L. Metcalfe and M.W. Golay: Final Report: Storage of Off-Peak Nuclear Power Through Hydrogen Generation, U.S. Army Corps of Engineers, FESA-RT-2005 (1975).

J.W. Stetkar and M.W. Golay, Simulation of the Behavior of a Brayton Cycle-HTGR-Powered Thermal Utility System for Total Energy Applications, Trans. Am. Nucl. Soc., 22, 601, (1975).

W. Boyd and M.W. Golay, Final Report: Economics and Technical Aspects of Coal Gasification, U.S. Army Corps of Engineers - FESA-RT-2012 (1976).

J. Kelly and M.W. Golay, Final Report: Economic and Technical Aspects of Gas Turbine Power Stations in Total Energy Applications, U.S. Army Corps of Engineers - FESA-RT-2013 (1976).

J.W. Stetkar, F. Best, and M.W. Golay, Final Report: Design of a Nuclear Powered-Total Energy System for Ft. Bragg, N.C. U.S. Army Corps of Engineers-FESA-RT-2011 (1976).

F.W. Stetkar and M.W. Golay, Design of An Optimal Total Energy System for a Large Military Installation, Trans. Am. Nucl. Soc. (1976).

A. Ribeiro, "Core Design for a Small HTGR", Ph.D. thesis, MIT, Department of Nuclear Engineering, October 1975.

3.2.5 Fuel Designs for Plutonium Recycle

Utilities are at the stage of considering the recycle of their reactor-produced plutonium as fuel enrichment for future core loadings. Several alternatives are available to the utilities and in order to evaluate these alternatives prior to the vendor selection and final core design, it is desirable to be able to make preliminary design calculations. The design methods available, outside of the vendor proprietary computer codes, are not necessarily applicable to plutonium systems even though they have been successfully used for the design of uranium cores.

The improvement and confirmation of calculational methods for plutonium systems has been the subject for graduate student research. Once the confirmed calculational methods are available, the research is then carried on to the preliminary fuel design studies. Recent investigations in plutonium recycle have been concerned with the development and verification of a methodology for obtaining steady state assembly and core relative power distributions for multiregion mixed oxide (PuO_2-UO_2) and uranium oxide fuels for large PWR's.

A modified version of the unit cell code LASER has been developed and calculated results have been compared with experimental lattice critical studies and multi-region critical lattice power distributions under a variety of loading schemes. Burnup studies and integral transport theory cell row comparisons are progressing. Application of the method to San Onofre-I and Maine Yankee has been performed as a part of the design evaluation for plutonium recycle in these reactors.

Investigators: Professor D. D. Lanning, Messrs. W.R. Jones, G.M. Solan and D. Morales

Support: Yankee Atomic Power Company

Related Academic Subjects:

22.32 Nuclear Power Reactors
22.34 Economics of Nuclear Power
22.35 Nuclear Fuel Management

Recent References:

G.M. Solan, "Neutronic Analysis of a Proposed Plutonium Recycle Assembly", S.M. and N.E. thesis, MIT, Department of Nuclear Engineering, August 1975 (also issued as MITNE-175)

3.3 Nuclear Materials and Radiation Effects

The nuclear materials program has four major objectives: (1) to provide students in the Department with sufficient background in the principles of physical metallurgy and physical ceramincs 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 conversion, energy transmission, and environmental technology as related to power production.

3.3.1 Subjects of Instruction

22.71J, Physical Metallurgy Principles for Engineers, is the introductory course in this sequence of study and is intended for students who did their undergraduate work in engineering and science fields which did not provide formal instruction in metallurgy or materials science. This course emphasizes the following topics: crystallography and microstructure; deformation mechanisms and the relationship of mechanical properties to metallurgical structure; thermodynamics and rate processes to include phase equilibria, recovery and transformation mechanism, diffusion, corrosion, and oxidation; mechanical property testing methods, strengthening mechanisms, fracture mechanics, fatigue and creep. Emphsis throughout is on materials and operating conditions involved in advanced engineered systems. This and subsequent courses are condicted jointly between th Department of Nuclear Engineering and the Department of Metallurgy and Materials Science.

22.72J, Nuclear Fuels, covers the principles of fissile, fertile, and cladding materials selection for various reactor fuel concepts based upon their nuclear, physical, and mechanical properties, clad interactions, and radiation behavior. The properties, irradiation behavior, design, and fabrication of oxide pellet fuels for light-water and fast-breeder reactors are especially stressed; however, metallic, coated-particle, ceramic-particle and cermet fuels for central power and space applications are also discussed. The elements of oxide pellet fuel behavior modeling including temperature and stress distributions, the mechanism of fuel restructuring, creep, swelling, fission gas release, energy and mass transport, and fuel-clad interactions are discussed in detail.

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. Topics include the theory of atomic displacement, spike phenomena, correlated collisions, inelastic scattering and range laws for both ordered and disordered lattices. Experimental and analytical methods for characterizing defect structures, determining the effects of various defects on physical properties, and describing the kinetics and rate laws for defect annealing are described.

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

3.3.2 Irradiation-Induced Stress Relaxation and Creep in Reactor Materials

The mechanical properties of nuclear materials are of great importance to reactor designers. In particular, two phenomena, creep and stress relaxation, can profoundly affect reactor performance and life under certain circumstances. In some cases, such as permitting stress relief in fuel cladding, these phenomena may be helpful. But in other cases, excess creep may adversely affect the dimensional stability of reactor core components. Thus an understanding of the circumstances that permit or inhibit irradiation-induced creep is necessary to optimize reactor materials design. The purpose of this investigation is to explore irradiation-induced creep in nickel and 304-stainless steel at low and intermediate temperatures and to determine the stress- and temperature-dependence of such creep. Thin specimen foils are bombarded under load with high-energy alpha and deuteron particles in an especially designed apparatus located at the NRL cyclotron. The specimen deformations due to radiation-induced creep are accurately measured and both temperature and particle beam densities are accurately controlled.

Investigators: Professor A. L. Bement, Dr. David J. Michel (NRL), Mr. P. Hendrick.

Support: Energy Research and Development Administration

Related Academic Subject:

22.71J Nuclear Materials and Radiation Effects
22.72J Nuclear Fuels
22.73J Radiation Effects in Crystalline Solids
22.75J Radiation Effects to Reactor Structural Materials

Recent References:

P.L. Hendrick, "Ion-Simulated Irradiation-Induced Creep", Ph.D. thesis, MIT, Department of Nuclear Engineering, September 1975.

P.L. Hendrick, D.J. Michel, A.G. Pieper, R.E. Surratt, and A.L. Bement, Jr., "Ion-Simulated Irradiation-Induced Creep of Nickel", to appear in proceedings of the October Gatlinburg Symposium on Radiation Effects and Tritium Technology for Fusion Reactors.

P.L. Hendrick, D.J. Michel, A.G. Pieper, R.E. Surratt, and A.L. Bement Jr. "Simulation of Irradiation-Induced Creep in Nickel", J. Nucl. Mater. (in press).

P.L. Hendrick, D.J. Michel, A.G. Pieper, R.E. Surratt, and A.L. Bement, Jr. "Ion-Simulated Irradiation-Induced Creep", Nucl. Ins. and Meth. (in press).

3.3.3 Strength Differential Effects in Zirconium Alloys

An investigation is being made into the occurrence of a strength-differential effect in the Zircaloy cladding for light-water reactor fuel elements and into the effect such a strength differential can have on the analytical predictions of cladding creep collapse during irradiation-induced fuel densification. The strength differential refers to the difference in the compressive and tensile yield strengths of a material. Preliminary analyses indicate that a strength differential can have a significant effect on cladding collapse predictions.

Investigators: Professor A.L. Bement, Messrs. G.E. Lucas, R. Ballinger

Support: Electric Power Research Institute and Wah Chang Albany Corporation

Related Academic Subjects:

22.71J Nuclear Materials and Radiation Effects
22.72J Nuclear Fuels
22.73J Radiation Effects in Crystalline Solids
22.75J Radiation Effects to Reactor Structural Materials

Recent References:

G.E. Lucas, "The Strength-Differential in Zirconium and its Effect on Clad Creep Down Analysis," S.M. Thesis, Department of Nuclear Engineering, December 1974

G.E. Lucas and A.L. Bement, "The Effect of a Zirconium Strength-Differential on Cladding Collapse Predictions", J. Nucl. Mater., 55, 246-252 (1975).

G.E. Lucas and A.L. Bement, "Temperature Dependence of the Zircaloy-4 Strength-Differential," J. Nucl. Mater. 57, (in press).

3.3.4 Fuel Performance Analysis During Normal and Transient Conditions

It has become increasingly evident in recent years that nuclear fuel reliability in light-water reactors depends on a number of highly complex, coupled relationships among fuel design, materials properties, and system operating parameters. The objectives of this research are to (1) systematically review the adequacy of current computer codes for fuel behavior analysis under steady state and transient conditions; (2) identify needed improvements to these codes; (3) develop appropriate subroutines; and (4) conduct analyses of various fuel operating modes under steady power and load-following conditions for the purpose of comparing fuel reliability and performance limits.

Investigators: Professors J.E. Meyer, A.L. Bement (ALB on leave of absence after 6/1/76), Messrs. Y.Y. Liu, M.A. Krammen, P.W. Baum, M.M. Dashti, S. Fujimoto, K.Y. Huang and S. P. Schultz.

Support: New England Utilities and the M.I.T. Energy Laboratory

Related Academic Subjects:

22.71J	Nuclear Materials and Radiation Effects
22.72J	Nuclear Fuels
22.73J	Radiation Effects in Crystalline Solids
22.75J	Radiation Effects to Reactor Structural Materials

Recent References:

A.L. Bement, "Interrelationships Between Nuclear Fuel Design Performance and Fabrication", Proceedings of the International Symposium on Nuclear Power Technology and Economics, Taipei, Taiwan, January 1975.

A.L. Bement, "Needs in Alloy Design for Nuclear Applications", Battelle Colloquium on the Fundamental Aspects of Structural Alloy Design, Seattle Washington and Harrison Hot Springs, B.C. September 1975.

3.3.5 Simulation of Radiation Effects in Fusion Materials

The purpose of this research is to conduct analyses of various techniques, theories, and data to examine the degree of consistency, sources of error, and the probable validity of the data in simulating radiation damage in an actual fusion reactor environment. A critical evaluation of internal consistencies of available void simulation work to date to include consideration of near surface effects, material purity and characterization, and temperature and beam control is in progress. Also, a cooperative investigation of void formation in molybdenum, involving various particle beams, has been initiated, coordinated by Battelle Northwest Laboratories, The investigation at M.I.T. will employ high-energy Se^{++} ions to examine the effects of non-compatible ions on void nucleation and growth. Investigations into the effects of CTR burn cycles on void nucleation and radiation creep were begun during the year.

Investigators: Professors A.L. Bement, K. C. Russell, Messrs. E. Ohriner, Y. Choi and S. Maydet

Support: U.S. Energy Research and Development Administration

Related Academic Subjects:

22.73J Radition Effects in Crystalline Solids
22.75J Radiation Effects to Reactor Structural Materials

Recent References:

Y. Choi, "Computer Simulation of the Effect of Fusion Burn Cycle on First Wall Swelling", S.M. thesis, M.I.T., Department of Materials Science and Engineering, February 1976.

Y.H. Choi, A.L. Bement, and R.C. Russell, "The Effect of Fusion Burn Cycles on First Wall Swelling", Proceedings of the October 1-3, 1975, Gatlinburg Symposium on "Radiation Effects and Tritium Technology for Fusion Reactors"

3.3.6 Interelectrode Insulator Development for MHD Generators

One of the critical components of a segmented MHD generator is the interelectrode insular which must stand off the Hall Potential, exhibit a high degree of thermal shock resistance over numerous operating cycles, and retain good chemical compatibility against slag and seed in the combustion environment and with the adjoining electrode materials. The purpose of this research is to examine in detail the interrelationships among composition, microstructure, and performance limits of candidate insulator materials. Bench scale measurements of thermal-mechanical, thermal-chemical, and electrical properties of specially tailored materials will be followed by long-term performance tests under simulated MHD operating conditions. Initial work involves the investigation of MgO and high-MgO refractories in model slags at elevated temperatures. In addition to determining the kinetics of corrosion and their dependence on system parameters, a variety of characterization techniques will be employed to elucidate the nature of the corrosion process.

Investigators: Professor A.L. Bement, Messrs. D.R. Uhlmann, H. Fujimoto

Support: Office of Coal Research

3.3.7 Engineering Workshop on MHD Materials

As the OCR Program for the development of MHD power generation progresses from its present stage of advanced component and subsystem development to a national program involving the construction of major test sites and demonstration plants, the amount of supporting materials technology under the program must increase dramatically. In order to assess current knowledge and technical capabilities for supplying highly specified materials, development materials properties data for component design, and finding solutions to critical materials problems an engineering workshop on MHD materials co-sponsored by the NSF and OCR was conducted at M.I.T. during November 20-22, 1974 and the proceedings of the workshop were widely distribution.

Investigators: Professor A. L. Bement

Support: National Science Foundation and Office of Coal Research

Recent References:

A. L. Bement, Proceedings of the NSF-OCR Engineering Workshop on MHD Materials. November 20-22, 1974, The Energy Laboratory, M.I.T., Cambridge, Massachusetts.

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

High radiation exposures to workers during maintenance of the primary coolant systems of present light water power reactors results in a significant cost which must be borne by the power consumers. The MITR is well suited to the development of an experimental facility which would be devoted to studying the basic processes involved in the production, activation and transport of radioactive corrosion products. A technical team comprising MIT staff members, from various relevant disciplines, is actively developing a proposal for an in-core loop at MITR which is designed to simulate part of the primary coolant system of a PWR.

Investigators: Professors O.K. Harling, D.D. Lanning, R. Latanision, G. Yurek, Dr. W. Hinkle, and Mrs. J. Bernard.

Support: U.S. Energy Research and Development Administration vis Energy Laboratory.

Related Academic Subjects:

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

3.3.9 Surface Effects in Fusion Reactors

The first walls of controlled fusion devices will be subjected to intensive irradiation by fast neutrons, photons and particles. These radiation fields have implications for the plasma maintenance as well as for the structure of the first wall and energy conversion blanket.

Surface effects studies addressing some parts of the overall CTR first wall problem are being carried out in partnership with researchers at the Pacific Northwest Laboratory of the Battelle Memorial Institute, a principal ERDA laboratory.

Investigators: Professor O.K. Harling and J. Woo, MIT and Drs. David L. Styris and M.T. Thomas at Battelle

Support: U.S. Energy Research and Development Administration

Related Academic Subjects:

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

3.3.10 Bulk Irradiation Damage Studies to Simulate CTR Effects

The fast neutron radiation fields in future controlled thermonuclear reactors (CTR's) will adversely affect the mechanical properties of first wall structural material. Development of the required understanding of damage effects and a design data base are needed prior to the design of the experimental power and demonstration power reactors (EPR and DPR). Facilities used to test materials for fusion reactor applications are inadequate, since the gas production associated with displacement damage in the CTR cannot readily be simulated in a fast fission reactor, a need has developed for CTR damage simulation.

Use of the MITR for the simulation of CTR effects is being investigated. The approach is based upon use of the double thermal neutron nickel capture reaction $^{58}Ni(n,)$ $^{59}Ni(n,)$ ^{56}Fe to produce helium and the fast flux in MITR to simultaneously produce displacement damage.

Investigators: Professor O.K. Harling and K.C. Russel, Ms. S. West and Mr. E. Daxon

Support: M.I.T. Energy Laboratory

3.4 Nuclear Chemical Technology

Many parts of the nuclear fuel cycle outside of the reactor involve large scale chemical reactions. These include the preparation of uranium ore, the enrichment of uranium, the reprocessing of special fuel and waste disposal operations. In dealing with these important problems, a knowledge of nuclear chemical engineering is vital.

3.4.1 Subject of Instruction

22.76J, Nuclear Chemical Engineering - Applications of chemical engineering to the processing of materials for and from nuclear reactors. Fuel cycles for nuclear reactors; chemistry of uranium, thorium, zirconium, plutonium and fission products; extraction and purification of uranium and thorium from their ores; processing of irradiated nuclear fuel; solvent extraction and ion exchange as applied to nuclear materials; management of radioactive wastes; principles of and processes for isotope separation.

3.5. MIT Reactor Modification

The MIT Reactor has operated since 1958, most recently at a thermal power of 5,000 kw. Neutrons and gamma rays produced by the reactor have been used by many investigators for a great variety of research projects in physics, chemistry, geology, engineering and medicine. On May 24, 1974, the reactor was shut down to make preplanned modifications that are designed to modernize the reactor and to provide a threefold increase in 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.

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

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

Operation of the MITR-II has been on a routine basis at 2.5 MW since the spring of 1976. It is planned to complete the additional modifications for operation up to 5 MW by late fall of 1976.

Engineering studies and experiments on aspects of the new core have provided many opportunities for student research and participation and give unique practical training. Topics investigated by students include reactor physics calculations, neutron transport measurements in a mock-up of the new beam port and reflector configuration, fluid flow measurements on a hydraulic mock-up, heat transfer measurement and theoretical calculations on finned plates, safety analysis and fuel management studies, and construction, startup and checkout operation of the modified reactor.

Investigators: Professors. J.W. Gosnell, A.F. Henry, D.D. Lanning, N.C. Rasmussen, N.E. Todreas; Messrs. G. Allen, Jr., R. Chin, L. Clark, K. Collins, W. Emrich, S. Kauffman, J. Knotts, D. Labbe, U. Liu, B. Momsen, P. Scheinert, H. Shaffer, R. Swartz, W. Szymczak, S. Wu, P. Meagher, S. Grill, J. Shin, M.K. Yeung

Support: MIT Reactor Depreciation Research Account

Related Academic Subjects:

22.32	Nuclear Power Reactors
22.33	Nuclear Reactor Design
22.313	Engineering of Nuclear Reactors
22.314	Structural Mechanics in Nuclear Power Technology
22.901-22.904	Special Problems in Nuclear Engineering

Recent References:

H. Shaffer, "Starting and Testing of the Massachusetts Institute of Technology Research Reactor, MITR-II, S.M. Thesis, September 1975.

W. Szymczak, "Experimental Investigations of Heat Transfer Characteristics of MITR-II Fuel Plants, In-Channel Thermocouple Response and Calibration," S.M. Thesis, M.I.T. Department of Nuclear Engineering, September 1975.

G. Allen, Jr., D. Lanning, "Initial Power Distributions in the MITR-II", to be presented at the American Nuclear Society meeting, Washington, D.C., November 1976.

G. Allen, Jr., "The Reactor Engineering of the MITR-II Construction and Startup", Ph.D. thesis, M.I.T. Department of Nuclear Engineering, June 1976.

D. Lanning, L. Clark, Jr., J. Gosnell, G. Allen, Jr., "MIT Reactor Modification", to be presented at the American Nuclear Society meeting, Washington, D.C., November 1976.

3.6 Applied Radiation Physics

This program is primarily concerned with the utilization of neutron and laser radiation in application to material science problems. During the last few years a rather comprehensive program of experimental and theoretical studies of thermodynamic, structural, transport and vibrational properties of matter has been established. The techniques used in these investigations, which range from molecular dynamics of simple solids and fluids to diffusion and motility of biological macromolecules and cells, are inelastic scattering of thermal neutrons, intensity-correlation spectroscopy of light scattering, and computer simulation experiments. The program is unique among universities because it combines the capabilities of neutron scattering and light scattering, and much of its strength lies in the close interaction between in-house experimental and theoretical efforts.

3.6.1 Subjects of Instruction

The following subjects of instruction are offered:

22.04 Radiation Effects and Uses, an undergraduate course which discusses the current problems in science, technology, health, and environment which involve radiation effects and their utilization. Material is presented in an essentially descriptive manner with introductory lectures followed by special topics related to the various activities in the Department. Emphasis is on an overview and a general appreciation of the range of physical phenomena which one can later study in depth.

22.51 Interaction of Radiations with Matter, which treats the basic principles of the interaction of electromagnetic radiations and charge particles with matter. It includes an introduction to classical electrodynamics, quantum theory of radiation fields and time-dependent perturbation theory. Applications are made to laser spectroscopy, X-ray diffraction, photoelectric effect, Compton scattering, Bremsstrahlung, pair production, and passage of charge particles through matter.

22.52, Neutron Physics and Applications, treats the basic principles of neutron interaction with nuclei in matter and the inelastic scattering of thermal and cold neutrons in solids and liquids. Applications are selected to demonstrate the unique features of thermal-neutron scattering as a research tool in solid-state and liquid-state physics and molecular spectroscopy.

3.6.2 Neutron Spectrometry and Molecular Dynamics in Solids and Fluids

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

A three-axis crystal spectometer has been constructed at the M.I.T. reactor and put into operation in 1971. Because the M.I.T. reactor has been shut down for modificationa, neutron-scattering experiments have been carried out at the Argonne National Laboratory. The principal study conducted during this period was a series of measurements of incoherent scattering in hydrogen gases pressurized up to 2000 atmospheres. The density dependence of the self-diffusion coefficient was studied through the observed quasielastic line width, and the data confirmed the recent prediction (based on computer molecular dynamics simulation results) of correlation effects in dense fluids. The wave number dependence of the observed line width clearly showed deviations from behavior characteristic of hydrodynamic fluctuations. Such effects will be analyzed using kinetic theory as well as results obtained from computer simulation experiments (see Sections 3.6.4 and 3.6.7)

A study of molecular dynamics of surfaces has been initiated. Using a sample of properly processed Grafoil with an adsorbed monolayer of methane molecules, preliminary measurements of elastic and inelastic scattering were recently made at Argonne to investigate the process of two-dimensional diffusion on the surface. It is expected that neutron studies will yield valuable information on the relation between the macroscopic properties of adsorbed phases and the molecular interactions of surfaces.

Another project related to the present program of studies in molecular dynamics is photon intensity correlation measurement in laser scattering. This is described separately in Sec. 3.6.6.

Investigators: Professors S.H. Chen, S. Yip; Messrs. T.A. Postol, J. Chao.

Support: ERDA (cumulative since 2/1/69, $735,684; current, 2/1/76 through 1/31/77, $80,000).

Related Academic Subjects

22.52 Neutron Physics and Applications

Recent References

T.A. Postol, "Observations of Enhanced Self Diffusion in High Density Hydrogen by Incoherent Neutron Scattering", Ph.D. Thesis, Department of Nuclear Engineering, 1975.

T.A. Postol, S.H. Chen and K. Skold, "Observations of Enhanced Self Diffusion in High Density Gaseous Hydrogen by Incoherent Neutron Scattering", Proceedings of International Conference on Neutron Scattering, Gatlinburg, Tenn., June 1976.

J.C. Castresana, G.F. Mazenko and S. Yip, "Thermal Fluctuations in a Mixture of Hard Spheres", The Physical Review A, August (1976).

J.C. Castresana, G.F. Mazenko and S. Yip, "Thermal Fluctuations in Gas Mixtures", Annals of Physics (in press).

3.6.3 Neutron Molecular Spectroscopy

The primary purpose of this program is to apply the technique of neutron inelastic scattering to problems of molecular vibrations in large organic molecules and hydrogen-bonded solids. A new spectrometer is being completed at the M.I.T. Reactor which will have a multiple-analyser crystal coupled with a position sensitive neutron detector. This arrangement makes maximum use of the scattered neutrons over a wide solid angle so that the total efficiency of data collection is about fifty times higher than the conventional spectrometer.

The present program involves a two-pronged attack on the problem of molecular vibrations, acquisition of neutron-scattering spectra and quantitative interpretation of these spectra using lattice dynamics calculations.

During the modification of the M.I.T. reactor, neutron scattering measurements were carried out in collaborative efforts with other research reactor facilities. Spectra of acetic acid and two deuterated derivatives (CH_3COOH, CH_3COOD and CD_3COOH) and spectra of the hydrocarbons cyclopentane and cyclohexane were obtained in collaboration with the Solid State Science group at Argonne National Laboratory. In another joint study with Argonne information about the dynamics of the proton in cesium hydrogen dinitrate, an unusual hydrogen-bonded substance, was obtained. A study of glycine ($NH_3CH_2CO_2$ and $ND_3CH_2CO_2$) has been undertaken which involves measurements at the Institute Laue-Langevin in Grenoble, France. Excellent spectra of formic acid and its deuterated derivatives were obtained using the spectrometers at the Atomic Energy Research Establishment, Harwell, England.

The formic acid spectra provide the focus for our current calculational efforts. Computer codes have been developed to compute the eigenvalues and eigenvectors of molecular vibrations in crystalline formic acid using interactomic potential functions. These results are then used to analyze the experimental spectra and in this way one obtains a quantitative test of the potential functions used. When fully developed this technique will become a powerful method of studying molecular forces in the solid state.

Investigators: Professors S.H. Chen and S. Yip; Dr. C.V. Berney, Professor R.G. Gordon (Chemistry Dept., Harvard University), Professor P.K. Tseng (visiting), Mr. D.H. Johnson.

Support: NSF ($259,600 from 6/1/73 to 9/1/76; $90,000 from 9/1/76 to 8/31/77).

Related Academic Subjects

22.52 Neutron Physics and Applications

Recent References

C.V. Berney, "Neutron Scattering from Fermi-Resonant Vibrational Modes in Carbon Dioxide", Journal of Chemical Physics 62, 936 (1975).

B.S. Hudson, H. Karp and S.H. Chen, "Pseudorotational Motion of Methylcyclopantane observed by Neutron Inelastic Scattering", Journal of Chemical Physics 62, 4563 (1975).

J. Roziere and C.V. Berney, "Neutron-Scattering Spectrum of Cesium Hydrogen Dinitrate," Journal of the American Chemical Society 98, 1582 (1976).

S.H. Chen and S. Yip, "Neutron Molecular Spectroscopy", Physics Today, Vol. 29, No. 4, p. 32, April 1976.

C.V. Berney, D.H. Johnson, S. Yip and S.H. Chen, "Potential Function Colculations of Lattice Vibrations in Formic Acid and Comparison with Neutron-Scattering Spectrum", Proceedings of International Conference on Neutron Scattering, Gatlinburg, Tenn., June 1976.

C.V. Berney and J.W. White, "Deuterium Substitution in Neutron-Scattering Spectroscopy: Formic Acid and Deuterated Derivatives", in preparation.

3.6.4 Thermal Fluctuations and Transport Phenomena in Gases and Liquids

The study of space- and time-dependent fluctuations in gases and liquids has been a fundamental problem in nonequilibrium statistical mechanics for a number of years. These fluctuations are of interest because they are the basic properties of a many-body system and they determine the various transport processes that can take place in fluids. In the case of density fluctuations they can be directly measured by inelastic neutron and laser light scattering.

Current theories of thermal fluctuations are formulated in terms of space-time correlation functions. Such quantities can be obtained by solving an initial-value problem using appropriate transport equations. This is the kinetic theory approach which provides an explicit link between the microscopic description of molecular interactions and particle trajectories and the macroscopic behavior of transport properties and hydrodynamic processes.

The transport equations conventionally used to discuss transport properties of gases and liquids are the Boltzmann equation and the Enskog-Boltzmann equation. These equations are characterized by collision operators which treat the collision events as local in space and instantaneous in time, and at sufficiently high frequencies and short wavelengths such descriptions can be expected to break down. Recent studies of renormalized collision processes have led to the derivation of a generalized transport equation which goes considerably beyond the level of the Enskog-Boltzmann equation. The removal of the high-frequency and short-wavelength deficiencies is one significant improvement which will be important in the analysis of neutron scattering experiments. Another new feature is the inclusion of correlated binary collision events which lead to collective effects such as the non-exponential decay of autocorrelation functions at long times. These effects have been observed in recent computer simulation studies and measurements of self-diffusion coefficients.

Detailed calculations have been made to demonstrate that generalized transport equations provide the most systematic method for a unified study of thermal fluctuations in fluids at arbitrary frequencies and wavelengths. In these studies computer molecular dynamics data and neutron-scattering spectra were used to assess the quantitative utility of the theory.

Investigators: Professor S. Yip; Messrs. Juan Castresana and Paulo Furtado.

Support: NSF (cumulative form 6/1/67 to 4/30/76, $223,300).

Related Academic Subjects

22.51 Interactions of Radiation with Matter
22.52 Neutron Physics and Applications

Recent References

P.M. Furtado, "Propagation of Density Fluctuations in Simple Fluids: Collective and Single Particle Motions", Ph.D. Thesis, Department of Nuclear Engineering, MIT, 1975.

P.M. Furtado, G.F. Mazenko and S. Yip, "Hard-Sphere Kinetic Theory Analysis of Classical, Simple Liquids", The Physical Review A12, 1655 (1975).

P.M. Furtado, G.F. Mazenko and S. Yip, "Kinetic Model Description of Dense Hard-Sphere Fluids", The Physical Review A13, 1641 (1976).

P.M. Furtado, G.F. Mazenko and S. Yip, "Effects of Correlated Collisions on Atomic Diffusion in a Hard-Sphere Fluid", The Physical Review A, August (1976).

G.F. Mazenko and S. Yip, "Renormalized Kinetic Theory of Dense Fluids", a chapter in Modern Theoretical Chemistry, B.J. Berne, ed. (Plenum Press, New York, 1976), to be published.

3.6.5 Computer Molecular Dynamics Studies

The purpose of this project is to establish at MIT a capability to carry out computer experiments on solids and fluids using the technique of molecular dynamics simulation. Such experiments are designed to calculate the equilibrium and nonequilibrium properties of bulk matter given a knowledge of the interatomic interaction potential for the system. The simulation technique consists of numerically integrating the Newton equations of motion for a system of several hundred atoms with periodic boundary conditions. The atomic positions and velocities computed in this manner are then used to obtain various properties such as the equation of state, structure factor, and vibrational frequency spectrum.

A computer program MOLDY (for molecular dynamics) has been developed which can handle general continuous potentials. Equation of state data have been generated for solid argon using a Lennard-Jones potential and the results found to agree very well with recent measurements. Present studies include a series of simulation designed to yield thermodynamic properties of crystals with grain boundaries. MOLDY also can be used to simulate molecular systems where each molecule is treated as a collection of atoms interacting through bonding forces. This capability will be applied to the investigation of energy distribution problems in systems where dissociation and recombination processes can take place.

Another objective of the project is to study problems involving chemical reactions. A simulation program for hard spheres has been used to investigate nonlinear behavior of model systems where molecules can convert from one species to another by prescribed reactions. Calculations are in progress to elucidate the nature of thermal instability in a system where molecules can be de-excited if sufficient energy is provided by a collision event.

Investigators: Professors S. Yip and O.L. Deutsch; Mr. Thomas Kwok.

Support: Army Research Office - Durham ($75,000 from 7/1/74 to 6/30/76; $45,423 from 7/1/76 to 6/30/77.

Related Academic Subject

22.52 Neutron Physics and Applications

Recent References

J.A. Cox, G.H. Bishop, R.J. Harrison and S. Yip, "Determination of the Stress Tensor in Atomic Scale Computer Simulation of Lattice Defects", in Computer Simulation for Materials Applications, Nuclear Metallurgy, Vol. 20, Arsenault, Beeler and Simmons, ed. (National Bureau of Standards, 1976), p. 434.

G.H. Bishop, G.A. Bruggeman, R.J. Harrison, J.A. Cox and S. Yip, "Computation of Surface Tension in Molecular Dynamics Experiments", ibid., p. 522.

R.J. Harrison, J.A. Cox, G.H. Bishop and S. Yip, "Computation of Entropy in Grain Boundary Computer Simulations", ibid., p. 604.

O.L. Deutsch and S. Yip, "Simulation of Dynamical Properties of Molecular Solids", ibid., p. 639.

P. Ortoleva and S. Yip, "Computer Molecular Dynamics Studies of a Chemical Instability", The Journal of Chemical Physics (in press).

3.6.6 Light Scattering Study of Structure and Motility of Cells

A new technique for determining frequency shifts in the scattering of laser light by performing photon intensity correlation measurements has been developed. This is a completely digital technique in the time domain in which the function $\langle I(t)I(t+\tau)\rangle$ can simultaneously be measured at 128 values of τ by using a delayed coincidence method. The accessible range for τ in this instrument is from 1 sec to 1 microsec. Applications of the method to Rayleigh scattering from fluctuations in a fluid medium have enabled us to measure with accuracy a line broadening from 1 Hz to 1 MHz. The method is particularly suited for the study of slow density or concentration fluctuations near the critical points. Recently this technique has been applied to measurement of motions of micro-organisms such as bacteria or blood cells in solution. The usefulness of the method for measurement of macromolecular aggregation kinetics in solutions also has been investigated.

Investigators: Professor S. H. Chen; Messrs. W. Veldkamp, M. Holz.

Support: ERDA

Related Academic Subjects

8.251	Physics of Noise and Fluctuations
8.442	Statistical Optics and Spectroscopy
22.51	Interaction of Radiation with Matter

Recent References

S. H. Chen, P. Tartaglia, and P. N. Pusey, "Light Scattering from Independent Particles - Non-Gaussian Corrections to the Clipped Intensity Correlation Function," Jour. of Physics, A6, 490 (1973).

P. Tartaglia, T. A. Postol, and S. H. Chen, "Comment on Correlation of Scaled Photon-Counting Fluctuations", Jour. of Physics, A6, 135 (1973).

P. Tartaglia and S. H. Chen, "The Spatial Coherence Factor in Light Scattering from a System of Independent Particles," Optics Communications, 7, 379 (1973).

P. Tartaglia and S. H. Chen, "Intensity Correlation of Light Scattered from Hydrodynamic Fluctuations," Jour. of Chem. Phys., 58, 4389 (1973).

R. Nossal and S. H. Chen, "Effects of Chemoattraction on the Motility of E-Coli Bacteria," Nature New Biology, 244, 253 (1973).

J. P. Boon, R. Nossal and S. H. Chen, "Light Scattering as a Probe of the Wiggling Motions of Microorganisms," Biophys. J., 14, 847 (1974).

S. H. Chen, W. B. Veldkamp and C. C. Lai, "A Simple Digital Clipped Correlator for Photon Correlation Spectroscopy," Rev. Sci. Inst., 46, 1356 (1975).

S. H. Chen, M. Holz and P. Tartaglia, "Quasi-elastic Light Scattering from Structured Particles", (Applied Optics 1976).

S. H. Chen and M. Holz, "Medical Applications of Photon Correlation Spectroscopy," (Med. Research Eng. 1976).

J. Rouch, C.C. Lai and S.H. Chen, "Brillouin Scattering Studies of Normal and Supercooled Water", (J. Chem. Phys.1976).

3.6.7 Thermal Neutron Scattering Studies of Dense Gases

Neutron scattering measurements of density fluctuations in gases provide a test of current statistical mechanical theories in a region of wavelengths and frequencies which can not be probed by any other experimental method. The primary objective of this project is to carry out such experiments over a wide range of densitites and temperatures and to analyze the data using the methods of kinetic theory and computer molecular dynamics simulations.

Recent studies in kinetic theory have shown that correlated or ring collisions are important processes in developing a molecular theory of fluids. While there is reason to believe the effects of these dynamical events are best studied in gases, no quantitative comparison between theory and experiment has been attempted. The phenomena of interest involve couplings of different modes of fluctuations so the theoretical problem is basically nonlinear and difficult to analyze. In order to be able to extract quantitative information from the neutron data,fluctuation spectra will be calculated using renormalized kinetic theory for hard spheres (see 3.6.4) as well as computer molecular dynamics simulations with continuous potentials.

The sample cell is currently being constructed. Initial measurements will use oxygen and will be carried out at the Brookhaven National Laboratory. Later measurements will include gas mixtures containing hydrogen.

Investigators: Professors S.-H. Chen and S. Yip; Professor P.K. Tseng (visiting)

Support: National Science Foundation (69,700 form 7/1/75 to 8/31/77).

Related Academic Subject

22.52 Neutron Physics and Applications

3.7 Applied Nuclear Physics

A good understanding of nuclear physics is basic to the education of nuclear engineers and to the application of nuclear reactions. The following subjects are offered by the Department.

3.7.1 Subjects of Instruction

The basic instruction in applied nuclear physics is presented as a two-semester sequence of subjects.

22.111, Nuclear Physics for Engineers I, discusses nuclear phenomena including stationary states of nuclei including nuclear charge, radius, mass, moments, parity, and statistics. Also included are discussions of barrier transmission, radioactive transitions, alpha, beta, and gamma decay, binding energy, nuclear forces, and nuclear models.

22.112, Nuclear Physics for Engineers II, is a continuation of 22.111 and treats nuclear dynamics including energetics and cross sections for nuclear reactions, scattering and fission. The passage of charged particles through matter involving ionization, scattering, and radiation losses is treated as well as the interaction of neutrons and gamma rays with matter.

3.8 Medical Applications of the MIT Reactor and Other Neutron Sources

3.8.1 Subjects of Instruction

22.55J, Biological and Medical Applications of Radiation and Radioisotopes I - 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.

22.56J, Biological and Medical Applications of Radiation and Radioisotopes II - Includes advanced topics and may be taken after 22.55J or separately. Radiation biology including radiation chemistry and cellular and mammalian radiation effects. Stable and radioactive isotope tracer applications. Principles of radiological imaging including computerized tomography and ionography. Advanced topics in nuclear medicine including transverse section and positron imaging. Principles of radiation therapy including charged particle and fast neutron radiation.

This summer a very successful two-week special program was offered by Professor Gordon Brownell and Dr. Brian Murray of the MIT Department of Nuclear Engineering and Dr. R.E. Zimmerman, Department of Radiology, Harvard Medical School. The first week (22.83s) covered principles of nuclear medicine, and the second week (22.85s) covered those fields required for an understanding of computerized axial tomography.

3.8.2 In Vivo Neutron Activation Analysis

We have completely refurbished the Department's pulsable Texas Nuclear Cockcroft-Walton neutron generator so that the original specifications are realizable. Current experiments include investigating the radiative capture spectra produced in a large tissue equivalent target with the machine in a pulsable mode, dosimetry studies in various H_2O and tissue equivalent phantoms and designing a facility for the total body analysis of live Rhesus monkeys. A whole body counter utilizing six large NaI detectors has been built specifically for these monkey studies. In addition, transport code calculations have been used to engineer a partial body (for humans) analysis system utilizing four ^{252}Cf sealed sources. This type of facility can easily measure changes of Ca content in the human hand to within 2% while producing a negligible whole body dose.

Investigators: Professor G. Brownell, Dr. B. Murray, Messrs. R. G. Zamenhof, R. I. Pettigrew, M. A. Campbell and M. S. Saidi.

Support: National Institutes of Health

Related Academic Subjects:

22.29 Nuclear Measurements Laboratory
22.41 Numerical Methods of Radiation Transport
22.55J Biological and Medical Applications of Radiation and Radioisotopes I
22.56J Biological and Medical Applications of Radiation and Radioisotopes II

Recent References:

B.W. Murray, G.L. Brownell, J.A. Correia, J. Harvey and R. Zamenhof, "Envelopment of an *in vivo* neutron activation analysis facility at M.I.T." Invited paper, Trans. Am. Nucl. Soc., 18:96, 1974.

R.I. Pettigrew, O.L. Deutsch, B.W. Murray, "Partial Body *in vivo* Neutron Activation Analysis using ^{252}Cf", Phys. Can. 32, 9.1, 1976.

R.G. Zamenhof and B.W. Murray, "The Measurement of Total Body Elemental Composition by Radiative Capture *in vivo* Neutron Analysis: A Preliminary Study", Phys. Can. 32, 9.3, 1976.

3.8.3 Thrombus (Clot) Detection Studies

We have developed a multi-wire proportional counter (MWPC) for clinical testing at the MGH to image ^{125}I labeled thrombi in patients. The MWPC is filled with krypton and is specifically designed to measure the X rays from ^{125}I with a high spatial resolution. High resolution images of forming clots in the legs of patients recovering from surgery will mean that appropriate treatment can be given quickly to reduce the risk of pulmonary embolism. A second part of these studies involves the development of a superior ^{125}I-labeled tracer used in the clinical studies. In collaboration with Professor David Waugh (Department of Biology), we have established a laboratory in NW13 to label bovine and human fibrinogens in various ways so that a superior clot localizing agent can be developed.

Investigators: Professor G. Brownell, Dr. B. Murray, Mr. J. L. Lazewatsky

Support: Health Sciences Fund (MIT) and the National Institutes of Health

Related Academic Subjects:

22.55J Biological and Medical Applications of Radiation and Radioisotopes I
22.56J Biological and Medical Applications of Radiation and Radioisotopes II

Recent References:

J.L. Lazewatsky and B.W. Murray, "^{125}I-Labeling of Fibrinogen by the Chloramine-T Method without Protein Denaturation", Thromb. Res. 8:373, 1976.

J.L. Lazewatsky, R.C. Lanza, B.W. Murray, C. Bolon, R. Burns, M. Szule, "A Portable Multiwire Proportional Chamber System for High Resolution ^{125}I Imaging", Presented at the ERDA Symposium on X- and Gamma-Ray Sources and Applications, Ann Arbor, May, 1976.

3.8.4 Renewed Clinical Trial of Boron Neutron Capture Therapy

During the past twelve months, a research proposal seeking funds for a renewed patient trial of this therapy has been written, site-visited, and funded by the National Cancer Institute. The NCI requests that more physical and animal experimentation be performed before further funds are allotted for patient irradiations. The physical experiments and development include refurbishing the medical Therapy Facility characterizing the therapy beam, continuing our development of a rapid boron assay system (using ^{252}Cf sealed sources), and defining the dose distributions in a head shaped phantom. The animal experiments are designed to compare the effects of boron neutron capture therapy on normal brain tissues as compared to conventional gamma-ray therapy. When these studies are complete in early 1977 another application for human irradiation will be made.

Investigators: Professor G. Brownell, Dr. B. Murray, Mr. R. Pettigrew

Support: National Institutes of Health

Related Academic Subjects:

22.41 Numerical Methods of Radiation Transport
22.55J Biological and Medical Applications of Radiation and Radioisotopes I
22.56J Biological and Medical Applications of Radiation and Radioisotopes II

Recent References:

G.L. Brownell, B.W. Murray, W.H. Sweet, G. Wellum, and A. Soloway, "Reassessment of Neutron Capture Therapy in the Treatment of Cerebral Gliomas", in Seventh National Cancer Proceedings, AEC, 827-837, Philadelphia, 1973, J.B. Lippincott.

B.W. Murray, O.L. Deutsch, R.G. Zamenhof, R.A. Rydin and G.L. Brownell, "New Approaches to the Dosimetry of Boron Neutron Capture Therapy at MIT-MGH", Invited paper, IAEA, Vienna, 1975.

R.G. Zamenhof, B.W. Murray, G.R. Wellum, E.I. Tolpin and G.L. Brownell, "Boron Neutron Capture Therapy for the Treatment of Cerebral Gliomas: I. A Theoretical Evaluation of the Efficacy of Various Neutron Beams", Med. Physics, 2, 47, 1975.

O.L. Deutsch, B.W. Murray, "Monte Carlo Dosimetry Calculations for Boron Neutron Capture Therapy in the Treatment of Brain Tumors", Nuclear Technol., 26, 320, 1975.

G.L. Brownell, B.W. Murray, "Biomedical Aspects of Nuclear Engineering Education", Nuclear Technol. 27, 60, 1975.

R.A. Rydin, O.L. Deutsch and B.W. Murray, "The Effect of Geometry on Capillary Wall Dose for Boron Neutron Capture Therapy", Phys. Med. Biol., 21, 134, 1976.

3.8.5 Particle Track Etch Method for Pu Assay

The "particle track etch" method has been investigated to determine the suitability of the MIT Reactor for the irradiation and evaluation of animal and human tissues containing trace amounts of plutonium. In this method, any material containing a heavy-particle emitting nuclide is mounted on a glass, mica or plastic backing for a period sufficiently long so that a suitable number of particle tracks are registered in the backing material. The backing is then chemically etched to bring out the tracks so that they can be counted or otherwise evaluated, usually in an optical microscope. If the nuclide of interest is fissionable by neutrons, the sample and backing are irradiated, and the fission fragment tracks are then brought out by etching.

In previous work prior to modification shutdown of the MITR, the "ARIE" procedure (anneal-re-irradiate-etch) was developed to eliminate or reduce the background fogging; this permits samples of bone containing very low levels of Pu (0.015 μCi Pu/Kg body weight) to be irradiated to a fluence of 10^{18} n/cm^2 without loss of the bone image. The method is much faster than conventional autoradiography based on alpha emission, and it is the only possible method when concentrations are so low that the latter method requires an unfeasibly long time.

Current work involves optimization of the irradiation conditions, increasing the sensitivity of the method to permit assaying of even lower Pu concentrations, an investigation of the bone image mechanism, and trials with other track registering materials.

Interest in the radiobiology of plutonium increases as more and more of this element enters the fuel cycle for nuclear power plants. The ultimate objective is to develop a routine method for studying very low levels of Pu (and other fissionable nuclides) in human tissue.

Investigators: Mr. L. Clark, Jr., Professor D. Lanning, Mr. N. Meissami

Support: University of Utah (USNRC) ($6,000)

Related Academic Subject:

22.112 Nuclear Physics for Engineers II

Recent References:

M.H. Fellows, "Bone Image Generation in Lexan Polycarbonate from Neutron-Induced Autoradiography," SM thesis, MIT Department of Nuclear Engineering (May 1974).

M.H. Fellows, *et al.*, "An Improved Technique for Neutron-Induced Autoradiography of Bone Containing Plutonium," *Health Physics*, Vol. 29, p. 97 (July 1975).

3.8.6 The Development of Radiation Synovectomy in Arthritis

Radiation synovectomy for the treatment of rheumatoid arthritis of the knee has been used in Europe but side effects have precluded its acceptance in the United States. These include lymphocyte aberrations (10% of patients), and leakage of radioactivity from treated knees (52-91%). If leakage could be prevented, the advantages of this simple procedure would be enormous, especially since the results of radiation synovectomy compare favorably with those of surgical synovectomy.

In collaboration with Dr. C. B. Sledge, Robert B. Brigham Hospital, we have been investigating an approach based on the principle of using a short half life, beta admitting radionuclide which is readily produced by irradiation in the MITR and whose tissue beta penetration is effectively confined to the rheumatoid synovium. Retention of the isotope in the joint is made possible and leakage minimized by incorporating it with biodegradable particles of a larger size than previously considered for this application. The radionuclide ^{165}Dy has a 137 min half life and a maximum beta energy of 1.3 MeV and fulfills these criteria. Ferric hydroxide macroaggregates are used to incorporate the activity and are carefully sized to provide an optimum particle size distribution.

The particle system has been tested in normal rabbits and in the antigen-induced rabbit arthritis model. The leakage of activity out of the synovial sac has been found to be less than 0.33% at 5 and 24 hours after injection.

Investigator: Dr. D. J. Hnatowich

Support: National Institutes of Health

3.8.7 In Vitro Activation Analysis

The collaborative research in calcium metabolism between Dr. R. Neer, Endocrine Unit, Massachusetts General Hospital and the Nuclear Engineering Department has continued throughout the past year. The goal of this study is to permit the use of stable ^{48}Ca as a tracer to measure intestinal calcium absorption quickly and accurately with reduced radiation dosage to patients. The analysis for calcium-48 in precipitated patient urine samples is being accomplished by in vitro activation analysis. The analysis has been refined the past year to the point of clinical applicability and patient samples are now being analyzed on a regular basis. The method will now be exploited to improve our current clinical research in the effects of hydroyylated vitamin D metabolites in man, the normal adult requirement for vitamin D and its modification by dietary calcium and phosphorus, the role of disordered phosphate metabolism in the idiopathic hypercalciuria syndrome, and the optimum clinical management of patients with hyperparathyroidism, vitamin D resistance, or recurrent kidney stones with hypercalciuria.

<u>Investigator</u>: Dr. D. J. Hnatowich

<u>Support:</u> National Institutes of Health

3.8.8 The Development of the Osmium-Iridium Radionuclide Generator

The use of radionuclide angiocardiography in clinical practice is increasing since a relatively large number of hemodynamic parameters can be evaluated non-traumatically. A number of restrictions of radionuclide angiocardiography are apparent at the present time. Gamma scintillation cameras have limited spatial resolution. Technetium-99m, the most commonly used radionuclide for angiography does not allow multiple projections due to high residual background from previous injections. Similarly, serial studies to evaluate pathophysiologic progression of disease or the effects of to receive radiation beyond the observation period of 20 to 30 seconds.

In collaboration with Dr. S. Treves, The Children's Hospital Medical Center, we have been developing the ^{191}Os($T_{1/2}$ = 15.3 days)→^{191m}Ir ($T_{1/2}$ = 4.9 sec.) generator. Osmium-191 is produced in the MITR by the ^{190}Os(n,γ) ^{191}OsCl$_6^{-2}$ on an anion exchange resin and eluting with a solution of 8.7% NaCl at pH 2.2. Generators capable of providing 15 mCi of ^{191m}Ir in 1.5 ml of elutant have been constructed and larger units are planned.

Multiple radionuclide angiocardiograms were obtained on rhesus monkeys with adequate visualization of the superior vena cava, right heart, pulmonary artery, lungs, left heart aorta, and kidneys. The estimated radiation exposure for a 10 kgm child with ^{191m}Ir is about 1.2 mrads to the whole body while that due to ^{191}Os is 60 mrads. Improved diagnostic information and decreased radiation dose should make ^{191m}Ir useful in the diagnosis of cardiovascular disease on prematures and newborn infants.

Investigators: Drs. D. J. Hnatowich and S. Kulprathipanja

Support: National Institutes of Health

3.9 Quantum Thermodynamics

Professor Elias P. Gyftopoulos and Dr. George N. Hatsopoulos of the Mechanical Engineering Department continued their research on the foundations of quantum thermodynamics.

3.9.1 Subjects of Instruction

22.57J, General Thermodynamics I - presents the foundations of classical thermodynamics in a general way. Applications of thermodynamics to design and analysis of energy conversion systems and industrial processes. First part: the first and second laws of thermodynamics introduced together with the definitions of work, energy, stable equilibrium, available work, thermodynamic potentials, and interactions (work, nonwork, heat, mass transfer). Second part: thermodynamics applied to analyses of stable equilibrium properties of materials, and to analysis and design of systems and processes, including cryogenic and refrigeration cycles, power generation and conversion (conventional and nuclear), industrial installations, combustion, and propulsion.

22.572J, General Thermodynamics II - continuation of application of thermodynamics to analysis of systems and processes, including chemical reactions and chemical equilibria, combustion, interfaces between phases, and plasmas. Linear rate processes and phenomenological equations. Introduction to quantum thermodynamics by means of a unified presentation of quantum and thermodynamic principles. Relation of second law to irreducible quantal dispersions. Applications to special problems, including one particle system.

22.58J, Quantum Foundations of Mechanics and Thermodynamics, is a unified quantum approach to mechanics and thermodynamics deduced from three postulates of quantum physics and two postulates of classical thermodynamics. Definitions of state, change of state described by unitary transformations in time, equilibrium state, stable equilibrium state, and reversible processes. Definitions and determinations of adiabatic availability, available work and entropy for all systems, with one or many degrees of freedom, and all states, stable equilibrium or nonstable. Nature of irreversibility and its relation to field theory. Derivation of the general canonical distribution. Applications to bosons and fermions, and to ideal and perfect substances in stable equilibrium states.

3.10 Energy and the Environment

3.10.1 Subjects of Instruction

A total of five subjects of instruction are offered under the category of energy and the environment by the Department including a new subject 22.81 Energy Assessment. This subject will be offered by Professor David Rose in the spring term of 1977.

22.08J, Energy - Energy from a holistic point of view: provision, rational utilization and conservation, regulation, environmental effects, and the interconnectedness of energy with 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 sectiors: transportation, industrial, commercial and domestic. Regulatory, tax, and other institutional arrangements that affect production and use patterns. Environmental costs and opportunities associated with exercising various energy strategies, both existing and proposed. Domestic and international political, strategic and economic implications.

22.37, Environmental Impact of Power Production - An assessment of the various environmental impacts of producing thermal and electric power with currently available technology. Impacts compared 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.

22.80, National Socio-Technological Problems and Responses - A subject designed to acquaint the student with large socio-technological problems and our capabilities regarding them, in ways beyond discipline-oriented research. The structure and content of national problems; connectivity between problems and sectors. Review of present organizations at the working level (universities, national laboratories, industrial laboratories, etc.) the extent to which they relate to the decision-making levels, and the extent to which they match or mismatch their programs to the true scale of problems. Recent efforts to make new organizations or reorient present ones. Recent debates, programs and proposals related to energy and the environment used as particular examples.

22.81, Energy Assessment - 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 specific energy fields or fields in which energy is important, and who desire a holistic overview.

22.913/914, Graduate Seminar in Energy Assessment - Primarily designed as a communication medium among students conducting research in energy-related areas, and as a means for obtaining critical evaluation of their on-going research work. Covers topics ranging from technological comparisons to environmental, social, resource and political impacts, depending on current student and faculty interest. 22.914 is a continuation of 22.913 in the second term.

3.10.2 Hydrogen Economy Energy and Transmission Storage Technology

In work completed recently an investigation of the feasibility of hydrogen storage and transmission of hydrogen in liquid media was performed. The benefits of such storage are achievement of high stored energy densities and highly efficient energy transmission via pipelines. The storage methods examined include liquid dissolution of hydrogen, use of cryogenic liquid hydrogen, chemical reaction with a host liquid. The only feasible method is found to be the last, with the most attractive scheme being combination of gaseous hydrogen with benzene (C_6H_6) exothermically to form cyclohexane (C_6H_{12}); followed at the hydrogen utilization stage by endothemic dehydrogenation back to benzene (which is recycled). Such a scheme is proposed as the fundamental storage and transmission medium for possible future nuclear-based hydrogen economy technologies.

Energy storage densities obtained are similar to those observed for metal hydride storage, costs are lower; and long-distance energy transmission costs are found to be approximately 20% lower than those encountered with electrical power transmission. The technology for all stages of such a hydrogen economy scheme are either available currently, or are estimated to be easily within the capabilities of current design methods and material properties. Most importantly such a scheme would avoid the problems of hydrogen embrittlement of steels - which is seen currently to be the main impediment to the gas-based hydrogen economy.

Investigators: Professor M.W. Golay and Mr. M.J. Harper

Related Academic Subjects:

22.33	Nuclear Reactor Design
22.34	Economics of Nuclear Power
22.37	Environmental Impact of Nuclear Power

22.311	Engineering Principles for Nuclear Engineers
22.312	Engineering of Nuclear Reactors
22.314	Structural Mechanics in Nuclear Power Technology
22.80	National Socio-Technological Problems and Responses

Support: Energy Research and Development (through the Energy Laboratory)

Recent References:

M.J Harper, "Hydrogen Storage in a Liquid Medium", S.M. thesis, M.I.T. Department of Nuclear Engineering, 1976.

3.10.3 Waste Heat Disposal

Since the late 1960's waste heat disposal at power stations has become an increasingly conscientious and expensive problem. In recent years it has occurred that one power station (Quad Cities) was forced to install cooling towers in place of a once-through cooling system (at an estimated cost of $100 million), and the Environmental Protection Agency has mandated that in the future once-through cooling shall be prohibited unless it can be shown that the associated environmental impacts are negligible.

To address these problems, and others, work has been underway to develop technical options which will make waste heat disposal more economical, and to provide the means for reduction of the associated environmental impacts. The major areas of research activity are the following.

(1) Cooling Tower Drift Propagation and Effluent Reduction

In the environmental impact area past and current work has focused upon chemical drift from evaporative cooling towers and the carryover of entrained liquid droplets (and their dissolved solids) in the tower effluent stream. One of the major environmental impacts of evaporative cooling tower operation is that of drift salt deposition, which has been observed to cause metal corrosion, electrical switchgear arcing, and the death of vegetation. At several sites salt water cooling towers are currently planned, and as competition increases for fresh water sources it would be expected that use of contaminated makeup water sources would grow, as this occurs the associated problems of drift deposition can be expected to grow also.

An experimental and analytical effort is currently in the third year of funding with the goal of permitting improved drift eliminator designs to be developed, and of testing new concepts for drift-rate measurement. These efforts are centered around a wind tunnel which provides an environment similar to that of a cooling tower fill exit area, which permits different drift eliminator designs to be tested, and the dynamics of their operation to be observed. In addition to the wind tunnel the project has also involved the development of a laser-activated droplet spectrometer for use in eliminator efficiency measurements. This facility is currently being used for performance testing of a spectrum of commercially-available drift eliminators in which the observed parameters include droplet transmission as a function of droplet size, pressure drop and flow Reynolds number. This facility will also be used to test the feasibility of use of Na^{24} as a radioactive tracer in measuring salt drift flux. This is important since no reliable drift measurement method currently exists for field use.

In related work a model has been developed for prediction of drift propagation in the environment. It is currently being tested against available field data, and extended to predict two-phase flow effects.

(2) Economics and Technical Innovations

The work in economics and technology of waste heat disposal has involved two current and one earlier effort.

In economic modelling a computer program (MITDAS) has been developed which considers all of the available waste heat disposal technologies, and will calculate the minimum cost system configuration for a given mix of apparatus.

A particularly important application of the program has occurred in work focussed upon evaluation of the feasibility of a dry cooling heat rejection system, using a thermal storage reservoir. In this work the optimal dry cooling thermal storage pond (TSP) configurations (and attendant economic benefits) have been obtained at a spectrum of power plant sites in the United States. This effort has also involved a series of experiments at the MIT Civil Engineering Department's Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics - investigating criteria for the proper design of a flow-stratified thermal storage pond. It has been found that the greatest benefits of a dry cooling tower - TSP system occur at sites having high daily peak dry bulb temperatures (e.g. Winslow, Arizona or Needles, California). The benefits of the TSP arise because of protection of the power station from generation capacity penalties which would result from high condenser temperatures, and because use of a TSP would permit conventional, rather than new design modified, steam turbines to be used in the power station. The experimental work indicates in a simple-geometry reservoir that thermally stratified flows would result in short-circuiting of the pond and a loss of capacity. It has been found that use of simple slot-jet barriers at intervals along the pond's length induces adequate mixing for efficient pond performance.

In earlier work it has been found that the performance of natural draft cooling towers can be augmented economically through use of fans.

Investigators: Professor M.W. Golay, Messrs. J. Chan, F. Chan, E.C. Guyer.

Support: MIT Energy Laboratory ($30,000/year), EPRI ($8,500/year), ERDA ($4,500/year)

Related Academic Subjects:

22.37	Environmental Impact of Nuclear Power
22.311	Engineering Principles for Nuclear Engineers
22.312	Engineering of Nuclear Reactors
22.33	Nuclear Reactor Design
22.34	Economics of Nuclear Power

Recent References:

J. Chan and M. W. Golay, Numerical Simulation of Cooling Tower Drift Eliminator Performance, Trans. Amer. Soc. Mech. Engrs; (1976)

E.C. Guyer and M.W. Golay, "Evaluation of Combined Thermal Storage Pond-Cooling Tower Systems", Trans. Amer. Nucl. Soc., 22, 509 (1975)

E.C. Gyer, "Estimation of Drift-Droplet Salt Deposition from Spray Ponds," S.M. Thesis, MIT Department of Nuclear Engineering, (1974).

E.C. Guyer and M.W. Golay, "A Model for Salt Drift Deposition from Spray Ponds," Symposium of Physical and Biological Effects on the Environment of Cooling Systems and Thermal Discharges at Nuclear Power Stations, IAEA, Oslo, Norway (1974).

T.J. Flanagan, "Augmentation of Wet Natural Draft Cooling", SM Thesis, Department of Nuclear Engineering, MIT (August 1972)

T.J. Flanagan, "Augmentation of Natural Draft Evaporative Cooling Tower Performance," Trans. Amer. Nuc. Soc., 16 (1973).

3.10.4 Reclamation of Coal Strip Mines in Appalachia

This work proceeds in cooperation with the Civil Engineering Department and the Brookhaven National Laboratory, and will serve as an input to the BNL program for environmental assessment of energy options. Specifically, we are concerned with local and down-stream consequences of strip-mining, as an aid to judging its attractiveness in specific locations. We find that (1) the original concept of BNL, to make a general program for predicting the consequences of strip-mining, can only be implemented in a very approximate way; insufficient data on specific watersheds exists and will continue to exist for many years; furthermore, many of the transport mechanisms of pollutants cannot be well quantified at present. These results, though of negative nature, are useful in helping to describe realistically how precise or imprecise these modeling studies are liable to be. On the positive side, we can show that the present formula criteria for judging environmental impacts of specific future strip mining activites are inadequate, and we are improving them. The work thus leads toward a new formula-type criterion which, though still uncomfortably imprecise, is better than hitherto, requires a reasonable and modest amount of data pertaining to a specific area, and can be used in energy modeling studies.

Investigators: Professor David J. Rose and Mr. J. Perkowski

Support: Brookhaven National Laboratory

Related Academic Subjects:

22.37	Environmental Impact of Nuclear Power
22.80	National Socio-Technological Problems and Responses
22.08J	Energy

3.10.5 Assessment of Energy Options

Active study continues on comparative assessment in relation to nuclear power in its various forms, and also in relation to national energy policy. Many activities listed elsewhere could be re-cited here. The following, not listed elsewhere, are typical.

Safety, environmental, and other aspects of the liquid metal fast breeder program have been assessed and summarized for the U.S. Congress.

An analysis of the energy problem, dealing with sectorial interests, imperfect time perspectives, and other organizational and institutional faults has been carried to a first stage of public presentation, showing how the difficulties with energy presently experienced in 1976 could have been largely avoided by logical action apparent in 1970.

We have become increasingly concerned with the question of quantitatively comparing the risks and benefits of nuclear and alternate energy systems, both in the near term and in the far future. On this topic, we have completed a study comparing nuclear fission options with its alternatives, chiefly coal.

Investigators: Professors D.J. Rose and M.J. Driscoll

Related Academic Subjects:

22.37 Environmental Impacts of Power Production
22.80 National Socio-technological Problems and Responses
22.08J Energy

Recent References:

Safety and Environmental Issues Related to the Liquid Metal Fast Breeder Reactor and its Principal Alternatives, especially Coal, and Decisions about the United States Nuclear Breeder Program, by David J. Rose, Proceedings of the Subcommittee to Review the National Breeder Reactor Program, Joint Committee on Atomic Energy, United States Congress, July 1975.

The Energy Problem: Fragmented, Resource-Specific Approaches Don't Work, by David J. Rose, Proceedings of the American Association of Arts and Sciences Conference on Adapting Science to Social Needs, May 1976.

Nuclear Power - Compared to What?, by David J. Rose, Patrick W. Walsh, Larry L. Leskovian, American Scientist, Volume 63, pp. 291-299, May-June 1976.

3.11 Applied Plasma Physics

The role of controlled fusion power as the long range solution to the world's energy supply problem has become more obvious and the pace of research is quickening. International efforts in controlled fusion research have converged on several key experiments to be constructed during the next decade; the theoretical analyses are beginning to yield the results needed to predict reactor behavior; the engineering constraints have been determined and the extremely difficult task of designing an economical, power-producing reactor is occupying experts in many fields. The Nuclear Engineering Department is increasing its efforts in all of these areas, and in so doing has strengthened its ties with those national laboratories engaged in the controlled fusion program.

In addition to renewing its ties with the ALCATOR program and playing a major role in the design and construction of VERSATOR II, the plasma physics group of the Nuclear Engineering Department has just completed the first stage of an intense design study with Oak Ridge National Laboratory and greatly expanded the scope of its ERDA-supported "Fusion Technology Program". The Fusion Technology Program is an interdepartmental program supported by the development and technology branch of ERDA's Division of Magnetic Fusion Engineering. The program's goal is the investigation of various engineering problems of controlled fusion reactors with particular emphasis on radiation damage, reactor fueling, reactor blanket analysis, safety and environmental studies, and new concept development. During FY 1977, the program will involve a substantial fraction of the Nuclear Engineering Department's faculty: Professors O. Deutsch, M. Golay, O. K. Harling, L. M. Lidsky (Principal Investigator), P. A. Politzer, N. C. Rasmussen, D. J. Rose, and N. E. Todreas. In addition there will be faculty members from the departments of metallurgy and of Mechanical Engineering as well as some 15-20 graduate students and research associates.

The first phase of the joint MIT-ORNL technology study, "EBT-RX", has been completed. If, in fact, the physics of the situation turns out to be favorable, an EBT fusion reactor would allow steady-state operation at high power density in a mechanical arrangement that would alleviate the remote maintenance and accessibility problems common to the more intensively studied Tokamak reactors. Therefore, the EBT concept has become a subject of much interest. In addition to the primary goal of this project - the EBT-RX design study itself - the collaboration succeeded in acquainting a wider range of staff and faculty at M.I.T. with problems of CTR interest, set up an organizational model for implementing future moderate scale technology studies and furnished an excellent medium for motivating and educating students.

Our laboratory program in plasma physics includes experimental studies of the nonlinear properties of various plasma instabilities in an attempt to connect this difficult regime of plasma theory with experimental fact and to begin to assess the importance of various instabilities in causing plasma transport and defusion. Professor Politzer is particularly involved in this aspect of our work. We are developing several advanced diagnostics for ALCATOR and ALCATOR-C, most notably a surface-mounted, fast acting bolometer and an ultraviolet Doppler spectrometer capable of measuring ion temperature distributions in hot, dense plasmas of thermonuclear class. Professor L. S. Scaturro, a recent addition to our faculty, is playing an important role in both of these developments. Professor T. H. Dupree is continuing his investigations of transport phenomena in the limit of fully developed turbulence, the regime that seems to be the one of most importance for both thermonuclear and astrophysical studies.

3.11.1 Subjects of Instruction

The Department offers a comprehensive list of subjects in this field.

22.07, Preparation for Plasma Physics, which introduces the fusion processes and potential for energy production. Physical processes in ionized gases and discussion of the natural occurrence of plasmas in the universe. Basic concepts of plasma physics and introduction to the elementary electro-magnetic theory needed to describe plasma behavior. Elementary theory of plasma stability and transport.

22.610, Controlled Fusion Power - Survey of energy for the future, including resources, demand and cost, with emphasis on the 21st century. Introduction to controlled fusion concepts: fusion reactions, basic methods of producing and confining fusion plasmas; extraction of energy and regeneration of fuel. Introduction to technologies related to controlled fusion power: large magnetic field structures, lasers, heat transfer, materials. Description and critique of proposed fusion reactor schemes. The outlook for controlled fusion power, in the post-AD 2000 period. This course will include appropriate reviews of electromagnetic theory and other necessary skills, to prepare an entering graduate student for more specialized fusion studies in the Nuclear Engineering Department.

22.611J, Introduction to Plasma Physics - Introduction to plasma phenomena. The occurrence and generation of plasmas with applications to thermonuclear fusion, gas lasers, and astrophysics. Motion of charged particles in electric and magnetic fields; drifts; adiabatic invariants. Plasma models: kinetic equations, MHD and fluid approximations. Wave propagation in cold and warm plasmas; Landau damping. Simple equilibrium and stability analysis. Introduction to collisions and transport processes.

22.612, Plasmas and Controlled Fusion - Topics in plasma dynamics of current interest in thermonuclear research, such as: conductivity of highly ionized plasma; radiation losses; wave propagation; magnetic field structures; instabilities; dynamics of a thermonuclear system; critical review of confinement schemes; advanced diagnostic techniques; recent experiments.

22.621, Thermonuclear Reactor Design - Systems analysis and design of controlled thermonuclear reactors, development of criteria for CTR feasibility on basis of economic and technical considerations, detailed critical review of U.S. NRC's prototype references reactor designs, non-maxwellian reactors, laser induced fusion, blanket neutronics, fission-fusion symbiosis, radiation damage, environmental hazards.

22.622, Special Topics in Thermonuclear Reactor Design - Engineering physics of CTR subsystem: large superconducting magnetic materials and design, neutral beam generation and control, divertors and gas blankets, energy storage and recovery, structural material behavior. There will be a group design project chosen from topics of current interest, based on extending the formal lectures of the course. Object of the design project will be to study the integration of the wide range of plasma physics, technological and economic reality in a large scale research device such as a mirror reactor neutron source or break-even two component Tokamak.

22.63, Engineering Principles for Fusion Reactor - Introductory course in engineering principles and practices of systems relevent to controlled fusion. 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. Applicatons to fusion systems.

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

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

22.66, Transport Phenomena in Toroidal Systems - Diffusion of particles and energy across the magnetic field, caused by Coulomb collisions, represents a lower bound on containment. Whereas single particle drift orbits and the Fokker Planck collision operator are well understood, their implementation in plasma transport theory for inhomogeneous magnetic field geometry is complex and produces unforeseen physical effects. Review of collisional transport in straight magnetic fields, derivation of the drift kinetic equation for toroidal fields of the Tokamak type, kinetic theory of diffusion in the collisional, plateau, and banana regime to provide an understanding of the current literature of neoclassical transport. The relevance to thermonuclear experiments will be evident throughout.

22.67, Plasma Diagnostics - Diagnostic systems for measurement of plasma properties and behavior with emphasis on thermonuclear plasmas. Measurements of time averaged and fluctuating values of particle densities, particle energies, electric and magnetic fields. Techniques of electric and magnetic probes; methods involving emission, absorption, and scattering of r-f, microwave, optical, and x-ray radiation by plasmas; schemes involving emission or scattering of particles by plasmas.

22.68J, Introduction to Plasma Kinetic Theory - Collec- behavior in collisionless fully-ionized plasmas; theory of the Vlasov equation. Waves in plasma without magnetic field, particle-wave resonance; Landau damping. Resonant and non-resonant electrostatic instabilities. Dynamics of a magnetized plasma; particle drifts, currents, constants of motion; adiabatic invariants. Drift-kinetic equation; low-frequency instabilities. Examples of micro-instability in anisotropic plasmas. Microturbulence and "collion"; trapped-particle modes.

22.29, Plasma Laboratory, Introduction to the advanced experimental techniques needed for research in plasma physics and useful in experimental atomic and nuclear physics. Laboratory work on vacuum systems, plasma generation and diagnostics, physics of ionized gases, ion sources and beam optics, cryogenics, magnetic field generation and other topics of current interest.

3.11.2 Experimental Plasma Physics and Diagnostic Development

The plasma physics and controlled fusion group maintains a continuing program of experimental research and development in several areas supportive of the controlled fusion effort. This work is directed along two major lines, diagnostic and highly ionized plasma experiments. We are engaged in the development of diagnostic techniques for measurement of plasma parameters in large scale research devices, both those presently in operation (e.g., Alcator) and larger proposed facilities. New diagnostic techniques are needed because fusion research devices are approaching new regimes of plasma density and temperature in which many of the methods presently in use are no longer applicable. Furthermore, more detailed and accurate measurements are needed for comparison with new theoretical models of "reactor grade" plamas. Fortunately, the energy density in these devices is high enough to facilitate new measurement techniques. These diagnostic studies include the measurement of ion temperatures using Doppler broadening of the Lyman-α hydrogen emission line (a), the scattering of infrared radiation by a plasma (b), and the use of bolometric measurements to determine the overall power balance in large devices (c).

The second major area of experimental research involves the testing, in laboratory scale experiments, of the predictions of theories of plasma behavior. These tests are needed both to verify the theories which are being used in the design of large scale devices, and to provide information which will lead to further development of the theoretical models of a plasma. The experiments are conducted usually by one or two graduate students using plasma facilities specifically designed for each study. Among these experiments are studies of the effects of turbulence in plasmas (d), and of plasma stability in the presence of magnetically trapped particles (e). These programs are described in more detail below:

a) <u>High resolution Lyman-α spectrometer</u>

The measurement of ion temperatures, with good spatial and temporal resolution, is essential to our understanding of plasma behavior in large scale confinement experiments. As these devices increase in size, new diagnostic methods are needed. We have developed and tested several ion temperature diagnostics and are currently designing a device based on recent advances in the technology of spectrometric instruments. This spectrometer is based on the fact that the width of a spectral line emitted by a group of atoms depends on the Doppler shifts introduced by the motions of the individual atoms. Thus the line shape reflects the velocity distribution of the atoms. We take advantage, in this scheme, of the presence in any large plasma device of a few neutral hydrogen atoms which have the same energy distribution as the plasma ions in their neighborhood. In order to obtain good spatial resolution we must use the Lyman-α line of hydrogen (1215Å) which falls in the vacuum ultraviolet. The VUV spectrometer uses an echelle grating, working in the 47th order of diffraction to provide the dispersion needed to measure accurately the line shape. Since the light emitted from the center of the plasma escapes without being absorbed, this technique permits us to probe the entire cross-section of the plasma. The Lyman-α spectrometer is being designed to be compatible with the MIT Alcator confinement experiment.

b) <u>Scattering of infrared radiation by a plasma</u>

Sufficiently long wavelength radiation interacts with a plasma in a particularly interesting fashion. If the wavelength is properly chosen with respect to the plasma's characteristic (Debye) length and several other conditions are met, then the scattered radiation carried information concerning the plasma fluctuation spectrum, turbulence level and distribution, ion temperature, instability frequencies and spectral structure, etc. Unfortunately, this wealth of information is not easy to extract because the scattering coefficient is very small (typically one part in 10^{12} of the incoming radiation is scattered into the detector) and the frequency shift of scattered radiation is small (typically one part in 10^9). It is possible to overcome both of these formidable problems by using a laser with sufficient power to overcome the small scattering cross section and sufficient spectral purity to allow frequency resolution by advanced optical techniques. We have built a one hundred watt single-mode, single frequency laser for these measurements based on a 10.5 μ CO_2 laser operating in the oscillator-amplifier configuration. Even with such a source it is necessary to cool the complete optical path to liquid nitrogen temperature to reduce background thermal radiation and to cool the infrared detector itself to liquid helium temperature to enhance its sensitivity. The experiment is being carried out using the same target plasma previously used for our ruby laser Thompson scattering and CO_2 laser incoherent scattering experiments. These latter techniques are now in widespread use.

c) Energy flux measurements in Alcator

An important question in any large scale confinement experiment is the overall power balance. The energy provided to the plasma from external sources escapes from the plasma in the form of charged particles, neutral particles, and electromagnetic radiation, both in spectral lines and in continuous spectra. The relative distribution of power in these loss channels gives important information about the plasma confinement processes. We are using a bolometer installed in the vacuum chamber wall of the Alcator device to measure the time resolved energy flux to the wall. The use of various filter materials in front of the bolometer allows the measurement of either the total energy flux, or one or more of its components.

d) Turbulence in plasmas

The study of fluctuation phenomena in plasmas is important because electromagnetic fluctuations, whether coherent or turbulent, can strongly influence the transport of particles and energy across a confined plasma. The understanding of wave phenomena has progressed to the point where the linear properties of plasma waves, such as stability and propagation characteristics, are fairly well known. On the other hand the behavior of waves, and their influence on the plasma when they grow to large amplitude, is poorly understood. Our experimental work in this area is concentrated on measuring the influence of a specified spectrum of electric field fluctuations on the energy distribution of the particles in a plasma, and on the stability of this plasma. Because of the design of this experimental facility, we are able to measure the energy distribution as a function of time and thus to determine the nonlinear diffusion coefficients for direct comparison with the predictions of plasma turbulence theory.

e) Trapped particle instabilities

When plasma particles are confined in a magnetic well, they execute periodic orbits. Because of this low frequcency periodicity, they can transfer energy to waves in the plasma and thus drive instabilities. Our experimental work in this area has been concerned with the identification of a particular class of these instabilities related to the presence of trapped electrons. We are presently investigating the nonlinear physical phenomena which limit the growth of these instabilities. This study will give valuable information both for the development of the theory of nonlinear processes in plasmas and for the possible control of unstable plasma configurations.

Investigators: Professor L.M. Lidsky, P.A. Politzer and L. Scaturro

Support: Energy Research and Development Administration

Related Academic Subjects:

22.611 Introduction to Plasma Physics
22.612 Plasmas and Controlled Fusion
22.64J Plasma Kinetic Theory
22.65J Advanced Topics in Plasma Kinetic Theory
22.66 Transport Phenomena in Toroidal Systems

3.11.3 Fusion Reactor Technology

The demonstration of the scientific feasibility of controlled fusion power -- a milestone that might possibly be reached within ten years -- is not sufficient to ensure that fusion will become ultimately a significant contributor to our energy requirements. The development of controlled thermonuclear reactors for commercial power generation will require also the solution of many extraordinarily difficult technological problems. Many of these problems are similar to, but more difficult than, those associated with fission reactor technology. Thus, the Nuclear Engineering Department with its unique combination of skills and fission reactor expertise, is the ideal locus for a balanced attack for these problems. We are working on many aspects of fusion reactor technology in an interdepartmental program supported by the Development and Technology Branch of ERDA's Division of Magnetic Fusion Energy.

Although this program is relatively young, there have been substantial contributions to the national fusion program. During the past year, for example, the following results were achieved:

1) A study of helium-assisted void nucleation theory was completed.
2) A new theory was outlined for the stability of incoherent precipitates under irradiation.
3) Experimental studies of irradiation induced creep in reactor materials were performed using deuteron and alpha particle beams.
4) The design of the 14-MeV neutron source facility study was completed and construction was started.
5) Technology assessments were performed on several aspects of long, laser-heated solenoidal plasma devices.
6) A detailed study of a hybrid fission-fusion system was completed and published.
7) The preliminary design of an EBT fusion reactor was com-out in conjunction with ORNL.
8) The design envelope for a solid-pellet-loaded, helium-cooled blanket capable of operation with failed modules was delineated.
9) A numerical code was developed for the analysis of the interface between a fuel pellet and a fusion reactor plasma in the presence of magnetic fields.
10) An experimental device for the measurement of pellet ablation characteristics was designed and is nearing completion.

a) Experimental and Theoretical Studies of Radiation Damage

This project includes several existing research areas of importance to the CTR program (analytical studies of neutron effects, experimental simulation of neutron damage, and evaluation of high-energy neutron radiation facilities) and a new program in fission spectrum irradiation. During the first two and one-half years of this program analytical efforts have focused on developing a general, consistent theory of the nucleation and growth of voids and interstitial clusters in the presence of various defect sinks, traps, and gases. Additional theoretical studies related to the phase stability of alloys and to void formation under steady state and pulsed plasma operation were initiated. Concurrently, techniques were developed for conducting radiation creep experiments on significant size specimens with a variety of energetic particle beams, and a set of experiments was carried out in conjunction with Lowell University and NRL. A one-quarter linear scale "gas-target intense neutron source" facility for the experimental investigation of the dynamics of gas flow with intense ion beam heating was designed and is nearing completion. We are continuing our theoretical studies of alloy phase stability and of void nucleation and beginning to develop the analytical tools needed to predict displacement damage hope to begin such irradiations soon. Studies listed on this topic are carried out with colleagues in the Department of Materials Science and Engineering.

b) Technology Assessment

Technology assessment is a title covering a broad range of endeavors. The most salient feature is that it is a process designed to help one to make decisions: on one scale to decide, for example, whether it is worthwhile at this time, to invest a large fraction of technology development money in investigating liquid metal pumping; on another scale, to try to decide whether or not a particular fusion reactor concept appears almost incapable of extension to fusion reactor size; and in the most general sense, to continually assess the potential of fusion vis a vis other power sources in order to help set general policy. In our relatively small group at M.I.T., we have been active across this broad scale but only in carefully selected areas where we think the problem can be well-posed and our expertise bears on the question. We plan to continue choosing such targets of opportunity as they appear.

During the last eighteen months, we performed an assessment of long laser-heated solenoidal plasmas as fusion devices in order to explore problems related to engineering requirements of the magnetic field structures likely to be required and to assess the plausibility of the gas-blanket wall protection scheme proposed in the reference θ-pinch reactors. Our preliminary report shows that the magnetic field design puts severe limits on this type of device, a circumstance not much explored in assessments of the concepts by other groups. In this study, as in our blanket system studies, the goal of our work was to delimit allowable design envelopes for systems subject to many simultaneous constraints. Our initial conclusion is that there is no economically interesting design. Our study of the gas blanket cooling concept was specific. We conclude that a sharp, insulating boundary as postulated in the reference θ-pinch report is extremely unlikely to be formed. We further conclude that the engineering features required to inject gas with the uniformity and speed required if this concept is to work are not compatible with the other features required in the pinch concept. Working papers describing both these results in detail have been prepared and are being circulated throughout the community for comment.

c) Fission-Fusion Studies

These studies concern various aspects of fissile fuel generation in systems driven by fusion neutrons. Our previous work in this area has resulted in the development of a hierarchical structure suitable for description of the wide variety of interelated systems and some "Figures of Merits" suitable for choosing among alternatives. A set of expressions was developed suitable for calculating system dynamics and economics in a non-fissioning 233-U-breeding fusion reactor blanket. Recent work has concentrated on the use of fission plates to give a higher fissile neutron production rate per incident fusion neutron. These blankets have concomitantly large energy multiplication ratios and it becomes economically expedient to capture and convert the resultant energy. These hybrid systems differ from those considered elsewhere in that the fissile production takes place in a molten salt with relatively low fission product contamination. Thus the fuel cycle is simplified and made much more economical.

The potential value of hybrid or symbiotic fissile fuel generators is critically dependent upon the fuel and energy values assumed to exist at the time of introduction, and the particular fissile demand at that time with particular refer-plants. We have developed self-consistant economic models capable of determining the allowable cost of fissile producing systems as a function of pure fusion and pure fission core costs, electricity and fuel values, and the attainable Q of the fusion device.

We have developed a neutronically-optimized fusion reactor blanket design that represents tritium and breeds 2.27 fissile atoms per 14-MeV neutron. This design seems operable under reduction engineering constraints and appears fundamentally safe. We are now investigating in considerable detail some of the important engineering questions for this particular design - most notably those issues concerned with liquid metal pumping in high magnetic fields.

d) <u>High Aspect Ratio Toroidal Reactors - EBT</u>

The EBT experiment is the most advanced example of a class of moderate β, high aspect ratio, steady-state toroidal devices. This class has exciting potential if the physics can be extrapolated to the reactor regime. Because they are capable of operating at moderate β in steady state the system power density is higher, total cycle efficiency is increased and the problems associated with cyclic stresses are greatly mitigated. Furthermore, the high aspect ratio alleviates many of the mechanical arrangement, remote maintenance, and accessibility problems common to low aspect ratio machines. Because the physics of this class of device is still in the exploratory phase the reactor implications of EBT have not yet been fully explored. We are participating in a joint ORNL-MIT design study of the possible EBT based fullscale fusion reactor - EBTRX. The primary goal of the EBTRX study was the development of a conceptually realizable first order optimized EBT reactor model and a list of the critical assumptions and approximations implicit in these models. The reference design helped delineate the appropriate scale size, operating regime, support system requirements of such a reactor, and demonstrates the sensitivity of scale and operating characteristics to changes in system or plasma parameters. The first reference design has been completed and published as a joint ORNL-MIT report.

We are continuing to work in close conjunction with ORNL on two groups of problems. The first are concerned with detailed investigation of several important details of the reference design. The second group involves a more general study of the conceptual class of high aspect ratio toroids with particular attention paid to linked minimum B mirror systems. The EBT study has demonstrated that there are enormous conceptual advantages to be gained in such systems but it is by no means certain that the EBT physics can be scaled to reactor regimes or that the EBT is the best example of this class of device. A system of linked highly-stabilized mirrors is particularly interesting in that the increased surface/volume ratio may allow even more efficient utilization of the high β's that are conceptually possible in these devices.

e) Fusion Reactor Blanket Analysis

This program is engaged in the delineation of design envelopes for several fusion blanket concepts. These envelopes are determined by the constraints imposed by thermal hydraulic, neutronic, material, radiological and operational considerations. In such highly constrained systems, the definition of allowable "windows" and the explicit formulation of the complex multipartite tradeoffs furnishes a set of very important design tools and allows the rapid evaluation of single point designs. We have nearly completed an assessment of solid fuel, gas-cooled blanket systems subject to the additionally imposed constraint that they be capable of operation with failed components. We will next initiate a study of liquid lithium cooled blanket designs with our prime objective remaining that of identifying envelopes rather than specific design points.

A scalable blanket design based on individual helium cooled pebble bed modules was developed and used to quantify the tradeoffs between pumping power, operating temperature, tritium hold-up, and breeding ratio. Preliminary results of this study were presented at the D&T Blanket Engineering Workshop and in more detail in the doctoral thesis of F. Chen, "Thermal and Hydraulic Considerations for the Designing of a Solid Tokamak Blanket". Chen's work included the development of a thermal analysis code which allows the calculation of heat release as a function of radius in a variety of blanket configurations.

f) Pellet Fueling of Fusion Reactors

Our research program on pellet fueling combines analysis and experiment. We are preparing an experimental measurement of the ablation characteristics of solid material immersed in reactor grade plasmas and developing a computer code for analysis of the interface between a pellet and a reactor plasma. The experimental program is directed toward measurement of the shielding properties of the ablation cloud and will yield a direct measurement of the ablation rate of solid surfaces immersed in high-density plasmas. This information is needed to predict the pellet injection velocity required for a reactor fuelling and the resulting fuel deposition profile. The plasma for our experiment si furnished by a 30-cm linear Z-pinch which should provide energy fluxes in excess of $10^{21}eV^{3/2}$per cm^2 for up to 5 μsec. Since the steady state ablation cloud is thought to form in less than 100 nsec the Z-pinch will allow an effective simulation of the interaction.

The basic model assumed in the numerical analysis is that of a pellet surrounded by a cloud of ionized ablated material forming a cold, dense plasma which excludes the magnetic field from the region near the pellet surface and thus helps shield it from the energy flux. The shield plasma is modelled using the complete two-fluid equations in cylindrical geometry. The complete analysis involves seven coupled non-linear differential equations for density, temperatures, magnetic field and velocity fields.

g) Reactor Safety and Environmental Studies

This new program will apply the methodology developed for assessment of accident risks in U.S. commercial nuclear power plants (WASH 1400) to the analysis of safety hazards and to the development of reliability criteria for proposed full-scale fusion reactor plants and their components. The study will utilize the event-tree:fault-tree:consequence code technique developed by DoD and NASA and further specialized by ERDA for nuclear power plants in WASH-1400. This task will involve staff members familiar with reliability studies, with fusion reactor design, with the various engineering subdisciplines, and with hazard evaluation studies. The computer code used for WASH-1400 "consequence analysis" has recently been simplified and improved and is available to us for this study. The major effort will be the construction of event-trees for particular reference reactor designs and the development of reliability requirements based on admissable consequences. We expect that the development of reliability requirements will have strong impact on plant design.

The "safety" analysis described above does not address itself to "environmental" aspects of fusion reactor design that have received insufficient attention to date. There will be on-site radiation hazards during normal operation because of radiation and tritium leakage and the operational exposure necessitated by scheduled and unscheduled maintenance. Biological shielding of fusion reactors will be more difficult than that of fission reactors because of their greater physical extent and the necessity in most designs for large area straight penetrations of major regions of the blanket. We plan to develop semianalytical design techniques for guidance of engineering designs in this area (only highly specialized, one-shot numerical methods not capable of generalization have been used to date in the fusion program).

The problem of tritium release is important to both environmental and safety analysis in the sense described above. The development and verification of tritium transport models which can be used to identify the significant environmental sources and sinks of tritium is a difficult problem and one that is receiving insufficient attention. One particular concern will be the need to assess the consequences of the tritium contamination of a large watershed.

The long-range objective of this study is the development of a methodology suitable from environmental and safety analysis of proposed fusion reactor power plants and the application of this techniques to make quantitative estimates of fusion reactor plant hazards, comparative estimates of fusion reactor plant hazards vis a vis fission reactor and other fusion reactor designs, to develop design criteria to guide fusion reactor plant designers, and to furnish criteria by which postulated plant designs can be judged.

Investigators: Professors O. Deutsch, M. Golay, O, Harling, L. Lidsky, B. Mikic, P. Politzer, N. Rasmussen, M. Kazimi, D. Rose, K. Russell, N. Todreas; Visiting Scientist J. Woo, and approximately 15 to 18 associated graduate students

Support: U.S. Energy Research and Development Administration

Related Academic Subjects:

22.37 Environmental Impact of Nuclear Power
22.83 Reliability Analysis Methods
22.610 Controlled Fusion Power
22.612 Plasmas and Controlled Fusion
22.621 Thermonuclear Reactor Design
22.622 Special Topics in Thermonuclear Reactor Design
22.75J Radiation Effects to Reactor Structure Materials

3.11.4 Transport Processes in Fully Ionized Plasmas

The determination of the transport rate of particles, momentum, and energy across the confining magnetic field of a thermonuclear type plasma is one of the central problems of plasma theory. This transport is caused by Coulomb collisions as well as by collective oscillations producing micro-turbulence, or a combination of both. From this vast problem area, we have singled out the study of transport phenomena in toroidally confined plasmas of the Tokamak type. Starting from first principles (drift Vlasov equation and Fokker-Planck collision operator) our research concerns those problems of thermonuclear relevance that require mostly an analytic approach of theoretical plasma physics. Our results have frequently been the starting point for sizeable numerical evaluation of specific Tokamak questions of interest to the CTR laboratories.

Concerning turbulent transport, we are presently investigating Alfven-Wave turbulence in a fusion plasma created by the alpha-particles, the so-called "thermonuclear instabilities". A computer program has been written describing the time evolution of the alpha particle distribution function due to anomalous and collisional effects. Strong transient deviations from classical behaviour are observed.

Concerning collisional transport, our work centers around the so-called neoclassical theory. It has recently been extended from fundamental studies of approximate analytic forms of the Fokker-Planck operator, a complete theory of impurity ion diffusion in various mixed regimes of collisionality, and the effect of neutral hydrogen and charge exchange reactions on plasma transport, to applied problems such as an interpretation of toroidal plasma rotation observed in a particular Tokamak experiment, and alpha particle diffusion in a thermonuclear reactor as special cases of the impurity theory.

A new area of Tokamak-related plasma theory has been opened in collaboration with ORNL regarding analytic studies of plasma equilibrium in the high beta regime (beta = particle pressure/magnetic field pressure), under the constraint of magnetic flux conservation. The subject matter if of prime importance to the thermonuclear experiments at Oak Ridge and Princeton.

Investigators: Professor D.J. Sigmar, Dr. S.P. Hirshman, H.C. Chan, K. Rubenstein.

Support: U.S. Energy Research Development Administration, co-principal investigator with Professor J. McCune ($85,000 for FY 1976)

Related Academic Subjects:

22.65J Advanced Topics in Plasma Kinetic Theory
22.66 Transport Phenomena in Toroidal Systems
22.68J Introducation to Plasma Kinetic Theory
22.64J Plasma Kinetic Theory
22.611J Plasmas and Controlled Fusion

Recent References:

S.P. Hirshman and D.J. Sigmar, "Neoclassical Transport of a Multispecies Toroidal Plasma in Various Collisionality Regimes", submitted to Phys. Fluids.

J.F. Clarke and D.J. Sigmar, "Global properties of High Pressure Flux Conserving Tokamak Equilibria", submitted to Phys. Rev. Lett.

S.P. Hirshman, D.J. Sigmar, "Approximate Fokker Planck Collision Operator for Transport Theory", Phys. Fluids, 1976 (in press)

S.P. Hirshman, D.J. Sigmar and J.F. Clarke, "Neoclassical Transport Theory of Multispecies Plasma in Low Collisionality Regime", Phys. Fluids, 19 (1976) 656.

S.P. Hirshman, "Transport of Toroidal Plasma in a Mixed Collisionality Regime", Phys. Fluids, 19 (1976) 155.

D.J. Sigmar, "High Beta Tokamak", Review paper given at the "High Beta Workshop", Los Alamos Scientific Laboratory, July 1975.

3.11.5 Fusion Plasma Modelling and Reactor Synthesis

The behavior of a fusion plasma in a reactor environment is complicated by the synergetic effects of many basic processes. In order to interpret present generation of experiments and assess performance of conceptual systems, there is the need for a comprehensive model of the plasma with self consistent environmental conditions. The availability of such a model will also permit the synthesis of plasma physics and reactor engineering towards the design of more optimal controlled fusion systems. We have developed a basic format for construction of such models through assembly of computational modules (both analytical and numerical) of the relevant physical processes. This format is equivalent to a linearization procedure, which is valid if the time step is short compared to the characteristic time scale of the process. The modular construction then permits computation of the system dynamics simultaneously syntonic with the different time scales of the various processes.

The objective of this program is to develop a library of modules that can be assembled to model systems of interest that is physically realistic and computationally feasible and sufficiently versatile so that it can be continuously adapted and refined for use as a tool in plasma and reactor engineering to develop theories, design and interpret experiments and assess advanced concepts. For immediate usefulness, we have concentrated our effort on modelling mirror systems in order to assess and devise means to improve the energy balance of such systems. Modules have been developed to model gaseous electronics of plasma neutral interaction, wall reflux, energetic neutral beam trapping and scattering loss due to charged particle collisions. The modules have been assembled to model a radially inhomogeneous cylindrical plasma column confined by magnetic mirrors to examine the requirements for startup of a mirror fusion reactor. Current effort is being directed towards inclusion of multiple species, energy relaxation and fusion yield in order to assess the energy balance problem.

Investigator: Professor J. T. Woo

Support: U.S. Energy Research & Development Administration

Related Academic Subjects:

22.611J	Introduction to Plasma Physics
22.612	Plasma Physics & Controlled Fusion
22.63	Engineering Principles for Fusion Reactors
22.621	Thermonuclear Reactor Design
22.622	Special Topics in Thermonuclear Reactor Design
22.64J	Plasma Kinetic Theory
22.65J	Advanced Topics in Plasma Kinetic Theory
22.66	Transport Phenomena in Toroidal System

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 Science (or Doctor of Philosophy) in Nuclear Engineering. The duration and objectives of these programs are quite different.

The objective of the newly-instituted Bachelors degree program in Nuclear Engineering is to provide the student with a thorough mastery of scientific and engineering fundamentals together with comprehensive experience in their applications to problems in the field of nuclear engineering. This is accomplished through a curriculum under which the student, after completing Institute Science and Humanities requirements, selects coordinated subjects in thermodynamics, fluid flow, heat transfer, strength of materials and computer modeling taught by several of the other engineering departments; this, in turn, is followed up by Junior and Senior year subjects in Nuclear Engineering which include a design course and an S.B. thesis project. In this manner, the student is prepared either for immediate employment at the S.B. level in the nuclear industry, or for further, graduate level, training in Nuclear Engineering. In the latter case the student will, at the S.B. level, have already completed all of the core curriculum subjects now required of our S.M. students who enter without a nuclear engineering background.

The objective of the Master's program is to provide students who have had sound undergraduate training in physics, chemistry or engineering with the equivalent of one year of graduate education in nuclear engineering. Although full knowledge of the subject matter and techniques of nuclear engineering cannot be obtained in one year, graduates of this program are given a sound base of knowledge which prepared 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 a 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 are required to pass a searching and difficult general examination and then to 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 six fields of study mentioned in the introduction:

1. Reactor Physics
2. Reactor Engineering
3. Nuclear Fuel and Power Management
4. Applied Plasma Physics
5. Nuclear Materials Engineering
6. Applied Radiation Physics

Most candidates for the Master's degree specialize either in some combination of Reactor Physics and Reactor Engineering under the more general heading of Fission Reactor Technology, or in Applied Plasma Physics, Nuclear Materials Engineering, or Applied Radiation Physics.

The Nuclear Fuel and Power Management field includes so many different topics that students generally require more time than is available in the one-year Master's program. The two-year Engineer's degree program seems well-suited to the needs of students wishing to become thoroughly trained to work in this field. Other fields appropriate for Engineer's degree candidates are Reactor Engineering, Applied Plasma

Physics and Nuclear Materials Engineering.

All six fields 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 six 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 are intended principally for undergraduates. Subjects 22.89 Basic Electronic Instrumentation Laboratory, 22.311 Engineering Principles for Nuclear Engineers, and 22.71 Physical Metallurgy Principles for Engineers, are intended for graduate students who did not have the material as an undergraduate but need the material for graduate work.

Subjects designated "J" are taught jointly with other Departments, e.g. Physics, Mechanical Engineering, Metallurgy and Aeronautics and Astronautics.

Undergraduate Subjects

22.001	Seminar in Nuclear Engineering
22.003J	In Pursuit of Arms Control
22.02	Introduction to Applied Nuclear Physics
22.03	Engineering of Nuclear Power Reactor Systems
22.04	Radiation Effects and Uses
22.06	Nuclear Engineering in Society
22.07	Preparation for Plasma Physics
22.08J	Energy
22.28	Introductory Nuclear Measurements Laboratory
22.85J	Introduction to Technology and Law

Nuclear Physics

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

Nuclear Reactor Physics

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

Nuclear Reactor Engineering

22.311	Engineering Principles for Nuclear Engineers
22.312	Engineering of Nuclear Reactors
22.313	Advanced Engineering of Nuclear Reactors
22.314	Structural Mechanics in Nuclear Power Technology
22.315J	Structural Mechanics in Nuclear Power Technology
22.32	Nuclear Power Reactors
22.33	Nuclear Reactor Design
22.34	Economics of Nuclear Power
22.35	Nuclear Fuel Management
22.36J	Two-Phase Flow and Boiling Heat Transfer
22.37	Environmental Impact of Nuclear Power
22.39	Nuclear Reactor Operations and Safety
22.571J	General Thermodynamics I
22.572J	General Thermodynamics II
22.58J	Quantum Foundations of Mechanics and Thermodynamics

Numerical and Mathematical Methods

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

Applied Radiation Physics

22.51	Interaction of Radiations with Matter
22.52	Neutron Scattering and Applications
22.55J	Biological and Medical Applications of Radiation and Radioisotopes I
22.56J	Biological and Medical Applications of Radiation and Radioisotopes II

Plasmas and Controlled Fusion

22.610	Controlled Fusion Power
22.611J	Introduction to Plasma Physics
22.612	Plasmas and Controlled Fusion II
22.621	Thermonuclear Reactor Design
22.622	Special Topics in Thermonuclear Reactor Design
22.63	Engineering Principles for Fusion Reactors
22.64J	Plasma Kinetic Theory
22.65J	Advanced Topics in Plasma Kinetic Theory
22.66	Transport Phenomena in Toroidal Systems
22.67	Plasma Diagnostics
22.68J	Introduction to Plasma Kinetic Theory
22.69	Plasma Laboratory

Nuclear Materials

22.71J	Physical Metallurgy Principles for Engineers
22.72J	Nuclear Fuels
22.73J	Radiation Effects in Crystalline Solids
22.75J	Radiation Effects to Reactor Structural Materials
22.76J	Nuclear Chemical Engineering

General

22.80	National Socio-Technological Problems and Responses
22.81	Energy Assessment
22.82J	History of Nuclear Engineering: A Case Study in the Interaction between Technology and Society
22.83	Reliability Analysis Methods
22.85J	Introduction to Technology and Law
22.89	Basic Electronic Instrumentation Laboratory
22.901 } 22.904	Special Problems in Nuclear Engineering
22.911	Seminar in Nuclear Engineering
22.912	Seminar in Nuclear Engineering
22.913	Graduate Seminar in Energy Assessment
22.914	Graduate Seminar in Energy Assessment

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

Civil Engineering

1.143	Mathematical Optimization Techniques
1.146J	Engineering Systems Analysis
1.159	Judgement, Prediction and Risk in Engineering Planning
1.192J	Social Impact Assessment of Engineering Systems
1.502	Structural Analysis and Design
1.581	Structural Reliability
1.77	Water Quality Control
1.78	Water Quality Management
1.84	Environmental Management: Concepts, Issues and Processes

Mechanical Engineering

2.03J	Dynamics
2.06	Vibration and Sound
2.092	Methods of Engineering Analysis
2.093	Computer Methods in Dynamics

2.14	Control System Principles
2.155	Dynamics and Control of Thermofluid Processes and Systems
2.151	Advanced Systems Dynamics and Control
2.20	Fluid Mechanics
2.25	Advanced Fluid Mechanics
2.283	Fluid Physics of Pollution
2.30	Mechanical Behavior of Solids
2.301	Advanced Mechanical Behavior of Materials
2.34J	Structures and Materials: Engineering Case Studies
2.41J	Thermodynamics of Power Systems
2.55	Advanced Heat Transfer
2.56	Conduction Heat Transfer

Materials Science and Engineering

3.14	Physical Metallurgy
3.25J	Physics of Deformation and Fracture of Solids
3.37	Deformation Processing
3.38	Behavior of Metals at Elevated Temperatures
3.39	Fracture Mechanisms in Metals
3.42	Physics of Solids I
3.43	Physics of Solids II
3.54	Corrosion
3.57	Case Studies in Materials Engineering

Electrical Engineering and Computer Science

6.013	Electromagnetic Fields and Energy
6.232	Dynamical Systems and Control
6.271J 6.272J	Introduction to Operations Research
6.681 6.682	Power System Engineering
6.683	Planning and Operation of Power Systems

Physics

8.06 8.07 8.08	Theoretical Physics
8.311 8.312	Electromagnetic Theory
8.321 8.322 8.323	Quantum Theory

8.341 8.342	Methods of Theoretical Physics
8.511 8.512	Theory of Solids
8.641 8.642	Physics of High Temperature Plasmas

Chemical Engineering

10.38	Analysis and Simulation of Chemical Processing Systems
10.39	Energy Technology
10.47	Ion Exchange
10.50	Heat and Mass Transfer
10.52	Mechanics of Fluids
10.56	Chemical Engineering in Medicine
10.70	Principles of Combustion
10.72	Seminar in Air Pollution Control
10.73	Seminar in Fuel Conversion and Utilization
10.86 10.87 10.88	School of Chemical Engineering Practice -- Oak Ridge

Ocean Engineering

13.21	Ship Power and Propulsion
13.26J	Thermal Power Systems

Economics

14.23	Economics of Fuel and Power

Management

15.065	Decision Analysis
15.081	Mathematical Programming
15.084J	Theory of Mathematical Programming and Discrete Time Optional Control

Aeronautics and Astronautics

16.551	Plasma Propulsion and Power Generation

Mathematics

18.085	Methods of Applied Mathematics for Engineers
18.175	Theory of Probability
18.275 18.276	Numerical Analysis
18.279	Analysis of the Finite Element Method

4.4 Independent Activities Period

The Independent Activities Period (IAP) is a three and one half week intersession between the Christmas-New Year holiday and the beginning of the spring semester. During this period, members of the M.I.T. community may organize and participate in activities that are academic, vocational, esoteric, or recreational in nature. Activities may be individual or group oriented, and the format is as varied as the subject matter. Students may earn credit for thesis work or for accelerated versions of courses which are regularly listed in the curriculum. In addition to highly-structured mini-courses and seminar series, the IAP offerings of the Nuclear Engineering Department have included many survey-type seminars, film showings, laboratory demonstrations, and workshops that are motivational in nature.

In January 1976 a variety of offerings were given. Professor D. Sigmar and P. Politzer gave six lectures on fusion, Professor E. Gyftopoulos gave five lectures on energy conservation, Professor O. Deutsch organized a series of historical films relating to the development of nuclear power, Professor N. C. Rasmussen gave four lectures on the methodology of the WASH-1400 report. Dr. Charles Berney and Professor S. Yip gave an overview of neutron molecular spectroscopy, and Dr. D. J. Hnatowich organized a discussion of the various ways that the MITR has and is being used in the field of medicine. Among the students offering topics of interest, Mr. Mark Gottlieb planned a discussion period which addressed the nuclear energy controversy, and also organized a program on hybrid reactors. Mr. Paul Bayless arranged a tour of the M.I.T. Reactor.

The Independent Activities Period continues to be popular, with a majority of Nuclear Engineering students participating in one or more activities throughout the Institute.

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. The seminars are under the direction and support of the MIT Education Research Center. Professor D.D. Lanning is the Nuclear Engineering Department Coordinator.

The program has provided an excellent vehicle for undergraduates to learn about the research activities in the Department. During the 1976 summer, thirteen undergraduates were engaged in projects within the Department.

4.6 Descriptions of New and Revised Subjects

The academic program of the Department has continued to undergo revision and updating. Since fall 1975, fourteen new subjects have been added to the curriculum. Three of these (Preparation for Plasma Physics, Engineering Principles for Fusion Reactors, and Introduction to Plasma Kinetic Theory) reflect the continued emphasis on fusion reactor technology.

As described in Section 4.8, a major part of the requirements for the Undergraduate Program consist of subjects already offered by other Institute departments. However, four new introductory subjects have been added to the curriculum as a result of the introduction of this program. These subjects are, 22.001 Seminar in Nuclear Engineering, 22.07 Preparation for Plasma Physics, 22.03J In Pursuit of Arms Control, and 22.28 Introductory Nuclear Measurements Laboratory.

In the field of nuclear medicine, the revision of one course, 22.55J, and the addition of another, 22.56J (Biological and Medical Applications of Radiation and Radioisotopes I and II) reflect the better integration of the Department's courses in nuclear medicine with the MIT Health Sciences and Technology (HST) program.

Additional courses added to the curriculum are Reliability Analysis Methods, Introduction to Technology and Law, Graduate Seminar in Energy Assessment, Energy Assessment, General Thermodynamics, and Numerical Methods in Reactor Engineering Analysis.

A. New Subjects

22.001: Seminar in Nuclear Engineering -- Survey of the technology and applications of nuclear power. Introductory discussion of the basic phenomena of fission and fusion power and related aspects of reactor design. The many applications of reactors as research tools in biology, earth sciences, medicine, and physics discussed by guest lecturers from the appropriate discipline. A demonstration of the MIT Reactor as a research tool given in the area of neutron activation analysis.

22.003J: In Pursuit of Arms Control -- Review and analysis of nuclear and non-nuclear arms and efforts at arms control since World War II. Focus on the interaction of technological factors, changing strategic concepts, intelligence estimates and political judgments in the decision-making process. Topics include nuclear proliferation, Strategic Arms Limitation Talks, Mutual and Balanced Force Reductions, new military technology and current trends in U.S. and Soviet weapons programs. Students learn to evaluate and to design alternatives to current government arms control and national security policy.

22.07: Preparation for Plasma Physics -- Introduction to fusion processes and potential for energy production. Physical processes in ionized gases and discussion of the natural occurrence of plasmas in the universe. Basic concepts of plasma physics and introduction to the elementary electro-magnetic theory needed to describe plasma behavior. Elementary theory of plasma stability and transport.

22.28: Introductory Nuclear Measurements Laboratory -- Basic principles of interaction of nuclear radiation with matter. Statistical methods of data analysis; introduction to electronics in nuclear instrumentations; counting experiments using Geiger Muller counter, gas-filled proportional counter, scintillation and semiconductor detectors. Applications to experimental radiation physics, neutron physics, health physics and reactor technology.

22.56J: Biological and Medical Applications of Radiation and Radioisotopes II -- Radiation biology including radiation chemistry and cellular and mammalian radiation effects. Stable and radioactive isotope tracer applications. Principles of radiological imaging including computerized tomography and ionography. Advanced topics in nuclear medicine including transverse section and positron imaging. Principles of radiation thermapy including charged particle and fast neutron radiation.

22.43: Numerical Methods in Reactor Engineering Analysis -- Numerical methods used in analysis of nuclear reactor engineering problems are studied. Topics include finite difference and finite element formulations in solution of heat conduction, fluid dynamics, structural component design, and transient system analysis problems.

22.571J: General Thermodynamics I -- Presentation of foundations of classical thermodynamics in a general way. Applications of thermodynamics to design and analysis of energy conversion systems and industrial processes. First part: the first and second laws of thermodynamics introduced together with the definitions of work, energy, stable equilibrium, available work, thermodynamic potentials, and interactions (work, nonwork, heat, mass transfer). Second part: thermodynamics applied to analyses of stable equilibrium properties of materials, and to analysis and design of systems and processes, including cryogenic and refrigeration cycles, power generation and conversion (conventional and nuclear), industrial installations, combustion, and propulsion.

22.572J: General Thermodynamics II -- Continuation of application of thermodynamics to analysis of systems and processes, including chemical reactions and chemical equilibria, combustion, interfaces between phases, and plasmas. Linear rate processes and phenomenological equations. Introduction to quantum thermodynamics by means of a unified presentation of quantum and thermodynamic principles. Relation of second law to irreducible quantal dispersions. Applications to special problems, including one particle system.

22.63: Engineering Principles for Fusion Reactors -- Introductory subject for advanced undergraduate and graduate students without previous background in principles and practices of systems relevant to controlled fusion. Mechanism and techniques 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.

22.68J: Introduction to Plasma Kinetic Theory -- Collective behavior in collisionless fully ionized plasmas; theory of the Vlasov equation. Waves in plasma without magnetic field, particle wave resonsnce; Landau damping. Resonant and non-resonant electrostatic instabilities. Dynamics of a magnetized plasma; particle drifts, currents, constants of motion; adiabatic invariants. Drift-kinetic equation; low-frequency instabilities. Examples of micro-instability in anisotropic plasmas. Microturbulence and "collision"; trapped particle modes.

22.81: Energy Assessment -- 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 specific energy fields or fields in which energy is important, and who desire a holistic overview.

22.83: Reliability Analysis Methods -- Principles of the methods of reliability analyses including fault trees, decision trees and reliability block diagrams. Discussion of 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 nuclear power reactors discussed.

22.85J: Introduction to Technology and Law -- An introduction to the basic principles and functions of law, using legal cases and materials arising from scientific and technical issues. Provides an understanding of the law and legal processes as they impact upon the work of engineers and scientists. Study of judicial law-making focuses on elementary civil procedure and how change in legal doctrine takes place. Examination of statutory law-making shows how federal and state power to govern grows as technology grows. Administrative law-making focuses on the regulatory agencies' role in controlling and supporting technology as well as the extent and curbs on their power. Study of law cases, using so-called "Socratic method", and of legal processes and doctrines provides insight into the lawyer's working methods. Law's task of resolving conflicts found in scientific and engineering alternatives sensitizes students to choice of values questions.

22.913/914: Graduate Seminar in Energy Assessment -- Primarily designed as a communication medium among students conducting research in energy-related areas, and as a means for obtaining critical evaluation of their on-going research work. Covers topics ranging from technological comparisons to environmental, social, resource and political impacts, depending on current student and faculty interest.

B. Subjects with Major Revisions

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

22.55J: Biological and Medical Applications of Radiation and Radioisotopes I -- 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.

22.612: Plasmas and Controlled Fusion II -- Topics in the physics of controlled fusion devices. Particle and energy confinement. Heating methods: resistive, r-f and laser, particle injection. Fusion reactor dynamics; energy flow and efficiency. Interaction of electromagnetic radiation fields with plasmas; applications to heating and diagnostics. Fast pulse systems; pinches and pellets. Shock waves in plasmas. Impurities in thermonuclear reactors; sources, transport, and effects on energy balance.

4.7 Iranian Program

The Nuclear Engineering Department has established a special program for the training of students from Iran. In the summer of 1974 the Iranian Government approached the Nuclear Engineering Department concerning the possibility of offering graduate training to a large number of students from Iran in the area of nuclear technology. After considerable discussion, it was concluded that such a program could only be established as a special program and not part of our regular on-going curriculum because of the number of students involved and because of the additional facilities the Department would require.

In the spring of 1975 agreement was reached between M.I.T. and the Atomic Energy Organization of Iran for the training of approximately 50 students at the level of S.M. degrees. The program duration is to be for two years for two classes each of approximately 25. Thus, the program began in September 1975 with the first class and their training will be completed in June 1977. The second class began their work in June 1976 and they will complete their program in June 1978.

The program involves more than just the Nuclear Engineering Department, as the students arrive for the summer and have special training in the English language and mathematics. As one of the conditions for the programs, the students must meet the regular admissions condition to M.I.T. Thus, the students are fully intellectually qualified, but the program is unique in that the space has been reserved for nominees of the Atomic Energy Organization of Iran.

In order to carry out such a program the Department has had to increase its faculty size by approximately five and also add space for the students. The space modifications were supported by the Atomic Energy Organization of Iran and provided the Department with about 25 new study carousels in building NW12. The impact of this large a number of students has also increased the number of teaching assistantships available for our regular students.

We have made it a policy to keep class sizes as close to the same size as they have been in the past and have added multiple sections for the major subjects which are impacted.

At the completion of the first year of the program, we have found the students' performance to be almost the same as that of regular foreign students. For the first semester there was a somewhat lower performance, but this was correlated with the English language difficulties. By the end of the second semester the students in the program were doing as well as our regular students.

We have also had a special study made of the program to determine its impact on the Department, its students, faculty and staff as well as the rest of M.I.T. As far as we can tell, there have been no adverse effects from this type of special program.

4.8 Undergraduate Program

Traditionally the Nuclear Engineering Program at MIT has been only at the graduate level. The introduction of an undergraduate curriculum in the 1975-76 school year reflects MIT's response to the growing demand for such a program from students prompted by the increasing needs of a maturing nuclear industry. Most of the major nuclear engineering departments in the country now offer such a program. In preparing the undergraduate program we reviewed the programs at a number of other schools. On the basis of the results of this survey we concluded it was an appropriate time to offer such a program at MIT. As described below the program incorporates many subjects from other MIT Departments which enables the program to be given in an efficient way by using already existing resources.

4.8.1 Description of Undergraduate Program

The undergraduate program in Nuclear Engineering is designed to prepare students for careers in the nuclear power industry, or for graduate study in nuclear engineering and related disciplines. The field is very broad and hence the program is arranged to provide the student with considerable flexibility, while meeting the intellectual demands of career preparation.

The curriculum contains four major components. The first is the Institute Science Requirement, which provides the student with the appropriate foundation in physics, mathematics, and chemistry. The second component is the Institute Humanities requirement which is included in all bachelor's degree programs. The third component is Engineering Principles, in which a student is expected to become familiar with the foundations of engineering practice. The particular areas the student is required to study include strength of materials, fluid flow, thermodynamics, heat transfer, and computer modeling of physical systems. Most of the engineering departments at the Institute offer subjects covering these topics. Thus there is considerable latitude in fulfilling this segment of the curriculum. The fourth component of the undergraduate curriculum is a broad-based introduction to the specialties of nuclear engineering. Thus, students take subjects dealing with the physical phenomena of interest in nuclear power generation, nuclear and reactor physics, and nuclear engineering design. In addition, students may choose electives in applied radiation physics and technology, plasma physics, fusion reactor engineering, or engineering of nuclear systems.

The curriculum is designed to serve the interests of those who wish to specialize early in their program, as well as students preferring to obtain a broad-based background. Students are encouraged to select subjects from several departments at the Institute in order to perceive the many aspects of science and engineering in a meaningful perspective. Students are permitted to use graduate subjects for their elective if they wish advanced training in some aspect of the field.

4.8.2 Subjects of Instruction

The following subjects of instruction are offered:

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

22.003J, In Pursuit of Arms Control: Analysis of the Past and Choices for the Future, a review and analysis of nuclear and non-nuclear arms and efforts at arms control since World War II. Focus is on the interaction of technological factors, changing strategic concepts, intelligence estimates and political judgments in the decision-making process. Topics include nuclear proliferation, Strategic Arms Limitation Talks, Mutual and Balanced Force Reductions, new military technology and current trends in U. S. and Soviet weapons programs. Students learn to evaluate and to design alternatives to current government arms control and national security policy.

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

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

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

22.06, Nuclear Engineering in Society, is an introduction to nuclear engineering within the broader context of national energy problems and the public concern for the environment and for safety. Included is a discussion of the research and development problems that must be solved so that nuclear engineering will be able to contribute to the solution of those national problems, an introduction to fission reactor technology (physics and engineering of nuclear reactors, reactor design and operation, fusion reactions, confinement systems, recent experiments on the scientific feasibility of fusion, future engineering problems), and social and public-related questions arising from the use of nuclear power.

22.07, Preparation for Plasma Physics, is an introduction to fusion processes and potential for energy production. Topics studied include physical processes in ionized gases and a discussion of the natural occurrence of plasmas in the universe, basic concepts of plasma physics and an introduction to the elementary electro-magnetic theory needed to describe plasma behavior, and the elementary theory of plasma stability and transport.

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

22.28, Introductory Nuclear Measurements Laboratory, covers basic principles of interaction of nuclear radiation with matter. Statistical methods of data analysis; introduction to electronics in nuclear instrumentations; counting experiments using Geiger Müller counter, gas-filled proportional counter, scintillation and semiconductor detectors. Applications to experimental radiation physics, neutron physics, health physics and reactor technology.

22.85J, Introduction to Technology and Law, is an introduction to the basic principles and functions of law, using legal cases and materials arising from scientific and technical issues. Provides an understanding of the law and legal processes as they impact upon the work of engineers and scientists. Study of judicial law-making focuses on elementary civil procedure and how change in legal doctrine takes place. Examination of statutory law-making shows how federal and state power to govern grows as technology grows. Administrative law-making focuses on the regulatory agencies' role in controlling and supporting technology as well as the extent and curbs on their power. Study of law cases, using so-called "Socratic method", and of legal processes and doctrines provides insight into the lawyer's working methods. Law's task of resolving conflicts found in scientific and engineering alternatives sensitizes students to choice of values questions.

5. RESEARCH FACILITIES

5.1 M.I.T. Reactor

As of July 1976, the M.I.T. Reactor became an Institute facility. This ended a 16-year period of operation during which the reactor was under the supervision of the Nuclear Engineering Department. During that time the MITR logged 63,083 hours at full power and 250,445 megawatt hours.

Since its shutdown in May 1974, the reactor has been redesigned and restarted (see Section 3.5). On July 1, 1976 it was designated an Institute Laboratory under the responsibility of the Vice President of Research. Dr. Otto K. Harling was appointed Director of the MITR Laboratory. In this new mode of operation it is hoped that the facility will be more broadly used by the MIT research community.

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

5.2 Cryogenic Facilities

A closed-circuit, low-temperature helium refrigeration plant has been instilled with a design capacity of 200 watts at 4.2 °K. This plant provides refrigeration for the cold neutron source and supplies liquid helium to an in-core cryostat.

Helium compressors and recirculators and gaseous helium storage tanks are located in Building NW12. Transfer lines carry compressed helium to, and return low-pressure helium from, the reactor containment building. Within the reactor containment building are located the heat exchangers, expansion engines and Joule-Thompson expansion valve which complete the refrigeration unit. A 1000-liter Dewar vessel provides interim storage for liquid helium and serves to decouple the facilities being refrigerated from the refrigeration plant proper.

This refrigeration plant and liquid-helium supply are available to serve experiments employing closed-circuit low-temperature helium refrigeration.

5.3 Texas Nuclear Corporation Neutron Generator

This 150-keV Cockcroft-Walton type accelerator with a versatile pulsing system is located in the accelerator vault of Building NW13. Beam current is 1 ma and either the D(d,n) or T(d,n) reactions may be used. The accelerator has been used for slowing-down investigations, heavy water diffusion parameter measurements, activation analysis experiments, accelerator studies and fusion blanket studies.

5.4 Nuclear Engineering Laboratories

This is a group of four laboratory rooms. Three are adjacent on the second floor of Building NW13 and the other is located in the rear of the first floor of Building NW12 The space is used for the research activities of a number o projects being carried out in the Department.

Three of the four rooms are equipped with laboratory-type benches and hoods. These rooms have been used extensively for chemical operations associated with the Organic Coolant Project, measurement of thermal contact resistances, the preparation of lithium-drifted detectors, radiation effects on methane, hydrogen-deuterium separation, and nuclear energy for space applications. The space is quite versatile and well suited for any type of chemical operation.

The fourth room, located on the second floor of Building NW13 is an open room used for physics experiments associated with counter developments and activation analysis. This room, as well as several of the others, has been arranged to permit setting up and checking out of large pieces of experimental equipment prior to putting them in the reactor.

In addition to the general laboratory facilities there are available in these laboratories three gas chromotagraphs, a high-temperature salt bath for viscosity and density measurements, a mass spectrometer, a 4096-channel analyzer, and a high vacuum system. A four-station, time-sharing electronic desk calculator has been installed.

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

5.5 Plasma Research Facilities

Principal plasma research facilities of the Research Laboratory of Electronics in use by the Nuclear Engineering Department are:

1. highly ionized arc column, 50-cm long
2. highly ionized arc plasma, 150-cm long
3. highly ionized plasma column, 3-meters long
4. toroidal non-adiabatic trapping experiment
5. high power lasers, both purchased and constructed in the laboratory.

This equipment of the Research Laboratory of Electronics is used extensively for individual student thesis research, but it is incapable of producing energetic plasmas on the scale available at the national laboratories. The National Magnet Laboratory at MIT has sufficient power and space for large plasma experiments and is where the Alcator plasma experiment is now under successful operation. Nuclear Engineering faculty and students are participating in operations and interpretation of results.

5.6 Computing Facilities

The Department makes extensive use of the facilities of the MIT Information Processing Center. These facilities include an IBM 370/168 for batch processing and an IBM 360/67 for time-sharing purposes. Access to the time-sharing system is via consoles scattered around the Institute. Several small electronic desk calculators are also available at various locations around the Department.

The Department has obtained a number of the more widely used reactor design and analysis codes from other nuclear computation centers and has adapted them to use with the MIT computers. These codes have been compiled in a departmental code library, where students wishing to use the codes are given assistance and instruction.

6. DEPARTMENT PERSONNEL

6.1 Faculty

Norman C. Rasmussen

Professor of Nuclear Engineering; Head of the Department
A.B. '50 Gettysburg; Ph.D. '56 (physics) MIT
Nuclear physics; gamma spectroscopy; reactor analysis; reactor physics measurements; reactor safety; environmental effects of nuclear power; reliability analysis.

Arden L. Bement

Professor of Nuclear Materials; on leave to Defense Advanced Research Projects Agency
E.Met. '54 Col. School of Mines; S.M. '59 U. of Idaho; Ph.D. '63 (metallurgy) U. of Mich.
Nuclear materials; radiation effects; physical metallurgy; materials research related to advanced energy conversion systems (fast breeder reactor, MHD and fusion).

Manson Benedict

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

Sow-Hsin Chen

Professor of Nuclear Engineering
B.S. '56 National Taiwan Univ.; M.Sc. '58 National Tsing-Hua Univ.; M.Sc. '62 U. of Michigan; Ph.D. '64 (physics) McMaster Univ.
Applied neutron physics; physics of solids and fluids; nuclear reactor physics; biophysical applications of laser light scattering.

Owen L. Deutsch

Assistant Professor of Nuclear Engineering
B.S. '69 Columbia Univ.; S.M. '73, Ph.D. '75 (nuclear engineering) MIT
Nuclear physics, applied radiation physics

Michael J. Driscoll

Associate Professor of Nuclear Engineering
B.S. '55 Carnegie Tech; M.S. '62 U. of Fla.; Ph.D. '66 (nuclear engineering) MIT
Fast reactor physics; reactor engineering; economics of nuclear power.

Thomas H. Dupree

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

Michael W. Golay

Associate Professor of Nuclear Engineering
B.M.E. '64 U. of Fla.; Ph.D. '69 (nuclear engineering) Cornell Univ.
Reactor engineering; reactor physics; fluid mechanics.

Elias P. Gyftopoulos

Ford Professor of Engineering; Chairman of Faculty
Dipl. in ME & EE '53 Athens; Sc.D. '58 (electrical engineering) MIT
Reactor dynamics; control system analysis; thermionic conversion; thermodynamics; reliability analysis.

Kent F. Hansen

Professor of Nuclear Engineering
S.B. '53, Sc.D. '59 (nuclear engineering) MIT
Reactor mathematics; neutral particle transport; computational methods; nuclear fuel management.

Otto K. Harling

Visiting Professor of Nuclear Engineering; Director MIT Reactor; Senior Research Scientist
B.S. '53 Illinois Inst.of Tech.; M.S. '55 Univ. Heidelberg; Ph.D. '62 Penn. State Univ.
Neutron scattering; experimental nuclear physics.

Allan F. Henry

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

Irving Kaplan

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

Mujid S. Kazimi

Assistant Professor of Nuclear Engineering
B.S. '69 U. of Alexandria, Egypt; M.S. '71, Ph.D. '73 (nuclear engineering) MIT
Reactor engineering; fast reactor safety.

David D. Lanning

Professor of Nuclear Engineering; Co-Director of the MITR Modification Redesign
B.S. '51 U. of Ore.; Ph.D. '63 (nuclear engineering) MIT
Reactor operations; reactor engineering; reactor safety; reactor physics measurements.

Lawrence M. Lidsky

Professor of Nuclear Engineering
B.E.P. '58 Cornell; Ph.D. '62 (nuclear engineering) MIT
Plasma physics; fusion reactor design.

Edward A. Mason

Professor of Nuclear Engineering; on leave to the Nuclear Regulatory Commission
B.S. '45 Rochester; S.M. '48, Sc.D. '50 (chemical engineering) MIT
Reactor fuel and power systems management; processing of nuclear materials; reactor engineering.

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; reactor engineering.

Peter A. Politzer

Assistant Professor of Nuclear Engineering
B.S. '64 MIT; Ph.D. '69 (plasma physics) Princeton
Plasma physics; controlled fusion.

David J. Rose

Professor of Nuclear Engineering
B.A.Sc. '47 British Columbia; Ph.D. '50 (physics) MIT
Controlled nuclear fusion; socio-technological assessment; management of science and technology.

Louis S. Scaturro

Assistant Professor of Nuclear Engineering
B.S. '72 Cooper Union; M.A. '74, Ph.D. '76 (plasma physics) Columbia
Plasma diagnostics; fusion technology.

Dieter J. Sigmar

Associate Professor of Nuclear Engineering; on leave to Oak Ridge National Laboratory
M.S. '6o, Ph.D. '65, Tech. Univ. of Vienna
Theory of fully ionized plasmas; controlled thermonuclear fusion research; statistical mechanics of plasmas and fluids.

Neil E. Todreas

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

Lothar Wolf

Associate Professor of Nuclear Engineering
Dipl. Nuc. Eng. '67, Dr.-Ing. '70 (nuclear engineering)
Tech. Univ. Berlin
Reactor engineering; heat transfer; reliability analysis.

James T. Woo

Visiting Associate Professor of Nuclear Engineering (7/1/75-6/30/76)
B.S. '59 U. of Portland; M.S. '61 Stevens Institute of Technology; Sc.D. '66 (nuclear engineering) MIT
Plasma engineering; fusion technology.

Sidney Yip

Professor of Nuclear Engineering
B.S. '58, M.S. '59, Ph.D. '62 (nuclear engineering)
U. of Mich.
Transport theory; neutron scattering; statistical mechanics; radiation effects.

6.2 Complete Listing of Personnel (as of September 1976)

Professor

A. L. Bement
M. Benedict
G. L. Brownell
S. H. Chen
T. H. Dupree
E. P. Gyftopoulos
K. F. Hansen
A. F. Henry
I. Kaplan
D. D. Lanning
L. M. Lidsky
E. A. Mason
J. Meyer
N. C. Rasmussen
D. J. Rose
N. E. Todreas
S. Yip

Visiting Professor

O. Harling

Associate Professor

M. J. Driscoll
M. W. Golay
D. J. Sigmar
L. Wolf

Visiting Associate Professor

P. K. John

Assistant Professor

O. L. Deutsch
M. Kazimi
P. A. Politzer
L. Scaturro

Lecturer

S. Levin

Visiting Lecturer

H. Lurie

Instructor "G"

A. Forbes
G. Lucas

Administrative Officer

J. L. Cochrane

Administrative Assistant

D. Dutton

Visiting Scientist

P. K. Tseng
J. J. Van Binnebeek
C. Y. Yang

Senior Research Associate

C. V. Berney

Research Associate

B. Murray
J. O'Dell
R. Shanstrom
J. T. Woo

Research Affiliate

W. Veseley

Clerical Staff

I. Battalen
K. Earnshaw
J. Fenton
F. Grande
K. Hunter
E. Jones
P. Kelly
M. Levine
G. O'Keefe
D. Welsh

DSR Staff

R. Burns
W. Hinkle
D. Hnatowich
R. Kramer
S. Kulprathipanja
R. Morton

Teaching Assistants

F. Abtahi
D. Bley
M. Broussard
M. Campbell
D. Dube
E. Fujita
G. Greenman
R. Holland
J. Kelly
D. Kennedy
D. Laning
T. Luniewski
M. Lussier
M. Macher
R. Masterson
M. McKinstry
J. Olmos
G. Pine
R. Sawdye
J. Sefcik
E. Simmons
G. Was

Research Assistants

R. Ballinger
C. Barbenhenn
J. Bartzis
F. Best
T. Bjornard
W. Boyd
J. Chan
F. Chang
Y. B. Chen
R. Chin
C. Chiu
A. Cook
J. Fisher
A. Forbes
K. Garel
S. Glazer
S. Goldman
S. Grill
A. Hershcovitch
M. Krammen
T. Kwok
W. Lenz
A. Levin
J. Y. Liu
Y. Liu
F. Martin
T. McManamy
P. Meagher
R. Potok
T. Rodack
K. Rubenstein
A. Salehi
J. I. Shin
M. Stiefel
C. Thomas, Jr.
M. Todosow
C. N. Wong
B. Worley
N-K. Yeung

7. DEPARTMENTAL STATISTICS

Statistical Summary

Academic Year Sept-June	Sept. Registration: Under-grad	Regular	Special	Total	Degrees Granted: B.S.	S.M.	Nuc.E.	Sc.D, Ph.D.	Total	No. of Professors	No. of Subjects Offered
51 - 52	------ none -------				-------- none --------					1	none
52 - 53	none in nuclear				-------- none --------					2	4
53 - 54	-	8	-	8	-	4	-	-	4	2	5
54 - 55	-	20	-	20	-	13	-	-	13	2	5
55 - 56	-	46	-	46	-	10	-	-	10	3	6
56 - 57	-	74	-	74	-	32	-	-	32	5	7
57 - 58	-	93	1	94	-	31	-	2	33	6	8
58 - 59	-	95	6	101	-	44	-	7	51	8	12
59 - 60	-	102	6	108	-	32	-	5	37	10	14
60 - 61	-	112	10	122	-	25	1	7	33	10	16
61 - 62	-	118	8	126	-	34	-	11	45	13	17
62 - 63	-	109	8	117	-	27	1	12	40	15	20
63 - 64	-	103	10	113	-	20	2	13	35	15	21
64 - 65	-	124	6	130	-	24	3	14	41	16	24
65 - 66	-	125	6	131	-	30	3	15	48	16	25
66 - 67	-	122	6	128	-	28	11	22	61	18	26
67 - 68	-	132	4	136	-	27	2	13	42	17	27
68 - 69	-	127	3	130	-	35	6	14	55	18	28
69 - 70	-	128	-	128	-	31	8	22	61	20	28
70 - 71	-	111	3	114	-	27	4	14	45	19	37
71 - 72	-	117	1	118	-	20	2	19	41	20	35
72 - 73	-	113	1	114	-	29	5	14	48	20	37
73 - 74	-	127	2	129	-	32	12	8	52	22	44
74 - 75	-	139	7	146	-	38	4	7	49	22	46
75 - 76	22	178	2	202	-	39	8	24	71	26	61
				Totals	0	632	72	243	947		

8. STUDENTS

Some background information about the 200 full-time students registered in the Department in September, 1975, is presented in Tables 8.1 and 8.2. In past years a plurality of our students have come from undergraduate programs in Physics, with Mechanical Engineering second. We now find Nuclear Engineering undergraduates the single largest discipline.

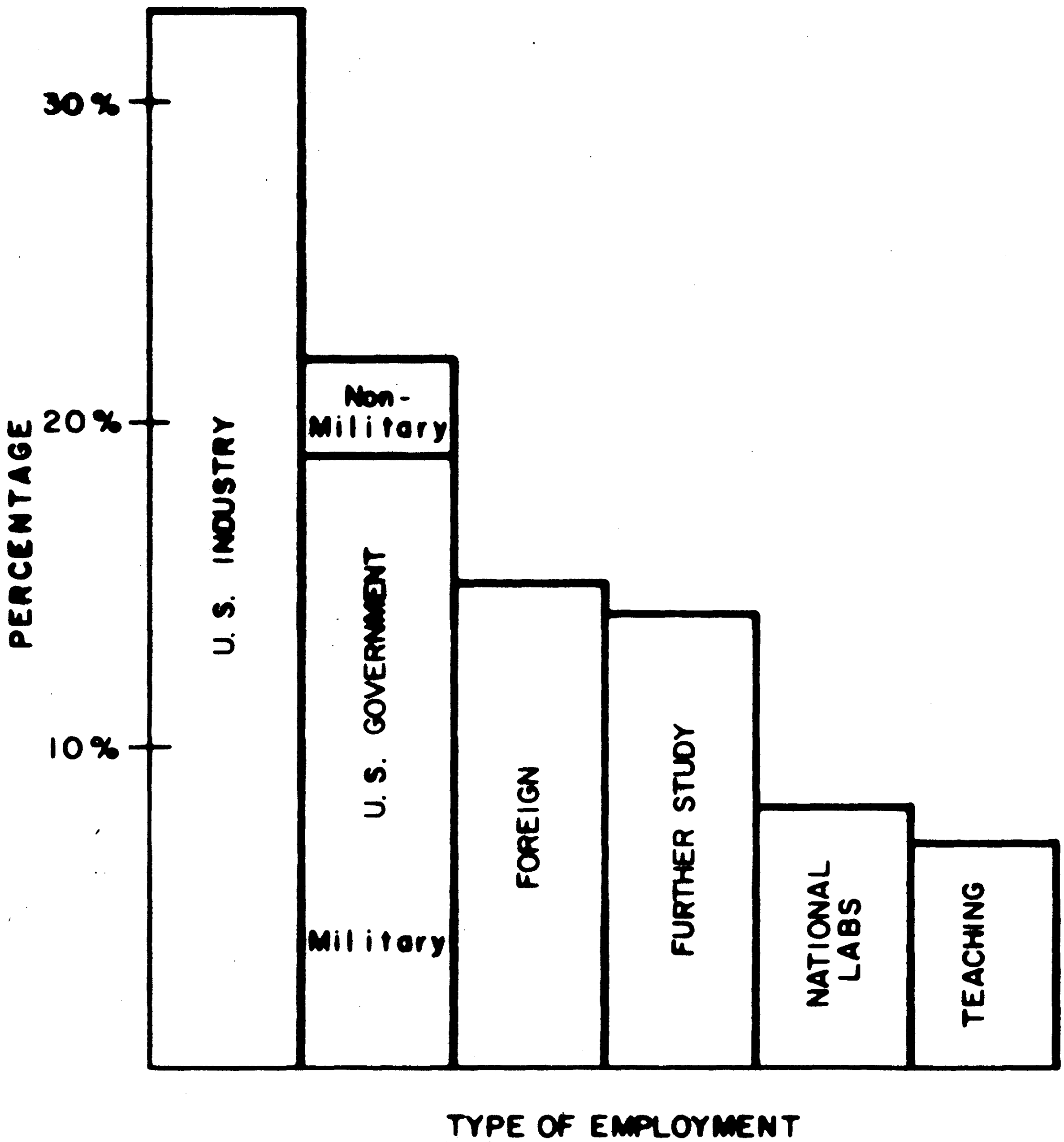
The distribution of schools from which our domestic students are drawn is very widespread. The number coming from MIT remains under 20%, as it has for many years. The foreign student population is relatively high, approximately 40%, and reflects the widespread recognition among foreign countries of their need for nuclear power. More and more we see the trend of foreign governments sending qualified students to MIT for training in Nuclear Engineering.

Support for students has increased markedly in recent years. In 1973/74 we had 24 research assistants, while in 1975/76 we had 50. In addition, the number of individual students with company or government sponsorship is increasing. We have joined with other schools in urging that the new Energy Research and Development Administration establish an office of Nuclear Education and Training, as the AEC once had, to support fellowship and traineeship programs in Nuclear Engineering. We have also been most fortunate in having the support of the nuclear industry for a limited number of fellowships.

The distribution of activities of our graduates is given in Table 8.3. The breakdown among the categories of U.S. Industry and Research, National Laboratories, Further Study, U.S. Government, Teaching, and Foreign has changed very little in the past five years. However, we feel we are on the threshold of a significant change in the number of graduates going to U.S. Industry. The great manpower needs, discussed in the Introduction, are drawing a larger percentage of our very recent graduates to industrial positions with the Electric Utilities and Vendors. The distribution of types of employment are summarized in Figure 8.1.

Figure 8.1

Distribution of Employment of Graduates (Reported*)



* Excludes 78 students not reported.

Table 8.1

Background of Graduate Students Registered in Nuclear Engineering Department (Spring 1976)

By Profession (187)

Aerospace Eng. (1)
Bioengineering (1)
Chemical Eng. (8)
Chemistry (2)
Civil Eng. (3)
Electrical Eng. (14)
Electronics (2)
Electrophysics (2)
Engineering (8)
Eng. Science (1)
Eng. Physics (6)
Environment. Stud. (1)
Materials (1)
Mathematics (3)
Marine Eng. (2)
Mechanical Eng. (28)
Metallurgy (5)
Nuclear Eng. (45)
Nuclear Physics (1)
Physics (25)
Plasma Physics (1)
Radiochemistry (1)
High School (21)
Undefined (5)

By College (84)
(U.S. cit. only)

Brooklyn Polytech (1)
Carnegie Mellon (1)
CCNY (3)
Columbia (2)
Cornell (3)
Drexel (2)
Emory (1)
Geo. Wash. (1)
Ga. Inst. Tech. (1)
Hampshire (1)
Harvey Mudd (2)
Howard (1)
Iowa State (1)
Kalamazoo (1)
Lafayette (1)
Lowell Tech (3)
Marquette (1)
MIT (16)
McNeese State (1)
McGill (1)
Northwestern (1)
Notre Dame (1)
Oakland Univ. (1)
Penn. State (1)
RPI (3)
Rice (1)
Stanford (2)
SUNY (1)
Sweet Briar (1)
USMA (2)
USMMA (1)
USNA (2)
U. California (2)
U. Colorado (1)
U. Conn (1)
U. Florida (3)
U. Illinois (1)
U. Michigan (5)
U. Penn (1)
U. Tenn (3)
U. Virginia (2)
U. Wisc. (1)
Wagner Coll. (1)
Worcester Polytch. (1)
Yale (1)

By Country (187)

Argentina (3)
Brazil (7)
Canada (2)
Chile (1)
Costa Rica (1)
England (2)
France (3)
Greece (4)
Hong Kong (3)
Hungary (1)
Iran (26)
Israel (1)
Italy (1)
Jamaica (2)
Japan (3)
Jordan (1)
Korea (2)
Libya (1)
Mexico (2)
Pakistan (1)
Saudi Arabia (1)
Spain (5)
Taiwan (7)
Turkey (1)
United States (106)

Table 8.2

Sources of Financial Support
(as of September 1976)

Research Assistantships (39)*
Teaching Assistantships (23)*
MIT Fellowships (1)
NRC Traineeship (1)
NRC Fellowships (5)
NSF Fellowship (1)
NSF Traineeships (2)

CNEN - Brazil (1)
IAE - Braxil (2)
Brazilian Navy (1)
Sherman Knapp Fellowship (1)
General Electric Fellowship (1)
ITP - Spain (2)
Kennedy Scholarship (1)
GI Bill/VA (6)
Kanebo Ltd. - Japan (1)
Babcock & Wilcox Fellowship (1)
INER - ROC (2)
AEOI - Iran (20)
Westinghouse (1)
ERDA Traineeship (8)
Exxon Nuclear Fellow (1)
Thompson Fellow (1)
IAEA (1)
Brookhaven National Labs (1)
Health Science Technology Fellowships (4)
National Fellowship Fund (1)
Rockwell International Fellowship (1)
Joseph Warren Barker Fellowship (1)
Korean Army (1)
Mexican Fellowship (1)
Jordanian Fellowship (1)
French Navy (1)
Chilean Navy (1)
Argentinian Navy (2)
U.S. Navy (7)
U.S. Army (1)
Turkish Ministry of Education (1)
Special Iranian Program (35)

*As of 9/76.

Table 8.3

Activities of Nuclear Engineering Dept. Graduates -- July 1976

(Place of first employment -- information current as of July 1976)

U.S. Industry and Research [256] (30%)

Aerojet Nuclear
Air Research Mfg. Co.
Allis Chalmers (2)
American Electric Power
Amer. Science and Eng.
APDA (2)
Assoc. Planning Res.
Atomics Int. (10)
Avco (6)

Babcock & Wilcox (6)
Battelle Northwest (4)
Bechtel (3)
Bell Telephone Lab.
Bendix
Bettis (3)
Burns & Roe (2)

California Oil
Combustion Eng. (8)
Commonwealth Edison (10)
Computer Processing
Conn. Mutual Life Ins.
Consolidated Edison
Consultant
Consumers Power
Cornell Univ. (research)

Direct Energy Con. Lab.
Douglas United Nucl (2)
Duke Power & Light

Ebasco (2)
Edgerton, Germ. & Grier

General Atomic (2)
General Dynamics, Elec. Boat (7)
General Electric (18)
Gulf General Atomic (18)

Hercules
Hughes (3)
Hybrid Systems
Hanford Eng. Dev. Lab.

IBM (2)
Inst. for Defense Analysis
Internuclear Co.
Isotopes, Inc.

Jackson & Moreland (2)

Lane Wells
A. D. Little (2)
Lockheed
Long Island Lighting Co.

Management & Tech. Cons.
Martin-Marietta (2)
Maxson Elec.
McKinsey & Co.
MIT (research) (6)
Mobil Oil
Monsanto
MPR Associates

Nat. Acad. of Eng.
New Eng. Nuclear Corp.
New York law firm
North American Rockwell (2)
Northeast Util. Service
Northern Research & Eng. (3)
Nortronics
Nuclear Fuel Service (2)
Nuclear Mater. & Equipment
Nuclear Products
Nuclear Regulatory Commission
Nuclear Utility Services (4)

Perkin-Elmer Corp.
Philco
Planning Research Corp.
Princeton (research (4)
Public Serv. Elec. & Gas
Purdue (research)

Radiation Tech.
Rand Corp
RCA Research Lab.

Sanders Corp.
Science Applications
Scientific Data Systems
Smithsonian Astrophys. Obs.
Southern Calif. Edison (4)
S. M. Stoller Assoc.
Stone & Webster (10)
Systems Sci. & Eng.
Systems Control

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

Union Carbide
United Aircraft (3)
United Eng. & Constr. (2)
United Nuclear (5)
Univ. of Calif. (research)
U. of Maryland (research)

Vacuum Industries

Westinghouse (20)

Yale (research) (2)
Yankee Atomic (8)

<u>National Laboratories</u> [62] (7%)

Argonne (11)
Brookhaven (5)
Knolls Atomic Power (16)
Lawrence Radiation (5)
Los Alamos (10)
Oak Ridge (10)
Sandia (2)
Savannah River (3)

<u>Further Study</u> [109] (13%)

MIT (88)
Other (21)

<u>U.S. Government</u> [170] (20%)

Atomic Energy Commission (22)
Air Force (13)
Army (72)
Army Nuc. Def. Lab
Army Research Lab (2)
Ballistic Research Lab
Classified - Wash., D.C.
Coast Guard
Dept. of Commerce
Energy Res. & Dev. Admin. (3)
NASA
Naval Research Lab
Navy (48)
Peace Corps
Picatinny Arsenal
Dept. of Public Health

<u>Teaching</u> [52] (6%)

Amer. Univ. (Wash., D.C.)
Brooklyn College (CCNY)
Cal. State (Long Beach)
Carnegie Mellon Univ.
Case Institute
Catholic Univ. of America
Cornell
El Rancho High School
Georgia Inst. of Tech.
Howard University
Iowa State
Kansas State
Lowell Tech (4)
Loyola Univ.
Mass. Maritime Acad.
Michigan State Univ.
MIT (7)
Northeastern Univ.
Northwest Nazarene
Pennsylvania State
Princeton
Radford College
Renesselaer Polytech.
Swarthmore
Texas A & M
U.S. Military Acad.
Univ. of Brit. Columbia
Univ. of California (5)

Univ. of Florida
Univ. of So. Florida
Univ. of Illinois
Univ. of Kentucky
Univ. of Missouri (2)
Univ. of New Hampshire
Univ. of Texas
Univ. of Washington (2)
Univ. of Wisconsin

<u>Foreign</u> [118] (14%)

Belgium (9)
Brazil (13)
Canada (10)
Chile
Columbia, S.A.
England (2)
France (16)
Germany (2)
Greece (3)
India (13)
Indonesia
Iran
Israel (2)
Italy (5)
Japan (9)
Malaysia
Mexico
Norway
Pakistan (3)
Philippines
Poland
Spain (8)
Switzerland (6)
Taiwan (2)
Turkey (4)
Venezuela (2)

NOT REPORTED [78] (9%)

TOTAL 845*

*Records from early years are incomplete.

9. LIST OF THESES

The following theses were submitted to the Nuclear Engineering Department in February 1975:

V.A. Baldini, "Operations Research Problems in the Motion Picture Industry", SM Thesis.

J.G. Bartzis, "Axial and Transverse Momentum Balances in Subchannel Analysis", SM Thesis.

Y.B. Chen, "Preliminary Velocity Measurement in Edge Subchannels of Wire Wrapped Bundle by the Laser Doppler Anemometer", SM Thesis.

T.E. Collins, "Cost-Risk-Benefit Analysis of a Core Catcher for Pressurized Water Reactors", SM Thesis.

R. Eng, "A Method of Short-Range System Analysis for Electric Utilities Containing Nuclear Plants", PhD Thesis.

A. Hershcovitch, "Time Evolution of Beam Instabilities", SM Thesis.

G.E. Lucas, "The Strength-Differential in Zirconium and Its Effect on Clad Creep Down Analysis", SM Thesis.

M. Maekawa, "Analysis of the Safeguard System Against Nuclear Theft", SM Thesis.

C.A. Primmerman, "A Trapped-Electron Mode in Cylindrical Geometry", PhD Thesis.

J.P. Walkush, "High Pressure Counterflow CHF", SM Thesis.

M.-K. Yeung, "A Foil-Stack Method for Epithermal Neutron Spectrometry", SM Thesis.

The following theses were submitted to the Nuclear Engineering Department in June 1975:

G. Bjorkquist, "An Experimental Investigation of the Fragmentation of Molten Metals in Water", SM Thesis.

P. Carajilescov, "Experimental and Analytical Study of Axial Turbulent Flows in an Interior Subchannel of a Bare Rod Bundle", PhD Thesis.

D. Carleton, "Improving Theoretically Calculated Spectrum Approximations with Activation Data", SM Thesis.

F. Carre, "Development of Input Data to Energy Code for Analysis of Reactor Fuel Bundles", SM Thesis.

B. Chen, "Prediction of Coolant Temperature Field in a Breeder Reactor Including Interassembly Heat Transfer", SM Thesis.

G. Doumet, "Powdered Iron-Air Fuel Cell", SM Thesis (joint thesis for SB & SM in Chemical Engineering).

M. Doyle, "A Comparison of the Environmental and Social Impacts of a HTGR Total Energy System and of a Coal Fired District Heating System", SM Thesis.

K. Garel, "Light Scattering from Xenon Near Its Critical Point", SM Thesis (joint thesis for SB in Physics).

S. Kauffman, "Downflow Critical Heat Flux Measurements", SM Thesis (joint thesis for SB in Mechanical Engineering).

M. Ketabi, "The Breeding-Economic Performance of Fast Reactor Blankets", SM Thesis.

R. Knapp, "Thermal Stress Initiated Fracture as a Fragmentation Mechanism in the UO_2-Sodium Fuel Coolant Interaction", SM Thesis (joint thesis for Engineer's degree in Ocean Engineering).

C. Oosterman, "Experimental Investigation of Coolant Mixing in a Wire-Wrapped LMFBR Blanket Subassembly", SM Thesis (joint thesis for Engineer's degree in Ocean Engineering).

R. Pinnock, "Parfait Blanket Configurations for Fast Breeder Reactors", SM Thesis.

S. Riederer, "Computer Simulation Studies in Transverse Tomography", SM Thesis.

M. Stiefel, "A Study of Electron Echos in a Plasma Confined by a Quadrupole Magnetic Field", SM Thesis (joint thesis for SB in Physics).

A. Tagishi, "The Effect of Reactor Size on the Breeding Economics of LMFBR Blankets", ScD Thesis.

J. Wasenko, "51-Cr Labelled Platelet Turnover Studies in Calves", SM Thesis.

S.-T. Yang, "Finite Element Synthesis Method", PhD Thesis.

The following theses were submitted to the Nuclear Engineering Department in September 1975.

F. Abtahi, "Assessment of Oil Shale Deposits as a Source of Energy for the United States", NE Thesis.

R. Anoba, "Edge Channel Velocity Measurements in a Wire Wrapped LMFBR Prototype Blanket Bundle Using the Laser Doppler Anemometer Method", SM Thesis.

C. Chambers, "Design of a Graphite Reflector Assembly for an LMFBR", SM Thesis.

M. Cunningham, "Reliability Analysis of the Major Power Chain of an HTGR", SM Thesis.

O. Deutsch, "Molecular Dynamics Simulation of Solids", PhD Thesis.

T. Downar, "A Feasibility Study of Actinide Transmutation in a LMFBR", SM Thesis.

T. Eaton, "Gas-Cooled Fast Breeder Reactor Fuel Element Thermal-Hydraulic Investigations", ScD Thesis.

P. Hendrick, "Ion-Simulated Irradiation-Induced Creep", PhD Thesis.

J. Hendricks, "Finite Difference Solution of the Time Dependent Neutron Group Diffusion Equations", PhD Thesis.

D. Huber, "A Device for Measuring the Density Distribution in a Freely Expanding Hypersonic Gas Jet", SM Thesis (joint thesis for SB in Physics and Chemical Engineering).

S. Jabbawy, "Measurement of Temporal and Spatial Dependence of Plasma Density by Mach-Zehnder Interferometer", NE Thesis.

K. Klein, "Design and Construction of a NaI Whole-Body Counter System for Rhesus Monkeys", SM Thesis.

Y. Lukic, "The Response Matrix Method Application to Reactor Static Depletion", PhD Thesis.

L. Metcalfe, "Economic Assessment of Alternative Total Energy Systems for Large Military Installations", SM Thesis.

R. Morneau, "Improved Radiophotoluminescence Techniques for Gamma Heating Dosimetry", SM Thesis.

P. Roth, "Radiation Blistering: A Diagnostic Technique Using a Co_2 Laser", SM Thesis.

J.I. Shin, "Conceptual Design of an HTGR System for a Total Energy Application", NE Thesis.

G. Solan, "Neutronic Analysis of a Proposed Plutonium Recycle Assembly", NE Thesis.

R. Stengle, "Thermal-Hydraulic Analysis of a 100 (MW(E)) HTGR", SM Thesis.

W. Weaver, "Recovery and Enrichment of Uranium from Lignite", SM Thesis.

T. Wei, "The Finite Element Method for Neutron Diffusion Problems in Hexagonal Geometry", PhD Thesis.

B. Worley, "Determination of Equivalent Diffusion Theory Parameters", SM Thesis.

The following theses were submitted to the Nuclear Engineering Department in February 1976.

C. De Almeida, "Use of Response Matrix Technique in Nuclear Reactor Kinetics", PhD Thesis.

A. Alvim, "Finite Difference Techniques for Solving Multidimensional Kinetics", PhD Thesis.

T. Bjornard, "An Experimental Investigation of Acoustic Cavitation as a Fragmentation Mechanism of Molten Tin Droplets in Water", SM Thesis.

D. Botelho, "Multdimensional Finite Element Code", PhD Thesis.

W. Brewer, "The Design and Construction of a Linear Z-Pinch", SM Thesis.

D. Bruyer, "Breeding-Economics of FBR Blankets Having Non-Linear Fissile Buildup Histories", SM Thesis.

P. De Laquil III, "An Accident Probability Analysis and Design Evaluation of the Gas-Cooled Fast Breeder Reactor Demonstration Plant", PhD Thesis.

P. Chrisman, Jr., "Inertial, Viscous and Finite-Beta Effects in a Resistive, Time Dependent Tokamak Discharge", PhD Thesis.

D. Ehst, "Nonlinear Saturation of the Dissipative Trapped Ion Instability", ScD Thesis.

P. Furtado, "Propagations of Density Fluctuations in Simple Fluids: Collective and Single Particle Motions", PhD Thesis.

R. Galvao, "Non-Circular Cross-Section Tokamaks", PhD Thesis.

P. Kalambokas, "The Replacement of Reflectors by Albedo-Type Boundary Conditions", ScD Thesis.

M. Kalra, "Gamma Heating in Fast Reactors", ScD Thesis.

W. Kirchner, "Reflood Heat Transfer in a Light Water Reactor", PhD Thesis.

C. Kullberg, "Nonlinear Coupling between Three Waves in a Plasma", SM Thesis.

L. Lederman, "The Use of Finite Element Flux Shapes in Reactor Depletion Calculations", PhD Thesis.

Y. Liu, "A Probabilistic Approach in Nuclear Reactor Fuel Element Reliability Analysis", SM Thesis.

J. Mason, "Collocation Methods for Solution of the Static Neutron Diffusion Equation", ScD Thesis.

P. Morgan, "Plasma Chemistry in Hollow Cathode Discharges: Tantalum Pentoxide Reduction", SM Thesis.

A. Pant, "Simulation Study of a Theta Pinch First Wall", PhD Thesis.

T. Postol, "Observation of Enhanced Self Diffusion in High Density Hydrogen by Incoherent Neutron Scattering", PhD Thesis.

A. Ribeiro, "Core Design for a Small HTGR", PhD Thesis.

H. Shaffer III, "Starting and Testing of the Massachusetts Institute of Technology Research Reactor MITR-II", SM Thesis.

W. Szymczak, "Experimental Investigation of Heat Transfer Characteristics of MITR-II Fuel Plates, In-Channel Thermocouple Response and Calibration", SM Thesis.

The following theses were submitted to the Nuclear Engineering Department in June 1976:

D. Aldrich, "Parfait Blanket Systems Employing Mixed Progeny Fuels", SM Thesis.

P.-J. Ammann, "Significant Structural Considerations in Determining Spacing of Nuclear Fuel Rod Supports", SM Thesis.

R. Bennett, "Interferometric Investigation of Turbulently Fluctuating Temperature in an LMFBR Outlet Plenum Geometry", SM Thesis.

A. Cook, "The Feasibility of ^{233}U Breeding in Deuterium-Tritium Fusion Devices", NE Thesis.

M. Diffley, "Decision Analysis of Nuclear Turbine Missle Accidents", SM Thesis (joint thesis for SM in Civil Engineering also).

R. Gilliard, "Finite Element Equations for Heterogeneous Material Configurations", SM Thesis.

D. Johnson, "Computer Simulation in Neutron Spectroscopy", SM Thesis.

O. Kadiroglu, "Uranium Self-Shielding in Fast Reactor Blankets", ScD Thesis.

D. Komm, "Cyclotron Radiation in a Hot Dense Plasma", PhD Thesis.

P. Palacios, "Thermal/Hydraulix Analysis Methods for PWR's", NE Thesis.

J. Olmos, "Reactivity Insertion Transient Simulations for a One-Dimensional Slab Reactor", SM Thesis.

C. Schmidt, "Nuclear-Generated Synthetic Fuel Systems for Ship Propulsion", SM Thesis.

J. Stetkar, "Design, Construction and Testing of an Experimental Dual-Rotor Induction Motor", NE Thesis.

J.-F. Tichit, "Important Structural Considerations in Design of Steam Generator Tubesheets", SM Thesis.

J. Valente, "Multidimensional Modeling of the Rod Drop Accident", NE Thesis.

J. Wargo, "Critique of the Macro-Economic Aspects of Liquid Metal Fast Breeder Reactor Cost/Benefit Analyses", SM Thesis.

S.-S. Wu, "Experimental Verification of Breeding Performance of Fast Reactor Blankets", NE Thesis.