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NUCLEAR
ENGINEERING
DEPARTMENT

ACTIVITIES IN NUCLEAR ENGINEERING AT MIT

Massachusetts Institute of Technology
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Prepared by the Staff of the
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I. INTRODUCTION

This report has been prepared by the staff of the Nuclear Engineering Department at MIT as a guide to the educational, research, and other activities of the Department. In addition, information is provided on the Department's facilities, the faculty, and the students who together make up the Department. The information has been prepared for the use of the Department's Visiting Committee, present students, students interested in applying for admission to the Department, and others.

In the United States fission reactors are being used, and ordered, in record numbers. The present U.S. electrical generating capacity is estimated at nearly 400,000 megawatts, of which over 16,000 megawatts or 4% are nuclear. At present, there are approximately 170 nuclear power plants under construction or on order. In 1972, 36 new plants were ordered. The U.S. electric capacity is estimated to grow to 760,000 megawatts by 1980 with the nuclear share at 135,000 megawatts or 18% of the total. For the next 7 years the nuclear capacity of the nation is expected to grow twice as fast as the fossil portion.

The continued strong growth of the nuclear profession is reflected in the trend toward nuclear engineering education throughout the United States. There are now at least 63 colleges and universities in the U.S. which offer a nuclear engineering curriculum. Present enrollment for undergraduate degrees is approximately 1,440, while graduate enrollment is approximately 1,430. The latest available figures (1970/1971) show that 256 BS degrees and 510 graduate degrees were granted. The number is increasing with time. This Department awarded 33 Master of Science, 5 Nuclear Engineer, and 14 Doctoral degrees during the 1972/1973 year; total enrollment was 113 graduate students.

Our own statistics on application for admission confirm the upward trend in student interest. Counterbalancing the student interest is the problem of student support. The present student body size is determined by the available aid and not by the number of qualified applicants. For September 1972 we received 85 applications for admission and admitted 69. We were able to offer financial support to only 12 new students. As a result, only 28 new students enrolled in September 1972. The trend for the 1973-1974 academic year is similar, except that we have over 100 applications for admission, and only slightly increased student aid.

The Nuclear Engineering Department has academic and research activities in six areas of the nuclear profession. These areas are:

1) fission reactor physics
2) reactor engineering
3) nuclear fuel and power management
4) applied plasma physics and fusion reactor technology
5) nuclear materials engineering, and
6) applied radiation physics.

Academic degree programs have been developed in all of the above areas. Furthermore, the students and faculty are engaged in graduate level research at the frontiers of the above areas. The emphasis on the six areas is easily understood when one contemplates the breadth and nature of nuclear technology today. The fission reactor is on its way to becoming the principle source of electrical energy in the United States. Future demands for energy in the world will require continued development for fission technology, as well as the development of other prospective sources of energy, such as fusion reactors. Concomitant with the developments of energy sources are the related problems of materials to survive in the environments characteristic of both fission and fusion reactors. Furthermore, the importance of radiation as an industrial tool and as a potential health hazard require great efforts in the area of radiation physics. We feel our academic and research programs are in line with the current societal needs.

Although the Department offers graduate degrees only, there is a growing interest among undergraduates in the problems of energy and society. In order to meet the interest and needs of undergraduates, the Department has expanded its undergraduate program considerably. We still do not offer an undergraduate degree, but have joint 5-year programs with a number of other departments at the Institute. These 5-year programs are offered in connection with the Chemical Engineering, Civil Engineering, Electrical Engineering, and Mechanical Engineering Departments, as well as the Physics Department. These programs lead to a bachelor's degree in the student's undergraduate department as well as a master's degree in Nuclear Engineering. Further, the Department has close connections with the Interdisciplinary Program of Environmental Engineering in the School of Engineering at MIT.

The remaining sections of this report present a description of departmental programs. A summary of developments since March 1972 is given in Section 2. In Section 3, is presented a detailed description of the research and educational activities of the Department. In Section 4 the Department's curriculum is discussed, including the degree programs, fields of study and subjects of instruction. In Section 5, the research facilities which the Department operates, or which the Department has access to, are described. In Section 6 is a description of the Department's personnel, including the faculty and other personnel. Section 7 summarizes the Department's statistics for past years and Section 8 summarizes information regarding the students, past and present. Section 9 presents a listing of the graduate theses prepared in the Department during the academic year 1972-1973.

Section II. SUMMARY OF DEVELOPMENTS SINCE MARCH 1972

This section provides a summary of the Department's programs, planning, and developments since the last copy of the Activities Report was prepared in March 1972.

The academic program in the Department has evolved with the changing emphasis in the nuclear field. Fission technology has moved from a theoretical area to areas of design, engineering, and economics. Furthermore, there has been a growing cognizance of the energy problem in the role of nuclear power in the future. Professors Norman C. Rasmussen and Michael W. Golay introduced a new graduate subject on "Environmental Impact of Nuclear Power." The subject considered the problems of radiation and thermal discharge of nuclear plants, radioactive waste disposal, and reactor safety. We are also evolving new graduate subjects for the future. Professor Edward A. Mason is preparing a seminar for advanced level graduate students on "Current Developments in Nuclear Energy."

Professor Neil E. Todreas has been responsible for coordinating the organization of subject material on nuclear structural analysis and design, an area of increasing importance; several speakers in this field from industry gave a series of lectures this spring.

Although the Department does not offer an undergraduate degree, the development of subjects of instruction in nuclear engineering for undergraduates in other departments continues. Professor David J. Rose is developing a school-wide undergraduate subject on the overall topic of energy. Professor Irving Kaplan has introduced a new undergraduate subject, "Nuclear Engineering in Society" and Professor Michael J. Driscoll offered a new undergraduate subject, "Engineering of Nuclear Power Reactor Systems," for the first time. Professor Kaplan is also developing a new subject, "Physics of Nuclear Energy," and Professors Sidney Yip and Sow-Hsin Chen have developed a new subject "Radiation Effects and Uses"; both of these new subjects will be introduced in the 1973-1974 academic year.

The Department is active in special summer programs, which are short-duration intensive subjects, offered to practicing engineers and scientists, and are important components of continuing professional education. These programs are managed by faculty, and lectures are given by faculty and experts from industry and government. Professor Rasmussen in conjunction with Professor Arden Bement offers a program on Nuclear Power Reactor Safety. Professors Chen and Yip offer a program on Neutron and Light Scattering. Professor Brownell directs a subject on Physical Aspects of Nuclear Medicine. Professors Kent F. Hansen, Manson Benedict and Edward Mason offer a subject on Nuclear Fuel and Power Management. All of these programs have been well received by government and industrial organizations.

The MIT Research Reactor, directed by Mr. Lincoln Clark, Jr., has continued to serve as a prime research tool in the Department's research and instructional programs. During the 1972-1973 academic year, 12 graduate research thesis projects in nuclear engineering used the reactor. In addition, a total of 14 other theses involved use the reactor, with sponsorship from other departments. The principal instructional activities using the reactor included 4 Undergraduate Research Opportunities projects and 12 users in departmental subjects. Professors David D. Lanning and James W. Gosnell have been actively working on a major modification of the reactor to increase the neutron flux and facilities for experimental work. During the past year the AEC has approved the licensing of the reactor modification and final design is now underway. It is expected that construction will be completed by about June 1974.

Other research activities in the Department have also progressed at an active pace. Professors Chen and Yip and several students have continued their work in scattering for the study of the liquid state of matter. Professor Michael J. Driscoll and interested students have been active on a theoretical and experimental project on fast reactor blankets. Professor Brownell and several research associates and students have been working on problems of nuclear medicine and in the use of neutrons for therapeutic treatment of malignancies. Professor Allan F. Henry and involved students have been working in the area of reactor theory and physics with support of the Combustion Engineering Company. Professors Mason and Benedict have continued to work with students in the area of nuclear fuel economics and management, with the continued support of the Commonwealth Edison Company and recently the American Electric Power Company. Professors Henry and Hansen and students have been supported by the Atomic Energy Commission for research on methods of analysis for reactor kinetics. Professor Rasmussen has been on part-time leave from the Department to direct a special task force working for the U.S. Atomic Energy Commission on the quantification of the probabilities of nuclear reactor accidents and their consequences. Professor Michael Golay, who is serving as the Arthur D. Little Professor of Environmental Sciences and Engineering, has been working actively in the area of the environmental effects of energy production. Professor Neil Todreas has been conducting research with several students on heat transfer and fluid flow including two-phase flow and liquid metal and gas coolants. Professor Elias P. Gyftopoulos has continued work with Dr. George Hatsopoulos on problems of quantum thermodynamics, their work having lead to a new general formulation of thermodynamic principles. Professor Bement has been working in the areas of material properties for use in magnetohydrodynamic systems and in the modelling of nuclear fuel behavior. Professor Kaplan has continued his work in the history of science, particularly on atomic theory. In addition, he has been an active participant in a special undergraduate teaching program, "Concourse."

The area of controlled thermonuclear fusion and plasma physics is receiving increasing interest as the long-range solution to many of the world's energy supply problems. Professor Lawrence Lidsky has been active in MIT's large scale controlled fusion experiment, ALCATOR, which began operation this year. Professor Lidsky is on the steering committee for the experiment and has been active in developing various diagnostic techniques to determine the nature of plasma instabilities. Professor Ronald Blanken has been actively engaged in similar problems of plasma instabilities and general experimental plasma physics. Professor Thomas Dupree has continued his work in theoretical studies of plasma physics, in particular plasma kinetic theory.

The faculty of the Department have continued to make valuable contributions to the Institute, professional societies, and government committees. Professor Gyftopoulos has been elected to serve as Chairman of the MIT Faculty for the coming year, and Professor Henry has been serving as a member of the Committee on Educational Policy. Professors Bement, Rose and Mason have all been heavily involved in the conception and organization of the Institute's new Energy Laboratory, which was established during the year to carry out comprehensive research projects in the field of energy supply and utilization. Professors Hansen and Mason have continued their service as Directors of the American Nuclear Society. Professor Mason was appointed to serve on the AEC's Advisory Committee on Reactor Safeguards, while Professor Henry continued his service as a member of the Advisory Committee on Reactor Physics.

The most outstanding honor received this year was the granting of the U.S. Atomic Energy Commission's Enrico Fermi Award to Professor Manson Benedict. The award is the highest honor bestowed by the AEC, and the ceremony was attended by numerous members of the staff; the presentation was made by Dr. James R. Schlesinger, the Chairman of the U.S. Atomic Energy Commission. In addition, Professors Bement and Hansen were elected Fellows of the American Nuclear Society.

Professor Hansen was appointed Executive Officer of the Department and has assumed responsibility for some of the Department's administration. Professor Sidney Yip spent the

1972-1973 year on sabbatical leave. He remained in the Cambridge area working at Harvard University on theoretical problems of neutron and light scattering. Professor Manson Benedict completes 22 years of service to the Institute this year and became Institute Professor Emeritus on July 1. He plans to remain active in the Department lecturing and carrying out research. We are gratified his retirement will be only partial and look forward to continued benefits from his contributions.

Professor Ronald Blanken, after five years' service to the Department, has decided to leave the teaching profession; he will be sorely missed. The Department has been fortunate to obtain the services of two new faculty, Dr. Dieter J. Sigmar and Dr. Peter A. Politzer. Dr. Sigmar will hold a joint appointment as Associate Professor of Nuclear Engineering and Associate Professor of Aeronautics and Astronautics, while Dr. Politzer will be Assistant Professor of Nuclear Engineering. These two new faculty have been on the research staff at MIT and will teach and carry out research in plasma and fusion physics. Mr. Jack Scarborough, of NUS Corporation, will join the Department for one year as a part-time Visiting Professor to assist in the teaching and research activities in nuclear economics

Mr. John L. Cochrane has been promoted from Assistant to the Director for Business Affairs at the MIT Reactor to Administrative Officer for the Department; he succeeds Mr. Gordon W. Oro, who served as Administrative Officer for two years.

We were very gratified that this year the Babcock & Wilcox Company has established a Babcock & Wilcox Fellowship for the support of a student in the Department. Other industrial fellowship support has continued to come from Northeast Utilities for the Sherman R. Knapp Fellowship. Support of a graduate fellowship in nuclear engineering by the General Electric Foundation has benefited the Department annually since 1961; the grant was not renewed for 1973-74. In these days of declining federal fellowship support, such industrial fellowships play an important role in assisting graduate students with their education.

The total operating expenses for all Department activities, including the MIT Reactor, in the fiscal year 1972-73 were $1,893,000 of which $480,000 was charged to Institute General accounts and $467,000 to various Institute Fund and Reserve accounts. Sponsored research contracts and grants covered the remaining $946,000. This included $270,000 of sponsored research for which Department faculty were responsible but which is adminsitered through other Departments and Laboratories, such as the plasma physics and fusion research carried out by Department faculty and students in the Research Laboratory of Electronics. MIT Reactor operating expenses were $315,700, of which $170,000 was covered by sponsored projects, $37,300 was charged against Institute academic funds to cover teaching and unsponsored research use of the reactor, and $108,400 was deficit. In addition $135,200 was spent on the reactor modification and modernization, which is funded from the reactor depreciation reserve account.

III. RESEARCH AND EDUCATIONAL ACTIVITIES

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 between the work described in the following sections.

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, and the few group approximation. 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 point kinetics. Attention is directed to the application of reactor theory to actual reactor systems.

22.213 Nuclear Reactor Physics III which is a review of the current methods for predicting neutron behavior in complex geometrical and material configurations. This subject covers the transport theory, the systematic derivation of few-group procedures, homogenization methods, flux synthesis and finite element techniques.

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.

In addition 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 xenon transients and reactor power transients involving feedback.

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.

The subject 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.

Three courses in numerical and mathematical methods, 22.41 Mathematical Methods of Reactor Analysis, 22.42 Numerical Methods of Reactor Analysis, and 22.43 Advanced Methods of Reactor Analysis all deal with analytic and numerical methods useful in solving problems in reactor physics.

1.1 Thermal Reactor Physics

Emphasis in the Department's program in thermal reactor physics is directed towards applications in specific areas such as the redesign of the MIT Reactor, fuel assemblies for plutonium recycle, reactor kinetics, and nuclear fuel management in thermal reactors.

As a part of the MIT Reactor Redesign Project, a complete reactor physics calculational method was developed for use at MIT. This included bringing in available computer codes, making the codes operational on the MIT computer and revising the code for the specific reactor physics calculations that were required. Calculational methods were verified by comparison with experimental information available in the literature. Parametric studies were then made to assist in developing a final design. After the design was established, reactor physics studies were made of the fuel loading, and fuel management for optimum fuel utilization with burnup. Special research has been made in the area of two-dimensional reactor kinetics related to the safety analysis of the new core design. Experiments will be made at the startup of the new core to correlate with the calculated values of reactivity and power distributions. Other aspects of the MITR Redesign Project are presented in Section III-5.1.

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 spectrum analysis work mentioned in Section III-1.5 and to most of the kinetics activities in Section III-1.4. 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 III-2.3. Work on the purely thermal reactor problem of fuel element design for plutonium recycle and on certain safety studies is reported in Section III-2.4.

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 the effects that such errors have on predictions of both static and dynamic reactor behavior are being investigated.

b) The response matrix technique of predicting reactor criticality and flux distributions:

   This procedure treats as unknowns the partial neutron currents on the surfaces of fuel subassemblies or clusters. These currents are connected by predetermined coupling matrices that reflect the effects of local heterogeneous regions within the cluster, and this connection leads to a criticality condition. The scheme is thus an alternate approach to representing a heterogeneous region by use of equivalent homogenized parameters.

c) The finite element method applied to the prediction of criticality and flux shapes:

   When the use of equivalent homogenized constants to represent large regions such as fuel subassemblies or clusters is justified, the finite element method has been found to be a very efficient scheme for determining criticality and gross power distribution. A recent comparison of this method with the conventional finite difference technique for solving the group diffusion equations was made for a large PWR (The Zion-I Reactor). The finite element method gave results comparable in accuracy to the finite difference scheme in about 60% of the running time. More recently application of a standard acceleration procedure for solving the finite element equations has led to a further decrease of a factor of three in their running time.

d) Cell stitching techniques:

For situations in which the use of homogenized diffusion theory parameters may lead to erroneous predictions of power shape and criticality a "cell stitching" procedure is being developed. The basic idea of the method 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.

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 J.W. Gosnell, K.F. Hansen, A.F. Henry, D.D. Lanning; Messrs. L.O. Deppe, J.G. Kollas, S. Yang, T. Yarman.

Support: USAEC approximately $40,000/year; subcontract Combustion Engineering approximately $6,000.

Related Academic Subjects

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

L.O. Deppe, K.F. Hansen, "The Finite Element Method Applied to Neutron Diffusion Problems," COO-2262-1, MITNE-145, February 1973.

T. Yarman, "The Reactivity and Transient Analysis of MITR-II," PhD Thesis, Department of Nuclear Engineering, MIT, August 1972.

A.F. Henry, "Refinements in Accuracy of Coarse Mesh Finite Difference Solution of the Group Diffusion Equations," IAEA-SM-154/21, January 1972.

See also Section III-1.4.

1.2 Experimental Fast Reactor Physics

Research on fast breeder reactor blanket neutronics has been underway at the MITR for some five years now. The focal point of this work is the Blanket Test Facility, the heart of which is a special converter assembly designed to create a leakage spectrum simulating the core leakage from a large LMFBR. This facility is being used to irradiate mockups of the blanket and reflector regions of fast breeder reactors under an AEC sponsored research program.

Work is currently underway on the third blanket mockup, a simulation of a typical radial blanket for a demonstration plant size LMFBR. During the past year research was completed on an improved configuration using a high-albedo reflector. This design will permit improved fuel cycle economics if its projected advantages are confirmed by the analysis still in progress.

The research program involves extensive use of foil activation techniques to obtain data for comparison with state-of-the-art calculations. Data of interest include material reaction rate profiles (such as U-238 capture and Pu-239 fission), and neutron spectra unfolded from the foil activation measurements. Use has also been made of Li-6, He-3 and p-recoil neutron spectrometers and high resolution Ge(Li) gamma ray spectrometers. Experimental and analytical research is underway on the effects of heterogeneity on the neutron balance. Recently work has been initiated on gamma transport and energy deposition in blanket materials, including both experimental measurements and numerical calculations.

A parallel effort in the area of economics, fuel cycle analysis and material distribution optimization is being conducted to identify and evaluate advanced blanket configurations and fuel management schemes (see Section 1.3).

A second, smaller, converter assembly, designed to provide a clean fission-neutron spectrum, is in fairly steady use by Draper Laboratory researchers for fast neutron radiation damage studies in semiconductors.

The-blanket research program is entering the second year of the second three-year AEC contract.

Investigators: Professors M.J. Driscoll, D.D. Lanning, I. Kaplan; Engineering Assistant A.T. Supple; Computer Operations Assistant V.A. Miethe; G.J. Brown, G.A. Ducat, S.Y. Ho, J.L. Lazewatsky, A.M. Thompson, J.K. Chan, P. Scheinert, A. Leveckis, T.P. Choong, R.J. Kennerley.

Support: USAEC (approx. $165,000 in FY 1973)

Related Academic Subjects

22.211, 22.212, 22.213 Nuclear Reactor Physics I, II, III
22.32 Nuclear Power Reactors
22.34 Economics of Nuclear Power
22.35 Nuclear Fuel Management
22.41 Mathematical Methods of Reactor Analysis
22.42 Numerical Methods of Reactor Analysis
22.43 Advanced Methods of Reactor Analysis

Recent References

N.R. Ortiz, "Instrumental Methods for Neutron Spectroscopy in the MIT Blanket Test Facility," ScD Thesis, Department of Nuclear Engineering, MIT, May 1972.

A.M. Thompson, "Activation Profiles in Reactor Fuel Elements," B.S. Thesis, Physics Department, MIT, June 1972.

D. Lal, "Determination of the Neutron Spectrum in the MITR Transistor Irradiation Facility," B.S. Thesis, Chemistry Department, MIT, June 1972.

V.C. Rogers, I.A. Forbes, M.J. Driscoll, "Heterogeneity Effects in the MIT-BTF Blanket No. 2, Trans. Am. Nucl. Soc., 15, 1, June 1972.

M.J. Driscoll, D.D. Lanning, I. Kaplan, "LMFBR Blanket Physics Project Progress Report No. 3," June 1972.

1.3 Fast Reactor Analysis

A considerable amount of analytical and numerical work related to fast reactors has been carried out under the blanket research program described in Section III-1.2. A large portion of this work involves fuel burning calculations for the core and blanket regions. Research is currently underway on evaluation of:

a) improved reflector designs for LMFBR blankets

b) the use of thorium in place of depleted uranium in LMFBR blankets

c) the concept of including a completely internal blanket zone inside an LMFBR core.

A topical report has been issued which deals with the effect of heterogeneity on fast reactor neutron balances. A combination of various heterogeneous effects, primarily anisotropic diffusion, were found to reduce whole-core sodium void reactivity changes by on the order of one dollar.

Investigators: Professors M.J. Driscoll, K.F. Hansen, E.A. Mason; Messrs. C. Tzanos, M.V. Gregory, A. Torri, G.J. Brown, G.A. Ducat, P.J. Wood.

Support: Partly from AEC under BTF Project, see Section III-1.2.

Related Academic Subjects: Same as Section III-1.2.

Recent References

S.T. Brewer, E.A. Mason, M.J. Driscoll, "The Economics of Fuel Depletion in Fast Breeder Reactors," COO-3060-4, MITNE-123, November 1972.

M.J. Driscoll, D.D. Lanning, I. Kaplan, "LMFBR Blanket Physics Project Progress Report No. 3," COO-2250-1, MITNE-142, January 1973.

C.P. Tzanos, E.P. Gyftopoulos, M.J. Driscoll, "Optimization of Material Distributions in Fast Reactor Cores," Nuc. Sci. & Eng. (in press).

G. Ducat, M.J. Driscoll, N.E. Todreas, "The Parfait Blanket Concept for Fast Breeder Reactors," Trans. Amer. Nuc. Soc., 16, 1 (1973).

C.P. Tzanos, "Systematic Optimization of LMFBR Core Composition to Minimize Void Reactivity," Trans. Amer. Nuc. Soc., 16, 1 (1973).

M.K. Sheaffer, M.J. Driscoll, I. Kaplan, "A One-Group Method for Fast Reactor Calculations," Nuc. Sci. & Eng., 48, 459-466 (1972).

1.4 Reactor Kinetics

A broad study encompassing many aspects of the field of reactor kinetics with applications to both thermal and fast reactors has been underway in the Department for about five years.

A substantial amount of support for this research has been provided through a contract with the USAEC. The principal objective of that contract is to develop means of predicting the short term transient behavior of nuclear systems, most particularly LMFBRs. The physical problem is so complex that numerical solution of the appropriate mathematical statement of the problem is necessary.

To this end much of the research has centered upon finite difference methods. Methods for two-dimensional and three-dimensional problems have been devised and tested. Recently the one-dimensional time dependent, group theory code GAKIN has been rewritten to serve as a standard for testing other methods.

An alternative approach to the finite difference procedure is based upon the "finite element method" in which the solution is approximated by piecewise polynomials. The virtues of this approach are threefold:

1) the error bound between the exact and approximate solution can be determined,

2) the method is highly accurate so that complex solutions may be approximated with few unknowns,

3) the algebraic equations for the approximate solution are easily solved.

The application of the finite element method to space-time problems has already been tested for simple, two-dimensional problems. Testing for more complex geometrical situations is first being done for static problems as reported in Section III-1.2.

On a much longer time scale, the application of space dependent kinetics methods to depletion and xenon transient problems is also a matter of current interest. The potential gain in treating such problems as truly time dependent (rather than as a sequence of static computation) is that the usual searches for criticality and consistent temperature-density profiles can be avoided. The accuracy of the method for both depletion and xenon studies has now been established. Present studies are concerned with iterative procedures for solving the difference equations associated with the scheme.

Investigators: Professors K.F. Hansen, A.F. Henry; Messrs. J.G. Kollas, J.H. Mason, R.W. Sheaffer, Jr.

Support: USAEC. Approximately $40,000/year; subcontract Combustion Engineering $10,000/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

J.A.W. DaNobrega, "A New Solution of the Point Kinetics Equations," Nuc. Sci. & Eng., 46, 366 (1971).

W.J. Westlake, Jr. and A.F. Henry, "Reactor Depletion Analyzed as a Space-Time Problem," Nuc. Sci. & Eng., 49, 482 (1972).

J.C. Turnage, "A New Method of Solving the Multimode Reactor Kinetics Equations," Nuc. Sci. & Eng., 51, 67 (1973).

1.5 Spectrum Analysis

Attempts have continued to infer neutron spectra from foil activation measurements. The first method investigated was to combine linearly several precomputed "trial spectra" in order to match the experimental data. This scheme was unsuccessful for all but simple problems.

Introducing the possibility of "blending" the precomputer spectra provided some improvement but still gave unsatisfactory results for complex situations involving many resonances. A further generalization allowing for more curvature in the blending and permitting discontinuities in the spectra is being investigated.

Investigators: Professor A.F. Henry, Mr. A.C. Cerne, L. Lederman.

Support: USAEC. Approximately $300 for computer services

Related Academic Subjects

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

Recent References

A.C. Cerne, "Using Reactor Rates to Improve Multigroup Flux Approximations," SM Thesis, Department of Nuclear Engineering, MIT, August 1972.

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, fuel cycle analysis, and nuclear fuel and power system management.

A total of twelve subjects of instruction are offered under the category of reactor engineering by the Department, including a revised subject, 22.03, Engineering of Nuclear Power Reactor Systems, and a new subject, 22.38, Current Developments in Nuclear Energy. The following paragraphs present a description of all of the subjects in reactor engineering.

22.03, Engineering of Nuclear Power Reactor Systems, is a new undergraduate level offering for students desiring to concentrate on other disciplines, but with a minor program of studies in nuclear engineering. It deals with the principles of component and system design of current U.S. central station power reactors, including economics, heat generation, transfer and transport, and evaluation of safety systems.

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, fluid flow, heat transfer and strength of materials, with examples of applications to nuclear power systems.

22.312, Engineering of Nuclear Reactors, is the central subject in the power reactor engineering curriculum. It is taken as the initial reactor engineering course by students who have had undergraduate work in engineering principles. It deals with power plant thermodynamics and energy conversion cycles; energy production and distribution in power reactors; flow of incompressible and two-phase fluids; heat transfer by conduction, convection and boiling applied to nuclear systems; and mechanical design and analysis.

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 of central station and advanced power reactors. Topics treated include thermal design methods, core reliability analysis, engineering analysis of transients and loss-of-coolant accident, liquid metal heat transfer and fluid flow, earthquake engineering and mechanical design and analysis. Efforts are being made to increase the component of this course covering the area of nuclear structural engineering.

22.32, Nuclear Power Reactors, is a more descriptive survey of engineering and physics aspects of current nuclear power reactors. Design details are discussed including requirements for safety of light and heavy water reactors, high temperature gas-cooled reactors, fast reactors both liquid-metal and gas-cooled and 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 course for second year graduate students in which they carry out a 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 a specified engineering goal. The application of engineering judgment to make trade-off decisions among conflicting requirements is stressed. Different reactor systems are designed each year: two recent examples have been an analysis of offshore siting of nuclear power plants, and design of an ultra-safe version of a pressurized water reactor.

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, hydroelectric and pumped storage installations and nuclear power plants are taken up. Then 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 management.

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, dynamics and thermodynamics of forced convection two-phase flow, dynamics and thermodynamics of forced convection 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, is a new course dealing with the assessment of the effects of modern nuclear power plants, including radioactive pollution, thermal 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.

22.38, Current Developments in Nuclear Energy, is a new subject offered in seminar form which will deal with current topics in nuclear reactor design, licensing, construction, operation, performance and safety and the role of nuclear processes in providing energy. This subject will provide advanced graduate students with an opportunity to learn about the significant advances and problems in nuclear energy as they develop.

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 AEC licensing regulations.

In addition to regular courses, the Department has offered each year for the past seven years special summer programs on 22.95s 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 AEC Division of Licensing and Regulation. 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 were initiated by Professor Thompson and are being continued under the direction of Professors Rasmussen and Bement.

A special summer program 22.98s 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 Hansen.

Scientists, engineers, and managers from electric utilities, reactor vendors, government agencies, and universities have participated in both the safety and fuel and power system management programs.

The principal fields of research in power reactor engineering are reactor thermal analysis, power reactor safety, fuel cycle analysis, and power systems simulation studies.

2.1 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) numerical simulation of convective heat transfer
3) treatment of uncertainties in reactor thermal analysis
4) radiation-induced nucleation.

1) Coolant and Energy Mixing in Rod Bundles

An experimental and analytical program has been initiated under partial USAEC 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:

a) 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. This laser system is used to make pointwise fluid velocity measurements by scattering light from the naturally occurring microscopic particles within the fluid passing through the bundle. Experimental testing in both areas is presently underway. An analytic prediction model for coolant temperature distribution within a heated fuel rod bundle has also been developed.

b) Analysis and experimental water testing in small test sections representing a simple array of subchannels. In these test sections wire-wrap or other means of pin mechanical support is not simulated. These 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. Presently the tracer measurements and supporting analytic efforts are underway.

2) Numerical Simulation of Convection Heat Transfer

As computers grow in size and speed an increasing range of problems become available to numerical investigation. Among these are problems of fluid flow and heat transfer. Over the past ten years numerical simulation of fluid flows has been the interest of several investigators, mostly as a continuation of physically interesting problems which had been treated previously by analytical methods. Application of numerical analysis to engineering fluid flow and heat transfer has been the subject of recent graduate student research. In work to date the velocity and temperature profiles and heat transfer rates in single channel flows are obtained in the laminar and in the low-Reynolds number turbulent regimes. Ultimate interest is in providing an alternate method of analysis for heat transfer performance, which can be used in parallel with empirical correlations which are currently employed.

3) Treatment of Uncertainties in Reactor Thermal Analysis

In the thermal design of nuclear reactor cores, the temperature of certain elements (coolant, clad, fuel centerline) should not exceed specified limiting values. However, a certain number of failures could be permitted without affecting the reactor's safety while still providing for reliable operation. The method of correlated temperatures, developed by Westinghouse for the coolant temperature analysis, has been modified and expanded to enable analyses of the clad and fuel centerline temperatures. The modified method has been applied to analyze the clad temperatures of a core typical of the FFTF design.

Future work anticipated in this area is an analysis of the fuel thermal limits using this modified method for a core typical of the FFTF design and extension of the method to consider the statistical distribution inherent in the design limit itself.

4) Radiation-Induced Nucleation

Previous studies of the initiation of nucleation due to radiation have been extended. This study was originally motivated by the sodium void problem in sodium-cooled fast reactors resulting from the high superheats which might occur following sodium flashing. The aim was to determine if radiation-induced nucleation presents an inherent limit on the possible amount of superheat which is less than the approximate 200°F superheat then being assumed as an upper limit in some safety analyses. The experimental technique involved the suspension of a drop of test fluid in an appropriate oil to remove heterogeneous nucleation sites. Experimental measurements with fission products in water and in propylene glycol were obtained. These results and analytic results based on the previously developed energy balance method were compared with existing data obtained by other investigators. Attempts to correlate all this data with the energy balance method led to apparent inadequacies with the theory. Adjustments in the theory based on consideration of the ratio of the liquid to vapor density ratio has led to a method for predicting the onset of radiation induced nucleation in water and organic liquids.

Investigators: Professors N. Todreas, W. Rohsenow*, M. Golay; Messrs. T. Eaton, A. Hanson, E. Khan, W. Kirchner, H. Ninokata, Y. Chen, P. Carajilescov, P. Kolody, R. Guida, N. Oberle.

Support: USAEC (approximately $75,000/year)

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

D.W. Buckley, "Measurement of Secondary Flow Patterns in Non-Circular Channel Turbulent Flow Using Laser Doppler Velocimeter Techniques," SM Thesis, Department of Nuclear Engineering, MIT, June 1972.

*Department of Mechanical Engineering

P. Carajilescov, "A New Approach to the Treatment of Uncertainties in Reactor Thermal Analysis by Expansion of the Method of Correlated Temperatures," SM Thesis, Department of Nuclear Engineering, MIT, November 1972.

P. Carajilescov and N. Todreas, "Expansion of the Method of Correlated Temperatures for Treatment of Uncertainties in Reactor Thermal Analysis," Trans. Amer. Nuc. Soc., 15, 2, 835 November 1972.

P. Kolody, "The Feasibility of a Liquid Core Fuel Element," SM Thesis, Department of Nuclear Engineering, MIT, August 1972.

R.A. Guida, "Numerical Simulation of the Flow of Real Fluids with Heat Transfer," SM Thesis, Department of Nuclear Engineering, MIT, February 1973.

N.P. Oberle, "Radiation Induced Nucleation in Water and Organic Liquids," SM Thesis, Department of Nuclear Engineering, MIT, March 1972.

2.2 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 departments 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, for example:

a) In addition to being involved in the review and public discussion of emergency core cooling systems, Professor N.C. Rasmussen has been on half-time status this year to allow him to direct a study for the AEC in Washington. This study is an assessment of the overall risks to the public from accidents in nuclear power plants. The goal of this 18 month effort is to determine as realistically as practicable both the probability and implications of various hypothetical reactor accidents.

b) Professor E.A. Mason has now served one year on the Advisory Committee on Reactor Safeguards (ACRS), which, in addition to being a service to others, provides a valuable contact for the Department with current nuclear industry safety issues and manpower and education needs.

c) MIT has conducted for seven years now, a two week summer course in reactor safety, drawing lecturers and students from all sections of the international atomic energy community.

d) A number of thesis projects have recently been completed:

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

This project was initiated under USAEC 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 to date has focused on predicting the mechanism for the onset of fragmentation of the molten fuel, since the fragmentation process appears to be a necessary condition for the destructive vapor explosion. Available fragmentation data for a variety of interacting materials was surveyed and based on this review a hypothesis was developed linking the onset of fragmentation to cavitation within the hot material. The rarefraction wave passing through the hot material triggering the cavitation process was thought to have its origin in the dynamics of vapor film growth at the hot material - cool bath interface. A detailed transient heat transfer model for predicting the dynamic vapor film behavior was developed to permit quantitative comparison of this behavior to available experimental fragmentation results. Analytic and experimental work is continuing on this project to test the validity of the proposed cavitation mechanism.

2) Molten Fuel Movement in an Unfailed LMFBR Pin

In this work, a model for molten fuel movement in an unfailed pin subjected to an overpower transient was developed. A knowledge of the mechanisms that cause fuel movements inside an unfailed pin and eject fuel from a failed pin is a prerequisite for further studies in several LMFBR safety areas. The pressure due to the fission gases released and the volume increase of the melted fuel was considered to be the driving force. The primary assumption was that the trapped fission gas was released after the fuel had gone through heat of fusion. The model was applied to TREAT tests C5A and C5B. A computer-hand calculation combination was employed. The calculated behavior of the pins corresponded to the observed behavior.

3) Analysis of Partially Blocked Coolant Channels

This project was initiated to develop analytic methods of assessing the consequences of blockages in reactor coolant channels. Existing subchannel analysis models appear to satisfactorily predict cross flow due to natural flow redistribution effects, however, they do not seem suitable for use in analyzing cross flow due to coolant channel blockages. A transverse momentum model was developed, based on a variable width control volume, which adds an additional degree of flexibility, allowing a more accurate treatment of blockages. The model was verified against the limited existing experimental data for a two-subchannel geometry. Recommendations were made for additional experimental tests to permit further development of the proposed model.

4) Critical Flow Models in LOCA and Modeling of a Condensing Steam Jet

The present state-of-the-art in the modeling of two-phase critical flow was examined. In particular the Moody and Fauske models are analyzed and compared. The basic assumptions inherent in the Moody and Fauske models were examined to determine their adequacy in computing the blowdown of a boiling water reactor during the design basis loss-of-coolant accident. Analysis of these two models with the blowdown conditions stipulated by the owner and comparisons with experimental data revealed that an analysis of the blowdown by use of the Moody model with the stipulated conditions cannot yet be proven to be a conservative bounding approach. The designer has been requested to review this preliminary conclusion.

In addition the problem of modeling the condensation process of a steam jet in a water suppression pool was surveyed. Several qualitative correlations were obtained, but quantitative results were not obtained due to a lack of present understanding of the compressibility effects involved.

5) Reactor Core Meltdown Containment

An evaluation of core catcher designs for the retention of core meltdown products following a hypothetical loss-of-coolant accident, combined with failure of emergency core cooling, has been performed and a new concept involving the use of a graphite pebble bed was devised, analyzed and shown to have superior characteristics compared to other suggested designs.

6) Loss of Coolant Analysis

Studies in the area of loss of coolant accidents have been extended to the investigation of hypothetical pressure vessel rupture analysis for a PWR. Calculations of the fuel temperature and coolant distribution were made for blowdown transients with various assumed rupture sizes and positions. The assumed size of the hole in the vessel was taken to be a parameter and as this parameter was increased the transient approached an asymptotic value due to the choked flow condition at the various restrictions in the primary coolant loops. Thus for vessel ruptures (such as loss of pipe nozzles) that might be significantly larger than the double ended pipe break (but not a catastrophic rupture such as loss of the vessel head) it was calculated that the blowdown transient would not be significantly more severe than that for the double ended pipe break.

An addition to the above work, a new project has been initiated dealing with the effect of undercooling transients in gas-cooled fast reactors.

Investigators: Professors D.D. Lanning, N.C. Rasmussen, N.E. Todreas, M.J. Driscoll; Messrs. P. Doan, M. Kazimi, J. Kee, W. Brown, F. Bowman, J. Harris, J. Ferguson.

Support: Partial, AEC for LMFBR fuel-coolant interaction work; approximately $18,000/year GGA for GCFBR undercooling transients, approximately $30,000/year.

Related Academic Subjects

22.32 Nuclear Power Reactors
22.36J Two-Phase Flow and Boiling Heat Transfer
22.39 Nuclear Reactor Operations and Safety
22.94s, 22.95s, 22.96s Nuclear Power Reactor Safety (special summer programs)

Recent References

F.L. Bowman, "Reactor Core Meltdown Containment for Offshore Applications," SM Thesis, Department of Nuclear Engineering and Department of Naval Architecture and Marine Engineering, MIT, May 1973.

P.L. Doan, "Pressurized Water Reactor Loss-of-Coolant Accidents by Hypothetical Vessel Rupture," ScD Thesis, Department of Nuclear Engineering, MIT, August 1972.

M.S. Kazimi, N.E. Todreas, D.D. Lanning, W.M. Rohsenow, "A Criterion for Free-Contact Fragmentation of Hot Molten Materials in Coolants," Trans. Amer. Nuc. Soc., 15, 2, November 1972.

M.S. Kazimi, "Theoretical Studies on Some Aspects of Molten Fuel-Coolant Thermal Interaction," PhD Thesis, Department of Nuclear Engineering, MIT, May 1973.

J.A. Kee, "A Model for Molten Fuel Movement in an Unfailed LMFBR Pin," NucE Thesis, Department of Nuclear Engineering, MIT, September 1972.

W.D. Brown, "Flow Redistribution Around Partially Blocked Coolant Channels in Pressurized Water Reactors," NucE Thesis, Department of Nuclear Engineering, MIT, June 1973.

J.D. Harris, "Critical Flow Models in LOCA and Modeling of a Condensing Steam Jet," SM Thesis, Department of Nuclear Engineering, MIT, June 1973.

P.L. Doan, N.C. Rasmussen, D.D. Lanning, "Pressurized Water Loss-of-Coolant Accidents by Hypothetical Vessel Rupture," Proc. of National Topical Meeting on Water Reactor Safety, Salt Lake City, Utah, TID-4500, March 1973.

2.3 Nuclear Fuel and Power System Management

Since fuel charges for a typical 1100 MWe light water nuclear reactor amount to about $14 million per year and the fuel inventory value per reactor is about $30 million, the optimum design and use of nuclear fuel is of major economic importance to utilities. Nuclear power stations form only a part of the generating capacity for any utility or grid system so that the relationship between all generating units - nuclear, fossil steam, hydro, and peaking - in meeting the varying imposed energy load must be considered in planning for system optimization. Both short and long-range dispatching (i.e., power loading) for nuclear units is more complicated than for fossil units because of the batch-type loading of nuclear units and the heavy carrying charges in the value of the in-core fuel. In addition there are more fueling options available to the nuclear designer-operator (e.g., size, enrichment, distribution, and timing of reload batches for any given reactor) and there are more constraints to be observed (e.g., fuel and clad temperatures, fission product gas buildup, and local heat transfer). Since utility planning for the future is subject to uncertainties of load, unit availability and costs, probabilistic techniques are required. Furthermore, typical large utility systems have a large number of generating units available with an increasing number of nuclear generating units planned; thus there are a very large number of possible feasible strategies which must be considered in meeting the system demand for any given planning period.

A utility sponsored project is underway in the Department aimed at developing methods useful in arriving at management decisions for optimum system-wide planning of generating unit power loading, maintenance scheduling, and nuclear fuel reload design and timing.

A system simulation model is under development to allocate the probable load between available generating units (fossil and nuclear) over a period of five to ten years allowing for possible forced outages. This model will be coupled with another nuclear core simulator being designed to rapidly indicate the optimum reload batch sizes and enrichments for the nuclear units to meet their assigned energy duties. A third, costing model is being developed to determine the incremental costs of the various options in order to arrive at an optimum system strategy.

Another model is under development and testing to provide capability for optimizing the daily and weekly generations of nuclear energy between refuelings. The model includes provision for treating the effects of large fossil, peaking fossil, hydro and pumped storage generating capacity as well as nuclear reactors. This study is also expected to provide consistent methods for computing short-term system incremental costs for use in system-to-system energy sales.

Coupled to these simulation studies is a series of engineering studies of the performance of nuclear fuel in light water reactor cores aimed at determining the constraints which will be imposed on fuel reload flexibility (e.g. variation of batch size, enrichment, and distribution in the core) by engineering and safety constraints.

Investigators: Professors M. Benedict, E.A. Mason; Messrs. P.F. Deaton, J.P. Kearney, W.T. Miles, T.A. Rieck, H.Y. Watt, R. Eng, W. Zimmermann.

Support: Partial, Commonwealth Edison Company and American Electric Power Service Corporation, ∿$50,000/year.

Related Academic Subjects

- 22.211, 22.212 Nuclear Reactor Physics I, II
- 22.312 Engineering of Nuclear Reactors
- 22.34 Economics of Nuclear Power
- 22.35 Nuclear Fuel Management

Recent References

P.F. Deaton, "Utility System Integration and Optimization Models for Nuclear Power Management," PhD Thesis, Department of Nuclear Engineering, June 1973.

J.P. Kearney, "Simulation and Optimization of In Core Nuclear Fuel Management," PhD Thesis, Department of Nuclear Engineering, June 1973.

H.Y. Watt, "Incremental Cost and Nuclear In-Core Optimization," ScD Thesis, Department of Nuclear Engineering, MIT, June 1973.

W.T. Miles, "Fuel Management Strategies for Pressurized Water Reactors," SM Thesis, Department of Nuclear Engineering, MIT, June 1973.

P.F. Deaton, E.A. Mason, "A System Integration and Optimization Model for Nuclear Power and Management Planning," Trans. Amer. Nuc. Soc., 15, 373-375 (1972).

P.F. Deaton, E.A. Mason, "Parallel Derivation of Marginal Cost Pertinent to Utility System Optimization," Trans. Amer. Nuc. Soc., 15, 375-376 (1972).

H.Y. Watt, J.P. Kearney, M. Benedict, E.A. Mason, "Methods for Nuclear In-Core Optimization," ANS Topical Meeting on Mathematical Models and Computational Techniques for Analysis of Nuclear Systems, Ann Arbor, April 1973.

H.Y. Watt, M. Benedict, E.A. Mason, "Methods for Calculating Incremental Fuel Costs for Nuclear Energy," ANS Topical Meeting on Mathematical Models and Computational Techniques for Analysis of Nuclear Systems, Ann Arbor, Michigan, April 1973.

2.4 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. One such project is being partially supported by the NUS Corporation regarding the study of plutonium recycle fuel in the San Onofre-I Reactor.

Investigators: Professor D.D. Lanning; Messrs. D.L. Farrar, P.G. Mertens, H. Spierling, B.W. Momsen, W.R. Jones.

Related Academic Subjects

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

Recent References

H. Spierling, "The Value of Recycle Plutonium in Pressurized Water Reactors," PhD Thesis, Department of Nuclear Engineering, MIT, February 1972.

P.G. Mertens, "Analysis of Conventional and Plutonium Recycle Unit-Assemblies for the Yankee (Rowe) PWR," PhD Thesis, University of Ghent, Belgium. (research was conducted while a student at MIT)

2.5 Reactor Dynamics

Professor Gyftopoulos and one of his students are exploring the possibility of applying Markovian-model techniques to the problem of analysis of reliability of nuclear reactor systems. These techniques have been selected because they are suitable for handling effects of random failures on system reliability.

Professor Gyftopoulos and another student are investigating the problem of experimental identification of reactor dynamic parameters by using the principles of estimation theory and optimum control.

Investigators: Professor E.P. Gyftopoulos; Messrs. J. Papazoglu and P. Kalambokas

Support: **Partial**, Ford Professorship in Engineering

3. Nuclear Materials and Radiation Effects

The nuclear materials program has four major objectives: (1) to provide students in the Department with sufficient background in the principles of physical metallurgy and physical ceramics in order 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) conduct instructional and research programs into both the fundamental nature of radiation effects to crystalline solids and the interrelationships between radiation-induced structural changes and properties; and (4) explore initial materials problems on an interdepartmental and interdisciplinary manner in the general fields of energy conversion, energy transmission, and environmental technology as related to power production.

The introductory course in this sequence of study is 22.71J Physical Metallurgy Principles for Engineers which 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; thermodynamic and rate processes to include phase equilibria, recovery and transformation mechanisms, diffusion, corrosion, and oxidation; mechanical property testing methods, strengthening mechanisms, fracture mechanics, fatigue and creep. Emphasis throughout is on materials and operating conditions involved in advanced engineered systems. This and subsequent courses are conducted jointly between the 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 to include temperature and stress distributions, the mechanisms 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 into 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 corrosion 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. Case studies and comprehensive problems in reactor safeguard analysis and reactor component failures are conducted.

3.1 MHD Materials Coordination

Materials technology has been identified as one of the critical supporting technologies for the orderly development at commercial, open-cycle, MHD power generation plants. The durability and reliability of electrode, insulator, heat storage, and structural materials will be limited by the aggressive operating environments which involve extremely high temperatures, the presence of seed, and the carryover of significant quantities of sulfur and ash from the combustion process. In order to provide needed design information concerning the performance limits and degradation mechanisms of critical system materials, a comprehensive materials technology effort is required. Some elements of this effort have already been identified, and work is underway at several sites under contract with the Office of Coal Research. Furthermore, specific joint research investigations and tests involving materials have been agreed to under the joint USA-USSR Cooperative Program for Developing MHD Power Plants. In order to optimize the value of these research efforts, the following coordinated activities are being conducted:

a) Materials Program Review: timely reviews of program activities are being conducted to assess current materials technology, scope materials needs for advanced system design concepts, and resolve specific questions posed by the OCR program director.

b) Materials Selection: from periodic reviews materials of high promise are selected for investigation under the program and standard lots of characterized materials that have a common interest to more than one participating organization are selected for procurement under the program.

c) Research Procedures and Testing Methods: procedures for specimen design, research methods, and data analysis are reviewed with the purpose of optimizing the usefulness and reproducibility of data.

Investigator: Professor A.L. Bement

Related Academic Subject

22.71J Physical Metallurgy Principles for Engineers

Support: OCR $5,000.

Recent References

A.L. Bement, H.K. Bowen, R. Goodof, and D.R. Uhlmann, "High-Temperature Performance of Materials for Coal-Fired MHD Systems," presented at 12th Symposium on the Engineering Aspects of Magnetohydrodynamics, Argonne National Laboratory (1971).

J.E. Louis and A.L. Bement, "MHD Power Generation, An Assessment and a Plan for Action," Volume II, Briefings Before the Task Force on Energy of the Subcommittee on Science, Research, and Development of the Committee on Sciences and Astronautics, U.S. House of Representatives, 92nd Congress, U.S. Government Printing Office, Washington, D.C. (1972).

3.2 Materials For Advanced Energy Conversion Systems

The general objective of this study is to conduct a comprehensive technical assessment of the materials problems and issues associated with the development of new electrical power generation technology. The principal objectives are as follows:

1) to identify materials problem areas which are either known or predictable for each type of power generating system,

2) to specify the normal and extreme conditions coordination, stress, temperature, etc.) and the apparent demands on materials properties and behavior,

3) to project absolute limits in materials performance based upon their properties and to predict the extent to which these limits can be extended within the probable opportunities for new materials development,

4) to identify those instances where the unavailability of suitable materials is likely to have a significant impact on achieving technical and economic feasibility of new energy technologies within currently conceived time schedules,

5) to assess current materials research and development in support of new energy technology, to identify major gaps in the research, and to recommend areas requiring emphasis in order to provide necessary support for future technology needs,

6) to identify what important new industrial capabilities will be required in the areas of materials supply, processing, and fabrication in order to satisfy projected requirements for component design, site, performance limits and reliability,

7) to explore the range of options for employing substitute materials, expand alternate processing technology, or new composite materials or structures to expand flexibility in maligning design, cost, and supply/ demand objectives,

8) to project the extent to which current materials policies will impart on future materials availability from foreign, domestic, and recycled sources, materials handling and disposal, environmental management, and research incentives within government, the electrical power equipment supply industry, and the utility industry.

Investigators: Professors A.L. Bement and R. Kaplow*

Related Academic Subject

22.71J Physical Metallurgy Principles for Engineers

Support: MIT Energy Laboratory, Cabot Grant, Advanced Research Projects Agency $10,000.

Recent References

A.L. Bement, "Materials Problems in Advanced Energy Conversion," University Forum on National Materials Policy, National Commission on Materials Policy, MIT, May 30-June 2, 1972.

A.L. Bement and R. Kaplow, "Materials Limitations in Advanced Energy Conversion Systems," Report of the ARPA Materials Research Council Summer Conference, Centerville, Mass. (1972).

*Department of Metallurgy and Materials Science

R. Kaplow and A.L. Bement, "Materials Problems in Solar Energy Conversion," Report of the ARPA Materials Research Council Summer Conference, LaJolla, Calif. (1973) (in press).

3.3 Void Nucleation in Irradiated Materials

Experimental work has begun on the problem of void formation in irradiated metals. Equipment has been built which provides greater flexibility in the study of voids than has been previously available. The basic program calls for below room temperature electron irradiation followed by pulse-heating of the damaged sample into the temperature range of void formation. This method provides a number of advantages over most other techniques. The use of electron radiation allows the damage rate to be varied independently of the concentration of gas atoms. This will give an indication of the importance of such transmutation products as helium in the nucleation of voids within nuclear reactor materials. Below room temperature irradiation followed by pulse heating may provide a means of assessing the effect of impurity atom trapping of interstitials in the nucleation process. The experimental program should adequately simulate breeder reactor void formation while at the same time providing more flexibility in determining the basic process.

Investigators: Professors A.L. Bement and K.C. Russell*; Messrs. A.A. Dykes and R.G. Powell

Related Academic Subject

22.73J Radiation Effects in Crystalline Solids

Support: National Science Foundation
Advanced Research Projects Agency
Sloan Basic Research Fund

Recent References

A.A. Dykes and A.L. Bement, "Void Formation in Nickel by Flash Heating," J. Nucl. Meter., 42, 223-226 (1972).

A.A. Dykes, "Void Nucleation by Pulse Heating Irradiated Nickel," SM Thesis, Department of Nuclear Engineering, August 1971.

A.L. Bement, "Void Formation in Irradiated Austeritic Stainless Steels," Advances in Nuc. Sci. & Eng., 7, Academic Press, N.Y. (1973).

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*Department of Metallurgy and Materials Science

3.4 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 which permit or inhibit irradiation-induced creep is necessary to optimize reactor materials design. The purpose of this investigation is to investigate irradiation-induced creep in nickel and 304 stainless steel at low and intermediate temperature and to determine the stress and temperature dependence of such creep. Thin specimen foils are bombarded under load with high-energy protons in an especially designed apparatus, and the specimen deformations due to radiation-induced creep are accurately measured.

Investigators: Professor A.L. Bement, Dr. O. Harling and Mr. Peter Hendrick.

Related Academic Subject

22.75J Radiation Effects to Reactor Structural Materials

Support: Sloan Basic Research Fund, The Metal Properties Council $7,000.

Recent Reference

D.L. Bodde, "Irradiation-Induced Stress Relaxation and Creep in Reactor Materials," SM Thesis, Department of Nuclear Engineering, November 1971.

3.5 Mechanical Behavior of Zirconium and Zircaloy

Strain aging in zirconium, Zircaloy-2, and Zircaloy-4 in the temperature range 200-500 C is manifested by a number of behavior characteristics which include increased flow stress and yield point development during interrupted tensile tests, a decrease in steady state creep rate by several orders of magnitude, marked increases in the activation energy for creep, and discontinuous flow. Although a number of investigations have been conducted to determine the nature of strain aging behavior in zirconium and zirconium alloys, the detailed roles of substructure development and impurity effects are not yet understood. However, such an understanding has technological importance in the development of improved cladding for light water reactor fuel elements, since the temperature range for this anomalous behavior coincides with the operating temperature range of the cladding.

The objective of this investigation is to impart specially-tailored, stable deformation substructures in the Zircaloys by elevated-temperature deformation, develop improved mechanical properties in fuel cladding for light water reactor service, and characterize the starting and as-deformed microstructures to establish the effects of composition and precipitate distributions on substructure development. Special electron transmission microscopy and electron diffraction techniques are being developed and applied to aid in the demonstration studies.

Investigators: Professors A.L. Bement and J. Vander Sande* and Mr. Carlos Nocetti*

Related Academic Subject

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

Support: Wah Chang Albany Company $2,000.

Recent Reference

A.L. Bement, "Radiation Effects on Zirconium and Zirconium Alloys," Proc. of the United States-Japan Seminar on Radiation Effects in Metals and Structural Materials, Kyoto, Japan, September 28-30, 1971.

*Department of Metallurgy and Materials Science

4. Nuclear Chemical Technology

With the large number of nuclear power plants now coming into service, the chemical technology of the nuclear fuel cycle becomes of increasing importance. Engineers with combined training in chemical and nuclear engineering able to participate in projects concerned with uranium ore processing, uranium isotope separation, nuclear fuel reprocessing, and nuclear waste management will be in increasing demand. To provide greater visibility for this field, the Nuclear Engineering Department's subject 22.76, Nuclear Chemical Engineering, is being offered in the fall term jointly with the Chemical Engineering Department, and it is being adapted so that chemical engineers without prior nuclear engineering knowledge can profit from the instruction. To provide up-to-date inputs for instruction in these areas, industrial consulting work is being carried out on projects concerned with isotope separation, fuel reprocessing, and waste management.

The only current research activity at MIT in these fields is a process-engineering and economic study of the mass diffusion process for uranium isotope separation stages for this process have been worked out and a number of alternative process designs have been prepared. A correlation has been prepared of the thermodynamic properties of uranium hexafluoride and perfluoro-tributyl amine and their mixtures, the system to be used in this process. This correlation has been adapted to computer-aided calculation of process flow sheets to determine the equipment requirements and energy consumption of the process. The remainder of the project will involve economic evaluation of the alternative flow sheets to determine which design is optimum from the cost standpoint. Preliminary indications are that the energy consumption of the process will be substantially higher than gaseous diffusion, and thus it will not be economically attractive unless very low cost heat is available.

Classroom instruction is offered through the subject:

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

Investigators: Professor M. Benedict; Mr. C. Forsberg

Related Academic Subject

22.76 Nuclear Chemical Engineering

Recent Reference

M. Benedict, "Separation of Uranium Isotopes by Mass Diffusion Stages," ORO-157304, Part 2, October 15, 1971.

5. MIT Reactor Modification

5.1 MIT Reactor Redesign

The MIT Reactor has been in operation 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. Because of the age of the reactor, it will soon be prudent to shut it down for thorough inspection of the parts with replacement of those parts found to be near the end of their useful life. At the same time, it is planned that extensive modifications will be made to the reactor to modernize the reactor and to provide a threefold increase in the neutron flux available to experimenters.

As described previously*, the modified reactor core will be more compact than the present core, and will be cooled by light water instead of by heavy water. The new core will be surrounded laterally and at the bottom by a heavy water reflector. The new core will be undermoderated and will deliver a high output of fast neutrons to the heavy water reflector where the neutrons will be moderated and the resulting thermal neutrons trapped to produce the desired high flux. The present beam ports will be 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 present reactor to remain include the graphite reflector, thermal shield, biological shield, beam ports, heat exchangers, pumps, cooling towers and containment building.

The design of the new core has been completed including a complete safety analysis of the modified facility. This Safety Analysis was sent to the Division of Reactor Licensing of the AEC in November of 1970. Negotiations with the AEC continued through 1971 and 1972. These negotiations were mostly with regard to the existing parts of the reactor such as updating electronic systems, investigation of seismic

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*) The modification project has been discussed in detail in the last three Nuclear Engineering Department Visiting Committee meetings (April 18, 1969, December 3, 1970 and March 23, 1972).

effects, improvements in the containment system, and new formats for operating plans and procedures. By the end of 1972 the AEC had concluded their review and initiated their plans to approve the modification. On March 6, 1973 the "Notice of Proposed Issuance of Construction Permit" was published in the Federal Register, and on April 9, 1973 the AEC issued Construction Permit No. CPRR-118, authorizing the modification of the MIT Reactor.

Also, in January of 1973 the MIT Administration made a complete review of the role of the MIT Reactor. Questions relating to past and future costs and benefits were studied. Alternatives were reviewed including renovation of the present facility without modification. A design study was made on an improved fuel element for the present core. This study indicated that the flux at the beam ports can be increased by a factor of 1.35 while improving the thermal to fast neutron ratio by the use of "window" elements, i.e. elements with fuel removed from the line of sight of the beam ports. However, such alternatives would not give the modernization or flux enhancement that is possible with the modified reactor core. It was concluded that the plans for the reactor modification should be supported. Approval was given to proceed with the expenditure of modification funds after the construction permit was received from the AEC. Purchase requisitions have now been issued for the fabrication of the new reflector tank, core tank and internals.

In addition to the purchase of the necessary parts, plans and procedures are being prepared for each step of the disassembly and assembly together with the new operations manuals and start-up procedures. Preparations are being planned so that the reactor can be shut down in February or March of 1974, the modifications made, and the reactor restarted by July of 1974.

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. Equally valuable practical experience will be provided students during the 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, E. Barnett, R. Chin, L. Clark, K. Collins, L. Deppe, P. Furtado, D. Gwinn, C. Hove, A. Kadak, J. Knotts, T. Rieck, A. Tagishi, A. Torri, T. Yarman.

Support: MIT, Reactor Depreciation Reserve Account, $589,651 through April 1973.

Recent References

A.C. Kadak, "Fuel Management of the Redesigned MIT Research Reactor," PhD Thesis, Department of Nuclear Engineering, MIT, April 1972.

T. Yarman, "The Reactivity and Transient Analysis of MITR-II," PhD Thesis, Department of Nuclear Engineering, MIT, July 1972.

A. Tagishi, "Investigation and Design of On-Line Digital Noise Analysis System for the MITR," SM Thesis, Department of Nuclear Engineering, MIT, February 1973.

5.2 Cold Neutron Source

A project is being carried out at the MIT Reactor to investigate possible methods of creating and utilizing beams of very slow neutrons. An out-of-reactor liquid-helium cryostat has been designed and constructed for use with the medical therapy room beam. This cryostat was used to study possible means of reducing the effective neutron temperature and thus increase the number of low energy neutrons. The information obtained from these experiments has been used to design and construct a liquid-helium cooled cryostat located in the MIT thermal column.

The first thermal column cryostat was designed to contain a one foot diameter sphere of frozen heavy water (D_2O) as the moderator. Cooling for the thermal column cryostat is provided by cooling coils through which liquid helium is circulated. The liquid helium is produced by the Cryogenic Facility described in Section 5.3. These rather complex cryogenic systems have been installed and operated. The frozen sphere of D_2O in the thermal column has been cooled to the design temperature of 20°K while the reactor was operating at its normal full power of 5 Mw. Initial measurements were made of the neutron energy distribution in a beam of neutrons from the cryostat, both with and without the cold D_2O. A cold neutron gain of a factor of 10 was measured for neutrons whose wavelength was about 6A°. Although this is an appreciable enhancement of the cold neutrons, it is desirable to improve the intensity further. Also, the first cryostat was found to be difficult to operate. An improved D_2O container has now been fabricated and installed in the thermal column, consisting of a one foot diameter hemispherical bottom and a cylindrical upper section. This new design surrounds the re-entrant beam tube with more cold D_2O and will allow the use of neutron reflecting tubes for enhancement of the exit beam intensity. Measurements are in progress to determine the new cold neutron beam intensity and energy distribution.

Investigators: Professor D.D. Lanning; Messrs. G. Allen, E. Barnett, R. Chin, J. Huyett

Support: Sloan Fund (MIT), $87,042.

Recent References

R.C. Sanders, "Design of a Cold Neutron Source for the MIT Reactor," PhD Thesis, Department of Nuclear Engineering, MIT, June 1970.

R. Chin, "Design of a Cold Neutron Source for the MITR - A Follow-up Study," SM Thesis, Department of Nuclear Engineering, MIT, August 1971.

5.3 Reactor Cryogenic Facilities

The modified core of the MIT Reactor has provision for an in-core cryostat, in which materials can be irradiated at liquid-helium temperatures. At these low temperatures, structural defects caused by radiation are frozen in place and are not annealed, as would be the case at higher temperatures. This permits examination of the initial effects of radiation.

The in-core cryostat will be mounted in the center of the core where the flux of fast neutrons and gamma rays is highest. A sample tube will extend to the top of the reactor shielding where experiments can be made on irradiated specimens without warming the samples or with controlled warming, if desired.

An out-of-core assembly has been designed and constructed to test the design of the in-core facility. Data on forced convection boiling heat transfer as well as on flow rates and pressure drops for the liquid helium coolant were taken and analyzed. No instabilities were evident in the flow tests of the out-of-core cryostat; thus, operation of the in-core cryostat is also expected to be satisfactory.

To provide liquid helium for this in-core cryostat and to provide refrigeration for the cold neutron source described in Section 5.2, a helium refrigeration and liquifaction unit has been installed at the reactor. This unit was designed by Professor J.L. Smith of MIT for construction at the Cambridge Electron Accelerator and was partially completed there, but never used. It was declared surplus by the Atomic Energy Commission and was loaned to the MIT Reactor. It was moved to MIT, completed and installed at the reactor, with costs defrayed by the Sloan Fund for Basic Research and the reactor depreciation reserve account.

A number of modifications to the existing helium plant were accomplished during the year in order to improve performance reliability and to increase the liquid helium production rate to 75 liters/hr which is still less than the design value but sufficient for the planned experiments. Additional instrumentation and safety devices were also installed at various locations in the refrigeration and helium transfer systems in order to meet operational safeguard requirements for both the in-core cryostat and the cold neutron source.

Investigators: Professors A.L. Bement, D.D. Lanning; Messrs. E. Barnett, D. Gwinn, F. Berte, J. Rosati.

Support: National Science Foundation $18,000
MIT Reactor Depreciation Account, $153,272.

Recent Reference

F.J. Berte, "Prediction of the Thermodynamic Behavior of the In-Core Cryogenic Irradiation Facility at the MIT Reactor, Based on Tests in the Out-of-Core Mockup," PhD Thesis, Department of Nuclear Engineering, MIT, January 1971.

5.4 Neutron Radiography

A neutron radiography facility has been built and tested by the MITR Operations Group. This facility is designed to use the neutron beam in the Medical Therapy Room of the MITR.

The internal structure, shown by the use of conventional X-ray or gamma graph techniques, is a function of mass attenuation and is not effective for low density materials. Also, X-rays are not generally useful for radioactive materials due to the interference from the self-emitted radiations. On the other hand neutron radiography is sensitive to imaging internal structures of low atomic number whose scattering cross section is high such as hydrogen bearing materials.

The method being used at the MITR is a transfer technique. The neutron beam passes through the object and then activates an indium or a dysprosium plate. Imaging of the object is thus created by the relative radioactivity on the surface of the plate. The active plate is in turn removed from the beam and used to expose a photographic plate.

The capability of the system has been demonstrated and two SM thesis research projects have been completed involving studies of the resolution of the system and investigation of possible applications.

Investigators: MITR Staff; Messrs. K. Collins, D. Gwinn; Professor D.D. Lanning; Messrs. K. Edgar, E. Westberg.

Recent References

E.L. Westberg, "Neutron Radiography at MIT Research Reactor," SM Thesis, Department of Nuclear Engineering, MIT, May 1972.

J.K. Edgar, "Non-destructive Testing of High Strength Steel Welds by Neutron Radiography," SM Thesis, Departments of Nuclear Engineering and Ocean Engineering, MIT, May 1973.

6. Applied Radiation Physics

The Department's involvement with reactors and sources of radiation has led to an applied radiation physics program concerned with the radiations these sources emit and with the uses to be made of radiation. This program deals in a unified manner with neutrons, charged particles, gamma rays, and light and other electromagnetic radiations. It is concerned with the production of neutrons and gamma rays by fission reactors, the production of alpha, beta and gamma rays by radioisotopes, the production of electrons, positive ions, neutrons and gamma rays in particle accelerators, and the production of coherent electromagnetic radiation by lasers. Topics treated include the detection and measurement of radiation, the interaction of radiation with matter, the use of radiation in processing materials, the design of irradiators, biological effects of radiation and the use of scattering experiments with neutrons and coherent light to determine the structure and molecular dynamics of solids, liquids, and dense gases.

The following subjects of instruction are offered:

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 radiation fields and time dependent perturbation theory. Emphasis is given to the development of fundamental cross sections described in the interactions of light, x-ray, gamma-ray, and charge particles with atomic systems. The applications discussed include: emission and absorption of light; the theory of line width; Rayleigh, Brillouin and Raman scattering; laser spectroscopy; x-ray scattering, photoelectric effect; Compton effect; Bremsstrahlung; pair production; atomic collisions in boron and impulse approximation; and treats collisions of fast electrons and massive charge particles with atoms.

22.52, Neutron Physics and Applications, which treats the basic principles of neutron interaction with nuclei in matter. The principle applications are to cross section calculations for reactor design and to scattering experiments for the study of material properties. Other topics which are included are fast neutron cross sections, resonance absorption, neutron thermalization, and the general properties of inelastic scattering of thermal and cold neutrons in liquids and solids.

22.53, Radiation Engineering, which deals with the principles and practice of engineering application of radiation and radioisotopes. Attention is paid to radiation sources and machines, radiation interactions, dosimetry and shielding and radiation detection. Additional topics are tracer applications, radiation gauging, x-ray analysis, radiation, preservation, and processing, radioisotope power sources, and medical and biological application of radiation and radioisotopes.

22.54, Radiation Shielding, which introduces material relating to the shielding of nuclear reactors, accelerators and space vehicles. Topics which are discussed include the interactions of neutrons, gamma rays and charge particles in thick shields. Emphasis is given to the engineering aspects of shield design including shielding material, voids and ducts, heat removal and a description of shield design codes.

6.1 Thermal Fluctuations and Transport Phenomena in Gases and Liquids

The study of space- and time-dependent fluctuations in gases and liquids is a fundamental problem in nonequilibrium statistical mechanics. These fluctuations are of interest because they are the basic properties of any system of interacting particles 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. The emphasis of the present research is the development of theoretical methods for analyzing thermal fluctuations which eventually will result in a dynamical theory of fluids capable of treating fluctuation and transport phenomena at arbitrary wavelengths and frequencies.

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 world of molecular interactions and particle trajectories and the macroscopic behavior of transport properties and hydrodynamic processes. At present this approach offers the most systematic method of calculating time correlation functions in classical fluids.

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 (also called memory functions) 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.

The generalized transport equation appears to provide the proper foundation for a unified study of thermal fluctuations in fluids at arbitrary frequencies and wavelengths. Detailed calculations are underway to verify this expectation. Computer molecular dynamics data, neutron scattering spectra, and transport coefficient measurements are available to help assess the quantitative utility of the theory.

Investigators: Professor S. Yip; Dr. G.F. Mazenko, Messrs. J. Castresana, P. Furtado.

Support: NSF, $33,000/year

Related Academic Subjects

22.51 Interactions of Radiation with Matter
22.52 Neutron Physics and Applications

Recent References

C.D. Boley and S. Yip, "Spectral Distribution of Light Scattered in Dilute Gases and Gas Mixtures," Journal de Physique, 33, C1-43 (1972).

C.D. Boley and S. Yip, "Modeling Theory of the Linearized Collision Operator for a Gas Mixture," Physics of Fluids, 15, 1424 (1972).

C.D. Boley and S. Yip, "Kinetic Theory of Time-Dependent Correlation Functions in a Binary Gas Mixture," Physics of Fluids, 15, 1433 (1972).

G.F. Mazenko, T.Y.C. Wei and S. Yip, "Thermal Fluctuations in a Hard Sphere Gas," The Physical Review, 6A, 1981 (1972).

G.F. Mazenko, "Fully Renormalized Kinetic Theory. I. Self-Diffusion," The Physical Review, 7A, 209 (1973).

G.F. Mazenko, "Fully Renormalized Kinetic Theory. II. Velocity Autocorrelation," The Physical Review, 7A, 222 (1973).

G.F. Mazenko and S. Yip, "Fully Renormalized Kinetic Theory of Thermal Fluctuations in Liquids," paper presented at the Conf. on Molecular Motions in Liquids, Paris, July 1973. Proceedings to be published.

G.F. Mazenko, "Fully Renormalized Kinetic Theory. III. Density Fluctuations," submitted for publication in The Physical Review.

6.2 Lattice Dynamics of Molecular Solids

The study of low-frequency lattice vibrations in molecular solids provides detailed information about intermolecular forces and torques. For complex solids, it is often necessary to analyze spectroscopic measurements by treating the molecular units as rigid bodies capable of translations and vibrations. Without this simplification the large number of atomic degrees of freedom in each unit cell would make the calculations intractable. The rigid-molecule approach has been used to analyze the normal mode vibrations in a number of solids containing molecular ions. In the harmonic approximation the quantities of basic interest are the phonon dispersion relations and polarization vectors, and the frequency distributions. They are obtained by model calculations using the information derived from infrared and Raman spectra, elastic constant and dielectric measurements, and, wherever possible, neutron inelastic scattering data.

The related problem of vibrational properties of solids in the presence of defects also has been studied. The method of thermodynamic Green's function was used to calculate the phonon widths and shifts in cases where the mass difference between the impurity and host-lattice atoms and the change in nearest neighbor interactions are taken into account. General results applicable to zinc-blend lattices have been derived and numerical results for gallium phosphide containing various heavy and light impurities obtained.

Investigators: Professor S. Yip; Messrs. C.H. Kim, O. Kadiroglu.

Support: Picatinny Arsenal, Dover, N.J., $19,384/year.

Related Academic Subjects

22.51 Interactions of Radiation with Matter
22.52 Neutron Physics and Applications

Recent References

H.A. Rafizadeh, S. Yip, and H. Prask, "Lattice Dynamics of Rhombohedral Sodium Azide," Jour. of Chem. Phys., 56, 5377 (1972).

C.H. Kim, H.A. Rafizadeh and S. Yip, "Lattice Vibrations in Ammonium Chloride in the Low-Temperature Ordered Phase," Jour. of Chem. Phys., 57, 2291 (1972).

C.H. Kim and S. Yip, "Boron Impurity Effects in Gallium Phosphide Crystal," Jour. of Chem. Phys., 57, 4055 (1972).

6.3 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 1 Å).

A triple-axis crystal spectrometer has been constructed at the MIT Reactor and put into operation since 1971. The most recent experiment was a series of measurements of the energy distribution of thermal neutrons scattered by pressurized hydrogen gas. The observed quasielastic scattering line shapes showed a narrowing behavior with increasing pressure. This phenomenon of collisional narrowing has not been observed previously by neutron scattering. The measurements have been quantitatively analyzed in terms of kinetic theory calculations (see Section 6.1), and the results constitute a new test of the validity of the Enskog-Boltzmann equation. Another interest in the data stems from the fact that one can deduce information about three-particle correlations from pressure derivatives of the line shape.

Other activities associated with this project are the development of a neutron transmission experiment to determine density and concentration gradients in fluids and fluid mixtures, and the construction of a high resolution light-scattering spectrometer. The latter is based on the principle of intensity correlation and is well suited for studying fluctuations near the critical point.

Investigators: Professors S.H. Chen, S. Yip; Dr. P. Tartaglia, Messrs Y. Lefevre, T.A. Postol, P. Walsh.

Support: USAEC, $100,000/year

Related Academic Subjects

8.37 Neutron Diffraction
22.52 Neutron Physics and Applications

Recent References

T.A. Postol, "A Method of Measuring the Equation of State of Xenon Near the Critical Point by Neutron Transmission," SM Thesis, Department of Nuclear Engineering, MIT, January 1972.

Y. Lefevre, S.H. Chen and S. Yip, "Translational Line Narrowing in Pressurized Hydrogen Gas," in Neutron Inelastic Scattering (IAEA, Vienna 1972).

S.H. Chen, Y. Lefevre and S. Yip, "Dynamics of Liquid Gallium in the Supercooled State," paper presented at The 2nd Inter. Conf. on the Properties of Liquid Metals, Tokyo, September 1972. To be published in The Philosophical Magazine.

C.H. Chung, S. Yip and P.A. Egelstaff, "Dynamic Structure Factor Calculations and Neutron Inelastic Scattering," paper presented at the 2nd Inter. Conf. on the Properties of Liquid Metals, Tokyo, September 1972. To be published in The Philosophical Magazine.

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

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

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

S.H. Chen, Y. Lefevre, G. Mazenko and P.A. Egelstaff, "Pressure Dependence of the Incoherent Scattering Law and The Time-Dependent Triplet Correlation Function in Dense Hydrogen Gas," paper presented at the Conf. on Molecular Motions in Liquids, Paris, July 1973. Proceedings to be published.

S.H. Chen, Y. Lefevre and S. Yip, "Kinetic Theory of Collisional Line Narrowing in Pressurized Hydrogen Gas," submitted for publication in The Physical Review.

6.4 Light Scattering Study of Fluids Near the Critical Point and Mobility of Bacteria in Solution

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 $[I(t)I(t+\tau)]$ 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 μsec. Application of the method to Rayleigh scattering from fluctuations in a fluid medium has 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 and the motion of micro-organisms of biological interest in solution. The usefulness of the method for measurement of molecular transformation in solution also has been investigated.

Investigators: Professor S.H. Chen, Dr. P. Tartaglia, Dr. R. Nossal (NIH); Mr. C.C. Lai.

Support: National Institute of Health; MIT Sloan Fund for Basic Research. Cumulative support to date $100,000.

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

R. Nossal and S.H. Chen, "Light Scattering from Motile Bacteria," Jour. de Physique, 33, Suppl. No. 2-3, C1-171 (1972).

R. Nossal and S.H. Chen, "Laser Measurements of Chemotactic Response ofBacteria," Optics Communications, 5, 117 (1972).

C.C. Lai and S.H. Chen, "Light Scattering Intensity and Correlation Length of a Binary Critical Mixture," Physics Letters, 41A, 259 (1972).

C.C. Lai and S.H. Chen, "Evidence of Mode-Mode Coupling and Non-Local Shear Viscosity in a Binary Mixture Near the Consolute Point," Physical Review Letters, 29, 401 (1972).

S.H. Chen and P. Tartaglia, "Light Scattering from Non-Interacting Particles," Optics Communications, 6, 119 (1972).

S.H. Chen, P. Tartaglia and N. Polonsky-Ostrowsky, "A Method for the Clipped Intensity Correlation Measurement," Jour. of Physics, A5, 1619 (1972).

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

6.5 Neutron Molecular Spectroscopy

This is a recently initiated project the purpose of which 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 will be designed and constructed which will take advantage of the monochromating properties of bent copper crystals, the high reflectivity of pyrolitic graphite, and the efficiencies of position-sensitive detectors. By measuring the intensity and band shape of various vibrational modes in a series of saturated hydrocarbons (alkanes) one obtains information which can be used to help determine the multiple-minima potential functions in these systems. Similarly, neutron scattering data on a series of acids and amides (formic, formamide, acetic, acetamide, glycine) will significantly contribute to the present spectroscopic information derived mainly from infrared and Raman measurements.

Investigators: Professors S.H. Chen and S. Yip; Dr. C.V. Berney, Professor R.G. Gordon (Harvard).

Support: NSF, $60,000/year

Related Academic Subject

22.52 Neutron Physics and Applications

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 basic instruction in applied nuclear physics is presented as a two semester sequence of subjects:

22.111, Nuclear Physics for Engineers I, which 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, which 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.

7.1 Prompt Activation Analysis

There has been an active program in high resolution gamma-ray spectroscopy for a number of years. In recent years one of the major efforts has been the application of prompt activation analysis to elemental identification in industrial process streams. Work was done for the U.S. Bureau of Mines on the application of this technique to the sulfur analysis of coal. At least one commercial firm is now developing this method for commercial appliations.

Several other applications are being investigated including assay of fuel material to blast furnaces, the determination of the nitrogen content of fertilizers, and the determination of the ash content of coal. These techniques show some promise but also have a number of problems that would have to be solved before they could be successful for commercial operation.

Investigators: Professor N.C. Rasmussen; Messrs. J. Hamawi, B. Hui, R. Schaeffer, S. Rinehart, T. Dunn, S. May.

Support: None at present (formerly U.S. Bureau of Mines)

Related Academic Subjects

22.111	Nuclear Physics for Engineers I
22.112	Nuclear Physics for Engineers II
22.54	Radiation Shielding
22.29	Nuclear Measurements Laboratory

Recent References

S. Rinehart, "Determination of Nitrogen Concentration in Inorganic Fertilizer Using Prompt Gamma-Ray Spectroscopy," SM Thesis, Department of Nuclear Engineering, MIT, February 1972.

R. Schaeffer, "Prompt Activation Analysis of Coal and Iron Ore," SM Thesis, Department of Nuclear Engineering, MIT, January 1971.

S.A. May, "Analysis of Ash Content in Black Mesa Coal by Gamma-Ray Attenuation," SM Thesis, Department of Nuclear Engineering, MIT, May 1973.

7.2 Thermal Neutron Activation Analysis

The application of thermal neutron activation analysis to biological samples is restricted by the induction of interfering activities (principally ^{24}Na, ^{32}P, ^{42}K and ^{82}Br). Our efforts to develop a chemical method for the removal of these interferences has continued during the past year. We have chosen a chemical scheme similar to a system described at a recent symposium; the scheme is attractive in that it can be, and if funding is available, will be automated for use in the analytical aspects of biomedical research projects.

In collaboration with Drs. G. Tully and B. Neer, Endocrine Unit, MGH, we have developed a novel method for the study of calcium metabolish in man using activation analysis. The measurement requires two calcium tracers; the radioisotope ^{47}Ca, introduced orally, and the stable isotope ^{48}Ca, intravenously administered. Analysis of urine for each of the two isotopes along with a total calcium analysis by atomic absorption spectroscopy provide a measure of calcium absorption in the intestines.

Investigator: Dr. D. Hnatowich

Support: MIT

8. Biomedical Applications

MIT is involved in several programs in health sciences and technology. One of these involves the development of biomedical engineering curricula and research. For many years biomedical applications of nuclear science and technology have received attention both in the academic curriculum and in the research programs of this Department. The MIT Reactor has played a significant role in biomedical research at MIT.

Subjects of Instruction in this field include:

22.55, Biological Effects of Nuclear Radiation, which presents a review of the interactions of nuclear radiations with matter and the effects of energy absorbed from nuclear radiation on simple and complex chemical systems, various organisms and living tissue. Theories of the action of radiations on living matter are discussed and consideration is given to the various factors which affect the biological response such as time and type of radiation. The theory and practice of radiation dosimetry is presented along with special reference to practical applications. The biological and physical bases for safety standards are discussed.

In addition to this regular subject, a special summer subject, 22.83s Physical Aspects of Nuclear Medicine is also offered. The program covers new developments in radio-pharmaceuticals, instrumentation, data processing, and the use of these techniques in both diagnosis and therapy.

8.1 Particle Track Etch Method for Pu Assay

During the past year 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 tieeues 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 until sufficient particle tracks have been registered in the backing material, which 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.

Most of the work to date has been the study of irradiation conditions in the MITR for bone samples taken from the beagle colony at the University of Utah College of Medicine. The neutron doses for several levels of plutonium concentration have been determined. Proper irradiation temperatures, decay times after irradiation, and etch conditions bring out a bone image (for reasons not yet understood) which permit evaluation of the Pu distribution with respect to bone surfaces, marrow and cells. Interfering radiations, probably fast neutrons, cause fogging of the plastic backing, which obliterates the bone image at high fluences.

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 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.

Investigators: Mr. L. Clark, Jr.; Professor D. Lanning, Messrs. S. Kauffman and M. Fellows.

Support: University of Utah (USAEC), MIT

Related Academic Subject

22.112 Nuclear Physics for Engineers II

Recent Reference

M.H. Fellows, "Fission Particle Tracks in Solids," Report for MIT Subject 22.39 (May 1973).

8.2 Medical Applications of the Medical Therapy Facility of the MIT Reactor

During the past twelve months Professor Brownell and Dr. Brian Murray have performed, in collaboration with Dr. William Sweet of MGH, a series of experiments directed towards a renewed clinical application of boron neutron capture therapy in the treatment of intracranial neoplasms. These experiments may be placed into two categories: (a) the radiation of the brains of normal dogs to ascertain possible brain damage due to the boron neutron capture therapy treatment and (b) phantom studies on tissue equivalent gelatin head phantoms complete with a re-entrant cavity representing resected tumor mass.

a) Dog Irradiations at the MIT Reactor (MITR)

The primary purpose of these irradiations is to ascertain the damage to normal brain tissue under circumstances similar to what patients would be subjected to. The previous trial, during 1960-1962, taught us that although we can sterilize tumor tissue within the brain there is a significant risk of also damaging normal tissue around that tumor. In these studies we administered varying amounts of a new boron compound, $Na_2B_{12}H_{11}SH$, to a series of six dogs and then subsequently irradiated the brains of these dogs at neutron fluences similar to what we would use in a renewed clinical trial. Dr. Hiroshi Hatanaka, Professor of Neurosurgery in Japan, assisted

Drs. Sweet, Murray and Brownell in these studies. He also supplied us with the B-10 enriched sulfhydral compound for these studies. A significant amount of effort, preliminary to these studies, was actually making various attempts at fitting neutron collimators to the scalps and skulls of the dogs that we used. The brain of each dog was exposed by cutting a 5/8 inch diameter hole in their skull with a trephine cutter. With gold foil dosimeters to monitor the thermal neutron fluence and CaF_2:Mn TLD rods to monitor incident and capture gamma-ray fluxes based in the immediate irradiation area on and around the exposed brains of the dogs. These dogs were then placed at the therapy neutron portal and irradiated for various times. For comparison purposes we also irradiated a seventh dog who had received no boron compound to serve as a blank for our studies. After each dog was irradiated, he was quickly transferred to the animal research center in Southboro, Massachusetts, where they were looked after by a veterinarian. At the present time none of the seven dogs shows any sign of neurologic deficit or nervous system difficulties at all. We plan to keep several of these dogs alive for at least 18 months to 2 years in order that the late occurring ischemia will have a full time to develop. We consider these experiments to be of fundamental importance in not only understanding the radiation effects, if any, on normal brain tissue that the boron neutron capture therapy would have, but also in guaranteeing the safety of patients in any future clinical therapy.

b) Development of an In-Vivo Activation Analysis Program for the Determination of Whole Body Nitrogen, Phosphorus and Calcium

Professor Brownell, Dr. Murray and Robert Zamenhof (nuclear engineering student) are collaborating in developing a program directed towards the in-vivo activation analysis in man to determine whole body contents of various elements, such as nitrogen, phosphorus and calcium. As part of this development effort, we have interested Professor Vernon Young of the Nutrition and Food Sciences Department of MIT to collaborate with us in writing a proposal to seek funds for a real trial of whole body nitrogen content using in-vivo activation analysis. Furthermore, Professor Brownell conducted a symposium on the medical uses of the MITR on May 1, 1973, in which the in-vivo activation analysis program was highly accented.

Mr. Robert Zamenhof has had considerable experience in this area for his masters thesis at the University of Birmingham in England. Dr. Murray and Mr. Zamenhof have been conducting initial calculations to see whether the fast neutron component of the therapy beam in the medical therapy facility will be sufficient to use in a whole body in-vivo activation analysis program. The significant problem here is to produce a uniform thermal flux throughout the whole body in order to properly perform in-vivo activation analysis. We are also investigating the use of lithium deuteride (LiD) which will act as an incident thermal neutron shield and subsequently produce 14.2 MEV fast neutrons in a triton-deuterium interaction. Initial calculations show that we can obtain $1\text{-}2 \times 10^6$ neutrons per square centimeter per second flux at 14.2 MEV. This energy and this flux will be very adequate for producing a uniform thermal flux through a tissue mass of 50 cm diameter.

Investigators: Professor G. Brownell; Dr. B. Murray, Dr. W. Sweet; Mr. R. Zamenhof

Support: NIH and AEC

Related Academic Subject

22.55 Biological Effects of Radiation

9. Quantum Thermodynamics

Professor E.P. Gyftopoulos of this Department and Dr. G.N. Hatsopoulos of Mechanical Engineering have continued their investigations into the foundations of quantum mechanics and thermodynamics with emphasis on improved methods of exposition and on derivations of a number of important theorems from the fundamental postulates of the theory.

They also continued their studies of low energy plasmas such as those encountered in the interelectrode space of cesium thermionic converters. These studies concentrated on (1) range of validity of linear transport equations; and (2) derivation of rigorous plasma-sheath boundary conditions.

Investigators: Professors E.P. Gyftopoulos and G.N. Hatsopoulos*

Related Academic Subject

22.58J Quantum Thermodynamics

Recent References

E.P. Gyftopoulos and G.N. Hatsopoulos, "Thermodynamic Analysis of Metal Surfaces Covered by Electropositive Adsorbates," Proc. of 3rd Int. Conf. on Thermionic Electrical Power Generation in Julich, Germany, June 1972.

J.H. Keenan, G.N. Hatsopoulos and E.P. Gyftopoulos, "Principles of Thermodynamics," article in 1974 edition of Encyclopedia Britannica.

J.H. Keenan, E.P. Gyftopoulos and G.N. Hatsopoulos, "The Fuel Shortage and Thermodynamics," Proc. MIT Energy Conference, February 1973.

G.N. Hatsopoulos and E.P. Gyftopoulos, "Thermionic Energy Conversion," Volume I, Processes and Devices, MIT Press, Cambridge, Mass., June 1973.

*Department of Mechanical Engineering

10. Energy and the Environment

Intertwining of these topics no longer requires explanation; neither does their importance. The Nuclear Engineering Department is qualified and prepared to play a number of useful and possibly unique roles in the energy field, especially in relation to the proper role of nuclear energy.

Proper management of energy requires consideration of several general sectors: resources (and their alternate use), transformation of these basic resources into acceptable and useable energy forms, (e.g. generation of electric power via nuclear reactors), the economic, societal, and environmental costs of those transformation options, and the use of the energy so generated.

We work in several of these areas: energy source competition, which changes as the advantages of one system changes compared to the advantages of another; environmental effects, particularly (1) waste heat from nuclear reactors, (2) disposal of high level radioactive wastes, (3) general environmental effects of electric power production, (4) comparison of societal costs caused by nuclear power generations, as compared to those caused by various fossil fuel options; and finally research and development strategies for energy conservation and utilization.

Subjects of instruction offered are:

22.37, Environmental Impact of Nuclear Power, which presents an assessment of the various environmental impacts of producing electric power with currently available technology. The impacts of both fossil and nuclear fuel cycles are compared and discussion is included of fuel resources and extraction, power station effluents, waste heat disposal, reactor safety, and radioactive waste disposal.

22.80, National Socio-Technological Problems and Responses, which is designed to acquaint students with large socio-technological problems and our capabilities for dealing with them, in ways beyond discipline-oriented research. Topics of discussion include the structure and content of national problems and the connectivity between problems and sectors. A review of present organizations at the working level (including universities, national laboratories, industrial laboratories, etc.) is presented along with the discussion of the extent to which they relate to decision-making levels and the extent to which they match or mismatch their programs to the true scale of problems. Recent debates, programs and proposals related to energy and the environment are used as particular examples.

10.1 The Environmental Impacts of Electrical Power Production

Today electrical power accounts for 25% of all of the energy consumed in the United States. Consequently, the effects on the environment resulting from the production of electrical power are an important part of the ecological changes produced by the activities of our society. The environmental degradation associated with electrical power production -- in terms of its effect upon the average citizen -- is somewhat greater than the electrical share of the total energy market, since power stations tend to be located near to heavily populated areas. As a result, detrimental consequences associated with electrical power production (e.g. air pollution) are visited on many more people than if the same activity were conducted at a more remote location.

It is predicted that about 40% of our energy consumption will be in the form of electricity at the end of this century, and that by that time our total rate of consumption will be about 2-1/2 to 3 times as great as it is today. Thus, it is important that the mix of technical options chosen to meet this demand be chosen with a regard for producing minimal environmental degradation. Between now and the end of the century, new electrical power stations will employ, on a significant scale, only technology which is presently available or visible on the near horizon.

A study is now being made with the aim of assessing and cataloging the environmental impacts in order to recommend the "least total cost" set of technical mixes to be used in a variety of typical power plant siting situations.

The study will examine and contrast the disparate environmental prices paid in using fossil and nuclear power generating methods, taking into account improvements which can reasonably be expected to play a role in generating a significant fraction of the electrical energy in the next thirty years.

Investigators: Professors N.C. Rasmussen, M.W. Golay,

Support: MIT Environmental Laboratory

Related Academic Subjects

22.312 Engineering of Nuclear Reactors
22.34 Economics of Nuclear Power
22.37 Environmental Impact of Nuclear Power
22.80 National Socio-Technological Problems and Responses

Recent Reference

A. Ovi, "Decision Analysis Application to Nuclear vs. Fossil Alternatives for Electric Energy Production," SM Thesis, MIT, January 1973.

10.2 Modeling of Energy Source Competition

The United States is entering a time which will be characterized by rapidly increasing prices for natural gas and petroleum, and possibly also for coal -- depending upon the rate and type of new technology development. On the nuclear side the prospects for stable prices are much better, due to a near-term abundance of fuel and to the high likelihood of successful utilization of plutonium-recycle, efficient converter reactors, and fast breeder reactors. As fossil fuels become relatively more dear than nuclear fuels the incentives for nuclear substitution of fossil demand will grow. In many cases this will demand conversion from a non-electrical to an electrical energy supply. Such conversions will have the effect of reducing demand for fossil fuels, and will free them for alternative uses. However, the strength of the incentives for electrical substitution, and for the selection of electrical power to supply newly generated energy demand will depend upon the price of nuclear power. In all cases the nuclear power price is expected to remain low vis fossil energy prices; however, the range of possible variation can be significant, depending upon the reactor development and introduction sequence which occurs.

Work is currently underway to model the national interfuel competition, on a time scale extending to the end of the century. An existing model which describes competition between natural gas, petroleum, coal, and electricity is being refined to treat each of the fossil fuels as separately supplying electrical and a non-electrical demand. Electrical demand is also treated as being supplied by light water reactors -- both with and without plutonium-recycle -- by both burner and converter HTGR's, and by fast breeder GCFR's and LMFBR's. The goal of the work is to examine the effect of various reactor development and introduction sequences, coupled with a range of possible energy demand profiles in order to determine the possible impact of nuclear power in supplying national energy requirements and in reducing fossil fuel demand.

Investigators: Professor M.W. Golay, Dr. M.L. Baughman*, Mr. G. Daley

Support: National Science Foundation

Related Academic Subjects

22.34 Economics of Nuclear Power
22.37 Environmental Impact of Nuclear Power
22.80 National Socio-Technological Problems and Responses

Recent Reference

M.L. Baughman, "Dynamic Energy System Modeling-Interfuel Competition," PhD Thesis, MIT, Electrical Eng. Dept., September 1972.

10.3 Cooling Towers

Since about 1967 when large, thermally-inefficient nuclear power stations began to appear on the landscape the problems of waste heat disposal have received increasing attention. Most of these stations were built using once-through cooling, and the unprecedentedly large heat loads which they injected into the local aquatic environments resulted in larger ecosystem pertubations (e.g., fish kills) than had been common previously. The term "thermal pollution" soon became part of the environmental lexicon, and it came to symbolize an issue of contention between utilities and those opposing construction of new power stations. As opposition to once-through cooling has grown, it has become increasingly common for large inland nuclear stations to be designed using either cooling ponds or cooling towers for waste heat disposal. This has been done both in order to protect local water bodies from the waste heat perturbation, and in order to avoid the costly delays in issuance of an AEC operating license which can follow from objection by an environmental intervenor group.

The cost of an alternative waste heat disposal system can be large, being on the order of 10% of the overall station capital cost in the case of a cooling tower installation. The large amounts of money involved in such installations, and the wide scale of their introduction has generated fresh interest in the types of designs available, and possibilities for improvements. Work in this area has been, and is currently being performed in the Department. In a recently completed study the feasibility of augmenting the draft of large natural draft cooling towers is investigated. The aim is to find a method which would economically permit a reduced height chimney to be used in conjunction with a "peaking-type" draft assistance system. Draft augmentation methods investigated are steam heating of the tower effluent, steam jet injection into the effluent stream, and use of fans. It is found that all of the assistance schemes except use of fans fail as being too costly. However, the fan assistance methods is shown to permit net savings in tower costs-over-life at low tower heights. Shortly after the study was completed an American vendor announced an intention to market fan-assisted natural draft towers.

In the current work an experimental investigation is being performed of the causes and possible cures for drift losses from cooling towers -- the carryover of entrained liquid droplets (and their dissolved solids) in the tower effluent stream.

Areas of work include assembling a scaled-down cooling tower test section, proving an effective drift measurement method, and investigating the effects upon the magnitude of drift of such variables as moisture separator design, effluent superheat, tower fill design, and air stream speed.

Investigators: Professor M.W. Golay; Messrs. T. Flanagan and E. Guyer

Support: A.D. Little Professorship in Environmental Sciences and Engineering Funds

Related Academic Subjects

22.37 Environmental Impact of Nuclear Power
22.312 Engineering of Nuclear Reactors

Recent References

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

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

10.4 Technology Assessment of Nuclear Waste Disposal

A substantial assessment of the U.S. program for high-level waste disposal has been completed, with a report appearing in Science. The options seem substantially larger than have been so far explored, a situation now being remedied via revised and enlarged USAEC programs. In particular, chemical separation of nuclear wastes more completely into short-lived fission product and long-lived actinides permits turning the problem into one with a 500-year time limit, a conceivable period for continuing institutional concern. International issues, especially those related to Western Europe, receive continuing study, especially the roles of private industries, corporations, and Euratom. The European problem is exacerbated by a fragmentation, which leads to accentuation of benefits being received by one geographic and temporal sector, costs being born by other sectors.

Investigators: Professor D.J. Rose, Dr. G.C. Tenaglia; Messrs. G. Dials, A. Kubo

Support: MIT internal

Related Academic Subjects

22.35 Nuclear Fuel management
22.37 Environmental Impact of Nuclear Power
22.80 National Socio-Technological Problems and Responses

Recent References

A.S. Kubo, "Technology Assessment of High-Level Nuclear Waste Management," PhD Thesis, Department of Nuclear Engineering, MIT, April 1973.

G.E. Dials, "International Implications of High-Level Radioactive Waste Management in Western Europe," SM Thesis, Department of Nuclear Engineering, MIT, June 1973.

10.5 The Institutional Framework for Energy Research and Development

Institutional arrangements so far lead to the following apparent unbalances in development of energy options:

1) very little done (up to now) on energy conservation and more rational utilization, versus energy provision;

2) expenditures on energy provision heavily weighted in favor of electric power provision;

3) the electric sector heavily weighted in favor of nuclear energy.

Of course, some reasons for these unbalances are fairly apparent, such as the simple and direct economic rewards that accrue to energy providers, versus the diffuse and ill-defined rewards that accrue to the public (especially in future time) by energy conservation. Others are more complex. The aim is to identify new institutional frameworks, whereby these apparent unbalances are better illuminated and adjusted.

The work proceeds principally in the Center for Policy Alternatives at MIT.

Investigators: Professor D.J. Rose, Mr. David Marsh.

Support: The Energy Policy Project, Inc. (A Ford Foundation project).

Related Academic Subject

22.80 National Socio-Technological Problems and Responses

Recent References

National Academy of Energy COPEP Report, "Priorities for Research Applicable to National Needs," submitted to the National Science Foundation (1973).

D.J. Rose, Chairman; NAE-Committee on Public Policy Panel Report, "Program on Energy Research for NSF-RANN," November 1, 1973.

10.6 Societal Costs of Nuclear Versus Fossil Fuels

A program is just starting, connected with the Energy Laboratory, the Center for Policy Alternatives, and the Harvard School of Public Health. Epidemological data now available and becoming available indicate that the health costs of fossil fuel burning have been much higher than the expected health costs of nuclear options. Many of the data are imprecise, such as the probability of large nuclear accidents, and the long-term effects of low-level sulphur oxides and particulates. One arrives not at a single overall index of social acceptability, but a multi-valued assessment from which better policy decisions can be made.

Investigators: Professors M.W. Golay, D.J. Rose, N.C. Rasmussen, Dr. G.C. Tenaglia, Mr. F. Abtahi.

Related Academic Subjects

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

11. Applied Plasma Physics

The Department's research and educational activities in applied plasma physics are focussed primarily on the controlled thermonuclear reactor. For such a reactor to be feasible, it is necessary to confine a plasma of fully ionized deuterium and tritium at a temperature of around 100,000,000°K and a pressure of around 100 atmospheres for a respectable fraction of a second. The means now thought most practicable for providing plasma confinement under these extreme conditions is through specially shaped magnetic fields whose intensity may reach 100,000 gauss but there are proposals extant for devices which need no magnetic rield. The Department's plasma activities are of three general types: engineering studies of complete fusion power systems and detailed experimental and theoretical studies of well-defined constituent subassemblies described in Section 12.1; participation with other MIT departments in large-scale research on plasmas approaching the extreme conditions needed in a fusion power system, described in Section 12.2; basic research in the physics of dense, high temperature plasmas described in Section 12.3 and a number of small scale research projects listed by title in Section 12.4. Many of these smaller projects are related to the diagnostics needed for the study of hot, high density plasmas or at modeling, when possible, some of the relevant physics.

Study of the fundamentals of plasma behavior leads to improved understanding of astrophysical and ionospheric phenomena, magnetohydrodynamic energy conversion, ion propulsion, direct conversion thermionic diodes, and high-power gas lasers. The latter two topics are applications of particular present interest in the Department. Students of the Department concentrating on applied plasma physics therefore are trained not only to advance knowledge of controlled fusion and of the plasma field as a whole, but also to apply the fundamental science in other contexts of more immediate practical significance. In these plasma activities, the Department is an active participant in MIT's broad, interdepartmental program of research and instruction in plasma physics and its varied applications.

Plasma-related research by members of the Nuclear Engineering Department is funded by research grants and contracts administered by the Research Laboratory of Electronics and is carried out in close cooperation with investigators from Physics, Electrical Engineering and other MIT departments working in the Research Laboratory of Electronics.

The Department offers a comprehensive list of subjects of instruction in this field:

22.611, Plasmas and Controlled Fusion I, which provides a survey of the means of obtaining energy from fusion reactors. The topics discussed include atomic and electronic collision phenomena and transport and electromagnetic theory applicable to confined plasmas. Methods of producing and heating plasmas are investigated as well as electromagnetic methods of confinement. The material and energy loss processes and energy balances are dealt with. Discussion of recent experiments and diagnostic techniques are also included.

22.612, Plasmas and Controlled Fusion II, which treats topics in plasma dynamics of current interest in thermonuclear research such as: conductivity of highly ionized plasmas; radiation losses; wave propagations; magnetic field structure; instabilities; dynamics of a thermonuclear system; critical review of confinement schemes, advanced diagnostic techniques, and more detailed discussion of recent experiments.

22.62, Thermonuclear Reactor Design, which presents material relating to systems analysis and design of controlled thermonuclear reactors. Included are studies of the need of new energy sources, a critical survey of possible approaches to the generation of thermonuclear power, the development of criteria for CTR feasibility on the basis of economic and technical considerations. Other topics include studies of blanket neutronics and fuel breeding ratios, the design of prototype CTR power plants and possibilities of fission-fusion symbiosis.

22.63, Engineering Physics of Plasma Particle Devices, which treats the principles of accelerators and thermonuclear research devices including vacuum systems, magnets, acceleration methods, ion sources, targets, lasers, and laser diagnostics.

22.64J, Plasma Kinetic Theory, which treats a variety of topics including: the linearized Vlasov equations, Fokker-Planck and diffusion approximations to the average distribution functions, autocorrelation functions, resonant and non-resonant diffusion, free energy, energy and momentum conservation, resonant wave coupling, non-linear Landau damping, and strong turbulence theories. Selected applications of these topics are illustrated in discussing enhanced diffusion, stochastic acceleration, turbulent resistivity, shock waves, and radio emission.

22.65J, Advanced Topics in Plasma Kinetic Theory, which treats more advanced material including: theories of collective phenomena such as linear instability and non-linear saturation mechanisms in plasma, particularly in regimes described by the Vlasov-Maxwell equations. Other topics covered are the effects of wave-particle resonance; trapping and scattering of particles by waves; linear theory of instabilities in inhomogeneous plasmas; reflection and eigenmode problems in bounded systems; diffusion phenomena and anomolous resistivity associated with wave particle interaction. The relationships between theory and experiment were carefully explored.

22.69, Plasma Laboratory, which provides an introduction to the advanced experimental techniques needed for research in plasma physics and useful and experimental atomic and nuclear physics. Laboratory work is included on vacuum systems, plasma generation and diagnostics, physics of ionized gases, ion sources and beam optics, cryogenics, magnetic field generation, and other topics of current interest. Brief lectures and literature references are included to elucidate the physical bases of the laboratory work.

In addition to these subjects of instruction on plasmas and controlled fusion offered by the Nuclear Engineering Department, students in this field also take subjects offered by the Departments of Physics, Electrical Engineering, and Aeronautics and Astronautics, which along with the Department of Nuclear Engineering provide the academic base for plasma-related work at MIT.

11.1 Engineering Studies of Fusion Power Systems

Development of a feasible fusion power system requires solution of a host of problems, of which the most significant are:

a) provision of stable confinement for the plasma,

b) provision of materials for the vacuum wall surrounding the plasma which will withstand damage from the intense radiation emitted by the plasma,

c) provision of a large volume of high magnetic field, and accommodation of the high mechanical stresses such fields generate,

d) regeneration of the tritium consumed in the reaction by causing neutrons produced in the reactor to react with lithium,

e) efficient conversion of the energy released in fusion into electricity,

f) solution of these and other problems at a cost competitive with other means of electricity generation.

During recent years much progress has been made in improving our understanding of plasma confinement, and there now appears to be a fair probability that confinement can eventually be achieved at high enough temperatures and pressures for long enough times to support a self-sustaining fusion reaction. One of the most promising configurations for providing stable confinement is in a large torus, such as has been used in the successful Soviet Tokamak Reactor.

Several years ago the Department initiated studies of the characteristics of a complete fusion power system utilizing toroidal geometry for confinement. The assumption was made that stable confinement could be achieved, and engineering studies were made of means for solving problems (b-f) listed above. As additional information in the conditions needed for stable confinement became available, these studies were refined and extended. Extensive studies have been made of the effect of the principal design parameters -- size of reactor, temperature, pressure, magnetic field, and throughout -- on the quantities of principal engineering interest -- total power, energy and neutron flux on vacuum wall, tritium breeding ratio, and cost per kilowatt. Attention is being given to engineering problems of some of the principal components such as the vacuum wall, the lithium-bearing tritium-regeneration blanket, the radiation shield, the superconducting coils generating the magnet field, heat recovery systems, and the feed injection and product removal systems. A system design subject 22.62, Thermonuclear Reactor Design, is being taught to give students an understanding of the engineering problems and economic trade-offs in a fusion power system.

One outgrowth of these studies has been the finding that if fusion power systems become feasible, they would enhance the value of fission-breeder power systems. It appears that a fusion power system, fed with a mixture of deuterium and tritium and provided with a lithium blanket, may have a tritium doubling time as short as one month. It may, therefore, be advantageous to use some of the excess neutrons in a fusion reactor blanket to produce fissile plutonium and U-233 from U-238 and thorium respectively for use in fission reactors. Studies are being made of such symbiotic systems.

We have begun an experiment to determine the lifetime of the niobium first wall in a proposed theta pinch fusion reactor. We are simulating the actual conditions of the wall including surface and bulk heating and periodic shock loading in an attempt to determine the high temperature fatigue failure limit.

Investigators: Professors L.M. Lidsky, R.A. Blanken, P.A. Politzer, D.J. Rose; Messrs. A. Forbes, A. Pant

Support: USAEC

Related Academic Subjects

22.611 Plasmas and Controlled Fusion
22.612 Plasmas and Controlled Fusion II
22.62 Thermonuclear Reactor Design
22.63 Engineering Physics of Plasmas and Particle Devices

Recent References

D.J. Rose, "Controlled Nuclear Fusion: Status and Outlook," Science, 172, 797-808, May 21, 1971.

L.M. Lidsky, "Fission-Fusion Symbiosis," Proceedings of BNES Conference on Nuclear Fusion Reactors, pp. 41-53 (1969).

11.2 ALCATOR - The MIT High Field Toroidal Plasma Experiment

Work on this advanced experiment in high temperature, high-field plasmas originated at MIT in the Spring of 1969. The goal is to combine the unique facilities of the National Magnet Laboratory for producing high magnetic fields with the talents and interests of the interdepartmental plasma physics group at MIT.

ALCATOR is a toroidal device based on the Russian Tokamak experiments and distinguished by its very high toroidal magnetic field. The field - 120 kilogauss on the centerline of the 108 cm major diameter torus - allows the use of very high current densities to heat the plasma without exceeding certain well-established theoretical stability limits. The maximum pulsed power levels of the experiment will exceed 25 MW and peak stresses will exceed 85,000 psi. It will furnish the MIT research group with a plasma whose parameters are very close to those of possible future fusion reactors and so could serve to wet our engineering, diagnostic, and theoretical skills. Topics involving students in the Nuclear Engineering Department have included:

a) a numerical study of heating pulse evolution in Tokamak-like devices,

b) analysis of feedback stabilization of kink modes in toroidal plasmas,

c) effect of cross-section shape on plasma stability,

d) design of high-data rate Thompson scattering experiments,

e) design of vacuum UV Doppler shift experiments to determine ion temperature,

f) far infrared interferometer for density determination.

ALCATOR is now considered a nation fusion program, "Support Experiment," with definite program goals, set by the Washington office of the Division of Controlled Thermonuclear Research, USAEC. This requires tight scheduling and is coupled to stringent budgeting; consequently meaningful graduate student participation has decreased. After January 1974, under present plans ALCATOR will not be supporting any graduate student research although some work in progress will be continued using other funds if possible.

Investigators: Professors R.A. Blanken, P.A. Politzer, L.M. Lidsky; Messrs. L. Bromberg, D. Cook, D. Hutchinson, D. Komm

Support: USAEC

Related Academic Subjects

22.611 Plasmas and Controlled Fusion I
22.612 Plasmas and Controlled Fusion II
22.63 Engineering Physics of Plasma and Particle Devices
22.69T Plasma Laboratory

11.3 Plasma Theory

Theoretical research continues to place an emphasis on nonlinear problems. Of particular interest at the moment are effects arising from the clumping or clustering of particles in a plasma. When a large number of electric field waves are applied to a plasma, the resulting distribution function can be broken into several components. One component is the coherent response which has the same phases and wave numbers as the applied electric field waves. The coherent response produces the familiar plasma waves. In addition to the coherent response, there is a random granulation of the distribution function due to the highly nonlinear and therefore random motion of particles resonant with the waves. These granulations which have small phase space volumes, tend to behave as macro-particles in the plasma. This occurs because all the particles comprising the clump tend to have the same position and velocity and therefore move together through the plasma. In a tenuous, fully ionized plasma, collisional processes are weak and are proportional to the small charge on an electron or ion. Plasma clumps consisting of many electrons or ions have a large total charge and therefore can produce a great enhancement of collision-like processes. Two such processes are collisionless plasma which are currently being studied are: (1) the anomalous d.c. resistivity, and (2) the anomalous loss of plasma across magnetic field lines.

When a magnetic field is introduced into the plasma, the clumping effect becomes particularly interesting because the clumps develop structure similar to that of eddies in hydrodynamic turbulence. In fact, when one studies a limit in which the plasma equations approach the Navier-Stokes equations, the clumps do turn into eddies and exhibit the expected Kolmogorov spectrum. Thus it appears possible, in principle at least, to study the continuous transition from conventional weak plasma turbulence to strong fluid turbulence. We intend to study this transition between the two extreme forms of turbulence which have previously been thought to be unrelated.

Because of the extreme complexity of the equations describing these processes, the analytic treatment must of necessity be approximate. We are, therefore, undertaking computer simulations of various portions of the problem in order to check the theory and as a guide to developing better analytic treatment. Although simulating only portions of the total problem have some advantages in terms of understanding the results, our fragmented approach is made necessary by the extreme cost of computer simulations of the total problem. Such complete simulations are possible only in a very few laboratories in the United States.

Investigators: Professors T.H. Dupree, D.J. Sigmar; Messrs. D. Ehst, B. Hui.

Support: NSF and USAEC.

Related Academic Subjects

22.64J Plasma Kinetic Theory
22.65J Advanced Topics in Plasma Kinetic Theory

Recent References

T.H. Dupree, "Theory of Resistivity in Collisionless Plasma," Phys. Rev. Let., 25, 789 (1970).

T.H. Dupree, "Theory of Phase Space Density Granulation in Plasma," Phys. Fluids, 15, 334 (1972).

A. Bers, B. Coppi, T.H. Dupree, R. Kulsrud and F. Santini, "Turbulence in Confined Plasmas at High Electric Fields," to be published in Nuclear Fusion.

T.H. Dupree, "Non Wave-Like Dynamical Processes in Plasma," to be published in Comments on Plasma Physics.

11.4 Applied Plasma Physics Experimental Program

The applied plasma physics group maintains a continuous experimental program in plasma diagnostics and in such other areas where we believe we can attain experimental verification of theoretical predictions using facilities that can be designed and operated by one or two doctoral-level students. We have added a major new experimental facility to our laboratory: a Steady-State Linear Multiple (SLIM).

The SLIM facility is a magnetic quadrupole device designed for the study of the equilibrium behavior and low frequency stability properties of a plasma in an inhomogeneous magnetic field. This system is being used to study plasma phenomena which can occur in a large scale fusion device, but are difficult to observe due to limited access, short pulse operation, or diagnostic problems. The device produces a magnetic field which incorporates the various types of magnetic inhomogeneities found in large systems. However, the magnet is operated continuously, rather than in a pulsed mode, and the plasma it contains is sufficiently dilute to allow the use of electric probes. Because of the high power required to produce the quadrupole magnetic field, the device is installed at the National Magnet Laboratory.

Present efforts include the study of the characteristics of a class of low frequency, long wavelength instabilities which are driven by the periodic motion of ions which are trapped in the low field region of the magnetic configuration. These waves, if they occur in a fusion device, can very quickly destroy the containment properties of the device. Thus it is important to understand the physical mechanism which drives them and to develop means for interfering with this mechanism in order to eliminate them and to enhance the containment of the device. Other efforts in this category include:

a) collective regime ($\alpha>1$) scattering of 10.6 micron radiation - ion feature,

b) trapped particle driven instabilities in a collisionless plasma,

c) non-linear stabilization of half-cyclotron-frequency oscillations,

d) non-adiabatic scattering of charged particles in coherent perturbing fields.

Investigators: Professors R.A. Blanken, P.A. Politzer, T.H. Dupree, L.M. Lidsky; Messrs. M. Murakami, C. Primmerman, G. Pine, J. Hsia, A. Hershcovitz, D. Overskei, J. Robinson

Support: NSF and USAEC

Related Academic Subjects

22.63 Engineering Physics of Plasmas and Particle Devices
22.64 Plasma Kinetic Theory
22.65 Advanced Topics in Plasma Kinetic Theory
22.69 Plasma Laboratory

Recent References

C.E. Wagner, L.M. Lidsky and R.A. Blanken, "Experimental Observation of Half-Harmonic Instabilities in Hot-Electron Plasmas," Phys. Fluids, 14, 2447, November 1971.

M. Murakami and L.M. Lidsky, "A Method for Studying Distribution Function Evolution During Wave-Particle Interactions," Rev. Sci. Inst. (1972).

J. Robinson and L.M. Lidsky, "Identification of Transverse Kelvin-Helmholtz Turbulence in a Magnetoplasma Column," Can. J. Phys., 50, 1782 (1972).

12. Nuclear Engineering Department Seminars

As a means for informing the Institute community of important developments in the field of nuclear science and engineering on a timely basis, the Department conducts a series of seminars. These seminars are made possible by the fine cooperation of the nuclear industry in which individuals travel to MIT to spend a day with students and staff in the Department in discussions and in presenting the seminars. The seminar topics and speakers for the academic year 1972-1973 are listed below.

September 13, 1972
"The Nuclear Industry and Nuclear Engineering at MIT"
Edward A. Mason, MIT

October 25, 1972
"The Developing Trend of the Nuclear Power Plant Complex in the United States"
Sherman Naymark, Nuclear Services Corporation

November 1, 1972
"Correlations of Few-Group Cross Sections for Use In Depletion and Kinetics Codes"
Dr. Henry Honeck, E.I. DuPont deNemours Savannah River Laboratory

November 8, 1972
"The Physics of Plutonium Fueled Heavy Water Reactors and Related Problems on Reactor Control"
Dr. Tohru Haga, Power Reactor and Nuclear Fuel Development Corporation

November 29, 1972
"Plasma Physics in Magnetic Multiple Geometry"
Dr. Peter A. Politzer, MIT

December 6, 1972
"Laser Driven Fusion"
Dr. Keith Bruechner, KMS Fusion

February 14, 1973
"Containment of Fast Breeder Reactors, Recent Experience in Experimental Methods"
Mr. T.P. Speis, USAEC, Division of Reactor Development and Technology

February 28, 1973
"Reactor Pressure Vessels are Safe"
Dr. William E. Cooper, Teledyne Materials Research

March 7, 1973
"Fast Reactor Theory and Code Development"
Dr. Weston M. Stacey, Jr., Argonne National Laboratory

March 14, 1973
"Will LMFBR's Produce Economical Power?"
Dr. Bert Wolfe, General Electric Company, San Jose

March 19, 1973
Dr. Motoharu Kimura, Tohoku University

April 4, 1973
"Methods for Thermal Analysis of Reactor Fuel Rod Bundles - Current Status and Research Needs for Improvement"
Dr. Klaus Johannsen, MIT-TUB Exchange Program

May 2, 1973
"Xenon Oscillations in Large Pressurized Water Reactors"
Dr. William R. Corcoran, Combustion Engineering

IV. CURRICULUM

1. Degree Program

The Department offers programs leading to the degrees of 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 objectives of the Master's program is to provide students who have had sound undergraduate training in physics, chemistry or engineering with the equivalent of one year of graduate education in nuclear engineering. Although full knowledge of the subject matter and techniques of nuclear engineering cannot be obtained in one year, graduates of this program are given a sound base of knowledge which prepares them either for employment on nuclear projects or for more advanced graduate education. Minimum requirements for the Master's degree are two semesters of full-time graduate instruction including 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 a man 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 give a student advanced education in nuclear engineering and to challenge him to become a leading and original contributor to 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. Men completing the Doctor's program in Nuclear Engineering are prepared and motivated to work on the frontiers of nuclear technology.

2. Fields of Study

Although each student's program of study is arranged to suit 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.

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.

Introductory Subjects

22.02 Physics of Nuclear Energy
22.03 Engineering of Nuclear Power Reactor Systems
22.04 Radiation Effects and Uses (new 1973-1974)
22.06 Nuclear Engineering in Society

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
22.32 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
22.38 Current Developments in Nuclear Energy (new 1973-1974)
22.39 Nuclear Reactor Operations and Safety

Numerical and Mathematical Methods

22.41 Mathematical Methods of Reactor Analysis
22.42 Numerical Methods of Reactor Analysis
22.43 Advanced Methods of Reactor Analysis

Applied Radiation Physics

22.51 Interaction of Radiations with Matter
22.52 Neutron Physics and Applications
22.53 Radiation Engineering
22.54 Radiation Shielding
22.55 Biological Effects of Nuclear Radiation
22.58J Quantum Foundations of Mechanics and Thermodynamics

Plasmas and Controlled Fusion

22.611 Plasmas and Controlled Fusion I
22.612 Plasmas and Controlled Fusion II
22.62 Thermonuclear Reactor Design
22.63 Engineering Physics of Plasma and Particle Devices
22.64J Plasma Kinetic Theory
22.65J Advanced Topics in 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
22.89 Basic Electronic Instrumentation Laboratory
22.90 Special Problems in Nuclear Engineering

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

Civil Engineering

1.143 Mathematical Optimization Techniques
1.16J Special Studies in Systems Engineering
1.147 Engineering Systems Analysis
1.154 Simulation Methods
1.47 Mechanics of Materials
1.502 Structural Analysis and Design
1.77 Water Quality Control
1.78 Water Quality Management
1.80 Issues for Survival

Mechanical Engineering

2.02 Introduction to Systems Dynamics
2.03 Dynamics
2.06 Vibrations
2.092 Methods of Engineering Analysis
2.14 Control System Principles
2.151 Advanced Systems Dynamics and Control
2.201 Fluid Mechanics
2.25 Advanced Fluid Mechanics
2.283 Fluid Physics of Pollution
2.30 Mechanical Behavior of Materials
2.41J Thermodynamics of Power Systems
2.451 Intermediate Thermodynamics
2.452 Advanced Thermodynamics
2.55 Advanced Heat Transfer
2.56 Conduction Heat Transfer

Metallurgy

3.30 Strengthening Mechanisms in Metals
3.37 Deformation Processing
3.38 Behavior of Metals at Elevated Temperatures

3.39	Fracture Mechanisms in Solids
3.42 3.43	Physics of Solids
3.54	Corrosion

Electrical Engineering

6.03	Electromagnetic Fields and Energy
6.213 6.214	Dynamic Systems, Control and Optimization
6.251	Digital Computer Programming Systems
6.28	Probabilistic Systems Analysis
6.536	Probabilistic Models in Systems Engineering and Operations Research
6.551 6.552	Power Systems Engineering
6.601	Control System Theory
6.632	Electronic Instrumentation and Control

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
8.541	Neutron Diffraction
8.631J	Introduction to Plasma Physics

Chemical Engineering

10.38	Analysis and Simulation of Chemical Processing Systems
10.39	Principles of Combustion and Pollution Control
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

10.86 10.87 10.88	School of Chemical Engineering Practice-Oak Ridge School

Ocean Engineering

13.21	Ship Power and Propulsion
13.26J	Thermal Power Systems

Management

15.065	Statistical Decision Theory
15.081	Mathematical Programming
15.084J	Nonlinear Programming and Discrete Optimal Control

Aeronautics and Astronautics

16.561	Nuclear Rockets
16.59	Introduction to Plasma Kinetics

Mathematics

18.081	Methods of Applied Mathematics for Engineers
18.171	Probability
18.275 18.276	Numerical Analysis

4. Independent Activities Period

The Independent Activities Period has become a permanent part of the MIT academic calendar. The month of January is set aside to provide an opportunity for varied activities ranging from academic work for credit all the way to the various forms of rest and recreation. The Nuclear Engineering Department has used the Period to provide students with detailed instruction in very specialized areas. We have utilized the talents of the Department's staff itself, as well as bringing in experts in various areas from the nuclear industry. Examples from the past have included tutorial sessions on the use of digital computers and nuclear reactor codes; neutron activation analysis; and nuclear reactor transport. Program offerings have also been given in the area of energy and the environment, as joint offerings with several MIT departments and Harvard University. Professor David J. Rose has supervised this program. The Department has also offered training in use of the machine shops and a large number of short seminars. In the IAP of 1973, the Department also had two general seminars in conjunction with the Physics Department and the Philosophy Department. The first seminar, which was conducted by Professor David Frisch, discussed the decision to drop the atomic bomb on Japan in World War II. The second subject had to do with morality in contemporary technical problems, and was conducted by Professors Ned Block and Boruch Brody of the Philosophy Department.

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. In the past year five undergraduates participated in research work under the direction of Nuclear Engineering Department personnel. Dr. D. Hnatowich had a student work with him on the use of activation analysis methods for determining pollutants in air; Professor Chen had a student working on the triple-axis spectrometer; Professor Lidsky had a student working on the Alcator device, Professor Hansen had a student working in reactor kinetics; and Professor Lanning had a student working on the redesign of the MIT Reactor.

6. Descriptions of New and Revised Subjects

A. New Subjects

22.02 Physics of Nuclear Energy

Introduction to nuclear physics and neutron physics with emphasis on applications to nuclear engineering. Properties of atomic nuclei: isotopes and isotopic masses: nuclear reactions, cross sections for neutron induced reactions; radioactivity; liquid-drop model, nuclear fission. Diffusion and slowing-down of neutrons; neutron balance in nuclear reactors, criticality, neutron flux and power distributions. Application of simple reactor models to reactor control and reactivity; neutron energy spectra in thermal and fast neutron reactors. Conversion and breeding of fissionable materials.

22.04 Radiation Effects and Uses

Current problems in science, technology, health and environment which involve radiation effects and their utilization. Material properties under nuclear radiations. Medical and industrial applications of radioisotopes. Radiations and lasers in research. Radioactive pollutants and demographic effects. Laboratory demonstrations of methods and instruments in radiation measurements at the MIT Reactor. Material presented in an essentially descriptive manner and suitable for students interested in a general appreciation of the physical phenomena and their uses.

22.38 Current Developments in Nuclear Energy

Seminar dealing with current topics in nuclear reactor design, licensing, construction, operation, performance and safety and the role of nuclear processes in providing energy. (For advanced graduate students, enrollment limited to 10 by interview.)

B. Revised Subjects

22.03 Engineering of Nuclear Power Reactor Systems

Principles of component and system design, and operating characteristics of nuclear reactors for central station and marine power generation. Application of the various engineering disciplines contributing to reactor design to examine trade-offs involved in realization of system performance objectives. Examples selected from current and projected U.S. reactor designs.

22.29 Nuclear Measurements Laboratory

Properties of the particles and radiations resulting from the fission process. Principles underlying instrumental methods for detection and energy determination of gamma rays, neutrons and charged particles. Applications to experimental reactor physics, health physics and reactor technology. Laboratory experiments on scintillation, gas filled and semiconductor detectors; nuclear electronics such as pulse amplifiers, multichannel analyzers and coincidence techniques; and basic applications such as subcritical assembly measurements, gamma attenuation, and pulsed neutron techniques.

V. RESEARCH FACILITIES

1. MIT Reactor

The MIT Nuclear Research Reactor (MITR), which first went critical on July 21, 1958, has now completed fifteen years of successful operation. At the time of shutdown for the week at 0400 on Saturday, July 21, 1973, the reactor had logged 58,940 operating hours at full power and 231,594 megawatt hours. The first year was devoted to startup experiments, calibration, and a gradual rise to 1 MW power. Then followed fourteen years of three-shift operation -- at 1 MW until 1962, at 2 MW until 1965 and at 5 MW since then.

The MITR continues to be a most useful and reliable facility, and this section describes the part which it plays in the research and teaching programs of the Nuclear Engineering Department and of others, both inside and outside MIT. At the same time a very substantial effort is being devoted to an upgrading program designed to triple approximately the neutron flux at the experimental beam ports. This program is described in detail in another section of this report. The AEC construction permit was received last April, parts and fuel have been ordered, and it is now planned that the reactor will be shut down for about four months in the Spring of 1974 to make the change.

A summary of reactor operating statistics for calendar years 1970, 1971 and 1972 is provided in Table A, taken from the report to the Reactor Safeguards Committee for the year just completed. As in previous years, the reactor operated according to schedule with only a few interruptions for unscheduled maintenance. A July 1972 shutdown to replace a leaky heat exchanger lasted for two weeks and was one of the longest we have experienced.

In spite of this downtime, the reactor averaged 97 hours/week at full power (approximately 4.9 MW) and logged a total of 5045 hours at power. These figures for 1972 are very close to those for 1971, since much of the lost time was made up by running over several weekends at the request of experimenters. Normally the reactor starts up after maintenance work on Monday and shuts down early Saturday morning. Major maintenance and special operations, such as the annual building pressure test, are conducted on Saturdays, and on Sundays if necessary.

The research activities of Nuclear Engineering Department staff who utilize the reactor are described elsewhere in this report. These accounts do not cover research by other departments or by other universities and research centers which utilize radioisotopes activated in the MITR. Our periodic report of "Research and Educational Activities at the MIT Research Reactor," the next issue of which will be prepared shortly at the end of this fiscal year, describes all MITR activities.

In addition to the Department of Nuclear Engineering, a total of 18 other departments, study centers, and interdepartmental laboratories at MIT have used the reactor at one time or another since it began operation. Several of these are routine customers, such as the Departments of Physics, Metallurgy and Materials Science, Earth and Planetary Sciences, and the Draper Laboratory.

The Department of Physics, utilizing several neutron diffraction spectrometers, conducts elastic scattering studies in such areas as ferromagnetic prism refraction, refractive bending by magnetic fields, the Pendellosung fringe structure in Bragg reflection, the Kondo effect, diamagnetic scattering and others. Metallurgy and Materials Science students have used magnetic neutron scattering to study spin ordering in antiferromagnetic materials as a function of temperature. It is the above spectrometer experiments, along with those of the Nuclear Engineering Department, which will benefit most from the modification of the reactor core. Earth and Planetary Sciences investigators employ neutron activation analysis to study the distribution of rare-earth nuclides in geologic specimens as an indication of the origin and evolution of materials in the earth's mantle. Investigators from the Draper Laboratory have been using reactor facilities which provide fast neutron environments for studies of fast neutron and gamma radiation effects on the properties of semiconductors and circuits containing these devices.

Other MIT departments and laboratories have made less extensive use of the reactor during the year and are included in Item 13 of Table A, i.e. samples irradiated. This number also includes irradiations for other universities, research laboratories, hospitals and commercial organizations. It is less than in prior years due mainly to the loss of a commercial customer, who now has his own reactor, and the termination of radiochemistry research and training by MIT's Chemistry Department. Since January the rate of sample irradiations has risen to an annual rate of about 600 per year. During 1972 the Harvard Physics Department began installation of a liquid hydrogen target which uses a neutron beam taken out through the containment building wall (via an aluminum neutron "window" for measurements of the scattering cross section of para-hydrogen.

The USAEC's reactor-sharing program, mentioned in the last report, has been expanded to include Northeastern University and Wentworth Institute, as well as Boston University. Students from these educational institutions come to the MITR for indoctrination and practical training in reactor operation and experimental utklization, as part of nuclear technology courses taught otherwise by their own faculties. It is expected that this program will be further expanded to include additional schools in the Greater Boston area.

The financial details of reactor operation and capital expenditures are contained in Tables B, C, and D. For reactor revenue, Table B gives the actual figures for 1971-72 and 1972-73, which indicate a modest increase in funds received from outside MIT. Teaching and unsponsored use was down last year from the record highs of the two previous years due mainly to rescheduling of certain experiments into the present year as the result of problems with equipment and the availability of key personnel. 1973-74 revenue estimated is at $174,300, which is larger than an eight-month figure, because present users are expected to accelerate some experiments in anticipation of the modification shutdown, and some new uses are being developed.

Reactor operating expenditures are summarized in Table C(a). They are about $20,000 less in 1972-73 than in the prior year as a result of minimizing staff replacements and revising the operating schedule to reduce overtime; also 1971-72 contained some non-repeating charges. During the shutdown to carry out the physical modification of the reactor (now planned for the Spring of 1974), most salaries and wages normally charged to the operating account (line A-1) will become costs of the modification (line B-6).

Table C(b) lists expenditures of a capital nature which are essential to maintaining the reactor as a modern and useful facility. A number of comparatively minor modifications have been accomplished in past years, but the emphasis this year is heavily in the core modification (line B-6). It is deemed important that the plan, which has provided funds for these capital expenditures, be reinstituted once the core modification has been completed.

A comparison of revenues and operating expenses from 1958 through the current year is contained in Table D. During the first nine years of operation, we succeeded in nearly covering both direct costs and the $499,990 in overhead which was charged through June 1966. Cumulative figures for the first thirteen years of operation are given in the first column and for individual years thereafter. The deficits of recent years have in part been recovered through charges to overhead, so that the actual cost to MIT is the combination of the unrecovered deficit and the cost for teaching and unsponsored use of the reactor. The amount of the unrecovered deficit is not yet known for last year, but the sum of total deficit plus teaching and unsponsored use decreased by 17% from 1971-72 to 1972-73. The reactor staff and Department personnel are striving to reduce these costs by further substantial amounts through the addition of new projects and uses and through the AEC-financed reactor sharing program mentioned earlier. Some of the more promising prospects for additional use are in the medical field, as well as one already approved in the study of organic molecular structure by means of neutron inelastic scattering.

Table A

SUMMARY OF REACTOR OPERATION

		Calendar Year		
		1970	1971	1972
1.	Time of full power operation	4853.5	5065.6	5045.4
2.	Time of subcritical and low power operation for operating training	45.6	20.5	12.5
3.	Time for subcritical and low power operation for educational and other purposes	20.3	33.2	16.4
4.	Time approaching power	261.7	242.7	231.0
5.	Downtime for maintenance	499.3	478.2	598.6
6.	Downtime for refueling	65.2	72.1	75.3
7.	Time for completing reactor shutdown	235.8	259.7	246.0
8.	Time reactor is idle (no operation or maintenance)	2706.5	2587.9	2559.1
9.	Total hours in period	8760	8760	8784
10.	Average number of hours per week at full power	93.4	97.4	97.0
11.	Megawatt hours for year	23,782.2	24,821.7	24,722.5
12	Accumulated megawatt hours at end of year	168,796.8	193,553.4	218,275.9
13.	Total number of samples irradiated	796	789	452
14.	Number of samples irradiated for medical use	91	166	44
15.	Number of scrams	11	21	31

Table B REACTOR REVENUE

Item	DSR Project Number	Project Name (Department and/or Sponsor) — Fiscal Year:	1971-72 Actual (12 mos.)	1972-73 Actual (12 mos.)	1973-74 Estimate (8 mos.) (1)
1	73832 80371	Neutron Spectrometers (Physics & Metallurgy Depts., AEC and NSF)	89,093	92,448	72,000
2	73448	Neutron Spectrometer & Irradiations (AMMRC)	175	286	1,000
3	73929 80801	Neutron Spectrometer (Nucl. Eng., AEC)	31,811	24,867	20,000
4	80375	Fast Reactor Blanket Optimization (Nucl. Eng., AEC)	18,320	13,780	14,000
5	73004 73665 73740 80020 80915	Activation Analysis in Geochemistry (Geol., ONR)	1,900	3,110	1,500
6	11681 27716	Cold Neutron Research (Nucl. Eng., Sloan)	975	0	0
7	73450 80064	Reactor Sharing Program (AEC)	2,268	3,678	2,500
8		Neutron Activation Analysis Services	3,300 (2)	- (3)	2,000
9		Radioisotopes & Radiation Therapy (MGH)	- 210	1,491	1,500
10		Draper Laboratory	5,510	5,288	3,800
11		Miscellaneous	5,902	25,051	6,000
12	Total Anticipated Revenue from Sponsored Use		158,684	169,999	124,300
13	Use in Teaching & Unsponsored Student Research (including funds requested for additional utilization		76,258	37,334	50,000
14	TOTAL REVENUE		234,942	207,333	174,300

NOTE: 1) Based on renewal of contracts and 8 months of operation (4-month shutdown for core modification)
2) Performed for Industrial Concerns but not included in Miscellaneous Total
3) Services included in Miscellaneous and DSR totals. Total services provided in these areas - $1,949

Table C REACTOR EXPENSES

Fiscal Year:	1971-72 Actual (12 mos.)	1972-73 Actual (2) (12 mos.)	1973-74 Proposed (1) (8 mos.)
Operating Expenses (Acct. 11393)			
Salaries and wages	222,839	214,510	158,414
Summer salaries, faculty	1,500	1,570	1,648
Fringe benefits on 1&2 (16% to 12/31/71, 16.4% to 7/1/72, 17.1% to 7/1/73)	33,171	34,616	25,906
Materials and services	29,822	28,567	20,000
Replacement parts	6,858	----	10,000
Utilities	22,356	15,752	15,000
Insurance	15,218	15,218	16,000
Travel	925	625	2,000
Equipment	0	736	2,000
Other Direct Charges	2,580	4,154	3,000
Total Account 11393	335,269	315,748	253,968
Modification & Modernization (Accts. 11675-11683) (3)			
Sample Irrad., and handling fac. 11675	8,025	3,090	0
Operating and process systems 11677	3,256	2,783	0
Helium cryogenic facility for reactor 11680 (129,577 thru FY71)	23,025	7,001	0
Cap. exp. of moving refrig. & install. (76,461 thru FY71) thermal column cryostat 11681	8,097	11,619	0
Loan of reactor personnel to ALCATOR (11682)	8,943	269	0
In-core cryostat - design (11682)	-----	-----	21,000
Reactor core modification 11683 (363,724 thru FY 71)	132,440	110,463	580,000
Total Accounts 11675-11683	183,786	135,225	601,000

1) Based on 8 months of operation (4-month shutdown for core modification previously planned for 1972-73; now scheduled for 1973-74)
2) Based on Preliminary June Statement plus requested adjustments to June Final
3) These are funded from reactor depreciation reserve account, which was built up through June 1971 at the rate of app. $150,000/yr except for 11681 (item B4) which is funded by a Sloan Basic Research Grant.

Table D COMPARISON OF REVENUE AND OPERATING EXPENSES

	Fiscal Year:	Actual 1958-1971 Inception to 6/30/71 (13 yrs)	1971-72 Actual (12 mos)	1972-73 Actual (12 mos)	1973-74 Estimated (8 mos) (1)
1a.	Revenue from research and other sponsored use	$3,085,942	$158,683	$169,999	$124,300
b.	Teaching and unsponsored basic research (since 7/1/64)	194,836	76,258	37,334	50,000
c.	Total revenue	$3,280,778	$234,941	$207,333	$174,300
2.	Expenditures for direct cost	$3,113,715 (2)	$335,269	$315,748	$253,968
3.	Revenue				
	a) less direct costs	167,063	(100,328)	(108,415)	(79,668)
	b) less direct costs plus overhead	(332,927) (3)			

Notes: (1) based on 8 months of operation (4-month shutdown for core modification previously planned for 1972-73; now scheduled for 1973-74)

(2) not including overhead of $499,990 charged from inception through June 30, 1966

(3) overhead not charged after June 30, 1966

2. Cryogenic Facilities

A closed-circuit, low-temperature helium refrigeration plant has been installed with a design capacity of 200 watts at 4.2°K. This plant provides refrigeration for the cold neutron source described in Section 5.2 of Chapter III and supplies liquid helium to the in-core cryostat described in Section 5.3.

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 other experiments employing closed-circuit, low-temperature helium refrigeration.

3. Accelerators

3.1 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.

3.2 Kaman Pulsed Neutron Source

This is a sealed discharge tube neutron generator pulsed to 120 keV at up to 10 pps, and producing 10^7 neutrons per burst by the T(d,n) reaction. The power supply and housing for the tube were built at MIT. This pulsed source has been used for reactor lattice research and is available for other pulsed neutron experiments.

For research programs requiring a steady ion beam, the Department uses a 4 Mev van de Graaff accelerator at MIT's Lincoln Laboratory. This machine produces steady beams of either positive or negative ions. It is being used for the experiments on the scattering of protons from crystals before and after fast neutron irradiation to determine the nature of dislocations, described in Section 3.4 of Chapter III. The accelerator could also be used as an electron irradiator or as a steady neutron generator.

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 of 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. A liquid sodium loop has been proposed for installation on the ground floor of Building NW13.

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 chromatographs, 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.

In 1971 most of the space formerly occupied by the Nuclear Chemistry Laboratory in the front half of the second floor of NW13 was reassigned to this Department when the Chemistry Department ceased its activities in the field of nuclear chemistry. Six small radiochemistry laboratories and eight offices were transferred. The offices are used by faculty and research staff. Some of the small laboratories are in use for activation analysis and radioisotope production. A long-range plan for use of this space will be developed.

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 described in Section 11.2 of Chapter III is being constructed. Nuclear Engineering faculty and students are assisting in the design of this large, group experiment and will participate in operations and interpretation of results.

Faculty and students, along with their research equipment, have moved into excellent office and laboratory space in the new Fairchild Building, completed in the Summer of 1973 to house the Department of Electrical Engineering and Research Laboratory of Electronics.

6. Computing Facilities

The Department makes extensive use of the facilities of the MIT Information Processing Center. These facilities include an IBM 370/155 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.

VI. DEPARTMENT PERSONNEL
(August 1973)

1. Faculty

Edward A. Mason

Professor of Nuclear Engineering, Head of the Department.
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.

Arden L. Bement

Professor of Nuclear Materials
E.Met., Col. School of Mines '54; M.S. U. of Idaho '59; Ph.D. U. of Mich. '63 (metallurgy)
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; M.S. '32, Ph.D. '35 (physical chemistry) MIT
Processing of nuclear materials; isotope separation; reactor fuel cycles; nuclear power economics.

Ronald A. Blanken (resignation eff. 8/31/73)

Associate Professor of Nuclear Engineering
B.S. '61 Trinity College; M.A. '63 Dartmouth College; Ph.D. '67 (astrophysical sciences) Princeton University
Plasma physics; thermonuclear reactors.

Gordon L. Brownell

Professor of Nuclear Engineering; simultaneous appointment as Head, Physics Research Lab., Mass. 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

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

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.

Thomas H. Dupree

Professor of Nuclear Engineering and Physics
B.S. '57, Ph.D. '60 (physics) MIT
Mathematical physics; particle transport theory; plasma kinetic theory.

Michael W. Golay

Assistant Professor of Nuclear Engineering, Arthur D. Little Professor of Environmental Sciences and Engineering
B.M.E. U. of Fla. '64; Ph.D. '69 Cornell Univ. (nuclear engineering)
Reactor engineering; reactor physics; fluid mechanics.

James W. Gosnell

Assistant Professor of Nuclear Engineering; Asst. Dir. of Reactor Operations
B.S. '58 Nova Scotia Tech.' M.Sc. '59 Ga. Inst. of Tech.; Ph.D. '69 (nuclear engineering) MIT
Reactor engineering; reactor physics.

Elias P. Gyftopoulos

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

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.

Allan F. Henry

Professor of Nuclear Engineering
B.S. '45, M.S. '47, Ph.D. '50 Yale (physics)
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.

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

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

Peter A. Politzer

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

Norman C. Rasmussen

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

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.

Dieter J. Sigmar

Associate Professor of Nuclear Engineering
M.S. '60, Tech. Univ. of Vienna, 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

Associate 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.

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.

2. Complete Listing of Personnel (August 1973)

Professor

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

Associate Professor

R. A. Blanken
S. H. Chen
M. J. Driscoll
L. M. Lidsky
D. J. Sigmar
N. E. Todreas

Assistant Professor

M. W. Golay
J. W. Gosnell
P. A. Politzer

Sr. Research Associate

C. V. Berney
O. K. Harling

Research Associate

L. Clark, Jr.
G. F. Mazenko
B. W. Murray
H. C. Teh

Administrative Officer

J. L. Cochrane

Lecturer

S. Levin

Instructor

D. L. Cook

Visiting Lecturer

H. Lurie

Guest

R. R. Crangle

DSR Staff

G. C. Allen
R. J. Chin
K. D. Collins
D. A. Gwinn
D. J. Hnatowich
V. A. Miethe

DSR - Non-Staff

A. J. Abbott
L. Andexler
T. J. Casey
C. J. Crane
J. P. Knotts
W. McDermott
P. T. Menadier
P. A. Smith
G. Sullivan
A. T. Supple
F. L. Woodworth

Laboratory Service

K. J. Butler
C. E. DeAngelis
T. J. Green
R. E. Henderson
D. A. Lynch
J. J. Rosati
H. A. Saunders
J. E. Wasik

Clerical Staff

D. M. Dutton
C. M. Egan
M. J. Falco
C. Mitaras
V. M. O'Keefe
L. I. Wildman
M. L. Wolfe

Teaching Assistants

J. Aument
H. Chan
T. Choong
F. DeVita
C. Forsberg
P. Hendrick
J. Hsia
D. Hutchinson
K. Ip
S. Jones
P. Kalambokas
M. Kalra
C. Lee
Y. Lukic
F. Martin
B. Momsen
C. Primmerman
H. Watt
T. Wei

Research Assistants

F. Abtahi
G. Allen
G. Brown
D. Calabrese
J. Castresana
J. Chan
Y. Chen
W. Chow
G. Ducat
A. Forbes
P. Furtado
R. Eng
M. Gregory
B. Hui
S. Jabbawy
O. Kadiroglu
M. Kazimi
J. Kearney
J. Kollas
D. Komm
Y. Lefevre
R. McCrory
A. Ovi
A. Pant
J. Papazoglu
G. Pine
T. Postol
C. Primmerman
T. Rieck
R. Schaefer
A. Thompson
T. Wei
S. Yang
R. Zamenhof

VII. DEPARTMENT STATISTICS

Statistical Summary

Academic Year Sept-June	Sept. Registration: Regular	Sept. Registration: Special	Sept. Registration: Total	Degrees Granted: S.M.	Degrees Granted: Nuc.E.	Degrees Granted: ScD,PhD	Degrees Granted: 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
Totals				533	48	214	795		

VIII. STUDENTS

Table VIII-1 shows the background and sources of support of the 113 students registered in the Nuclear Engineering Department in September 1972. The following interesting points may be noted. About 85% of our students received their undergraduate training in professional fields other than nuclear engineering. Although the profession from which the largest number of students came is physics, the professions from which the majority of our students came are engineering oriented. The U.S. citizens among our students came from 38 different undergraduate schools; only 7 of these men did their undergraduate work at MIT. Thirty-eight percent of our students came from abroad, from 18 different foreign countries. This broad diversity of professional, academic and national student backgrounds provides a very stimulating environment for the Department's activities.

Sixty-seven of the students are partially or fully supported by funds administered or controlled by MIT, 5 by AEC Special Fellowships in Nuclear Science and Engineering, and 23 by other forms of national or international financial assistance.

Table VIII-2 lists the activities of the graduates of this Department, taken from information available to the Department in June 1973. Thirty-five percent of our graduates in the U.S. are associated with 93 different industrial and research organizations; 8% national laboratories; and 8% are employed by 36 academic institutions. Fourteen percent of our graduates are working in 26 foreign countries. This broad dispersion of students is a gratifying indication of the impact our educational and research programs are having on nuclear developments in the United States and abroad.

Table VIII-1

Background of Students Registered
in Nuclear Engineering Department
(September 1972)

By Profession (113)	By College (69)	By Country
Applied Science (2)	(U.S. citizens only)	Brazil (9)
Chemical Eng. (5)	Columbia (4)	Canada (2)
Chemistry	Cornell (3)	China (4)
Civil Eng.	Manhattan (2)	Formosa
Electrical Eng. (13)	MIT (7)	France (2)
Engineering (9)	Notre Dame (2)	Greece (3)
Eng. Science (3)	N.Y.U. (2)	Hong Kong (6)
Eng. Physics (6)	Purdue (3)	India (2)
Mathematics (4)	Stanford (2)	Iran
Mechanical Eng. (12)	U.S.M.A. (8)	Israel (2)
Nuclear Eng. (21)	U.S. Mer. Marine (4)	Italy (3)
Nuclear Sci.	U.S.N.A. (3)	Japan (2)
Physics (22)	Wisc. U. of (2)	Jordan
Marine Eng. (4)	Mich. U. of (2)	Korea (2)
Undefined (9)		Pakistan
		Spain
		Turkey
		U.S. (69)
		Venezuela

Sources of Financial Support

MIT Funds	
Research Assistants (23)	AEC Fellowships (5)
Teaching Assistants (19)	NSF Fellowships (2)
AEC Traineeships (12)	Central Electric
MIT Fellowships (2)	CNEN (5)
MIT Staff	FAPESP - Brazil (2)
NDEA Traineeship	French Electric
NSF Traineeships (2)	Hertz Fellowship
Sloan Traineeships (6)	Knapp Fellowship
T.J.T. Fellowship	Rotary International
	Self-Supported (18)
	U.S. Army (7)
	WARD Scholarship
	General Electric

Table VIII-2

Activities of Nuclear Engineering Dept. Graduates - June 1973

U.S. Industry and Research [216] (35%)

Aerojet Nuclear
Air Rsch. Mfg. Co.
Allis Chalmers (2)
American Elec. Power
Am. Science & Eng.
APDA (2)
Assoc. Planning Res.
Atomics Int. (10)
Avco (6)

Babcock & Wilcox (4)
Battelle Northwest (4)
Bechtel (2)
Bell. Tel. Lab
Bendix
Burns & Roe

California Oil
Combustion Eng. (6)
Commonwealth Edison (7)
Computer Processing
Conn. Mutual Life Ins.
Consolidated Edison
Consultant
Consumers Power
Cornell - rsch.

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

Ebasco
Edgerton, Germ. & Grier

General Dynamics, Elec. Boat (7)
General Electric (18)
Gulf General Atomic (14)

Hercules
Hughes (3)
Hybrid Systems

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

Jackson & Moreland (2)

Lane Wells
A.D. Little (2)
Lockheed

Management & Tech. Cons.
Martin-Marietta (2)
Maxson Elec.
McKinsey & Co.
MIT - rsch. (4)
Mobil Oil
Monsanto
MPR Associates (2)

Nat. Acad. of Eng.
New Eng. Nuclear Corp.
New York Law Firm
North American Rockwell (2)
Northeast Util. Service
Northern Rsch. & Eng. (3)
Nortronics
Nuclear Fuel Service (2)
Nuclear Mat. & Equipment
Nuclear Products
Nuclear Utility Services (4)

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

Radiation Tech.
Rand Corp.
RCA Research Lab.

Sanders Corp.
Science Applns.
Scientific Data Systems
Smithsonian Astro. Obser.
So. Cal. Edison (4)
S.M. Stoller Assoc.
Stone & Webster (9)
Systems Sci. and Eng.
Systems Control

Table VIII-2 (continued)

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

Union Carbide
United Aircraft (3)
United Nuclear (5)
United Eng. & Construction

Vacuum Industries

Westinghouse (19)

Yale - rsch. (2)
Yankee Atomic (4)

National Laboratories [53] (8%)

Argonne (9)
Brookhaven (5)
Knolls Atomic Power (16)
Lawrence Radiation (5)
Los Alamos (8)
Oak Ridge (6)
Sandia
Savannah River (3)

Further Study [65] (9%)

MIT (49)
Other (16)

U.S. Government [141] (21%)

Atomic Energy Comm. (15)
Air Force (12)
Army (66)
Army Nucl. Def. Lab.
Army Rsch. Lab. (2)
Ballistic Rsch. Lab.
Classified - WashDC
Coast Guard
Dept. of Commerce
NASA
Naval Rsch. Lab.
Navy (38)
Peace Corps
Picatinny Arsenal
Public Health, Dept. of

Teaching [48] (8%)

Amer. Univ. (WashDC)
U. of Bri. Columbia
Brooklyn College, CCNY
Univ. of Cal. (5)
Cal. State (L.Beach)
Carnegie Mellon Univ.
Case Institute
Catholic Univ. of America
Cornell

El Rancho High School

Florida, Univ. of
So. Florida, Univ. of

Georgia Inst. of Tech.

Howard University

Illinois, Univ. of
Iowa State

Kansas State

Lowell Tech. (2)
Loyola Univ.

Mass. Maritime Acad.
Michigan State Univ.
Missouri, Univ. of (2)
MIT (6)

New Hampshire, Univ. of
Northeastern Univ.
Northwest Nazarene
Notre Dame

Pennsylvania State
Princeton Univ.

Radford College
Renesselaer Polytech

Swarthmore

Texas A & M
Texas, Univ. of

Washington, Univ. of (2)
Wisconsin, Univ. of

Table VIII-2 (continued)

Foreign [90] (14%)

Belgium (9)
Brazil (5)
Canada (10)
Chile
Columbia, S.A.

England (2)
France (11)
Germany (2)
Greece (3)
India (12)

Indonesia
Iran
Israel (2)
Italy (5)
Japan (8)
Malaysia
Mexico
Norway
Pakistan (3)
Philippines
Poland

Spain (6)
Switzerland (6)
Taiwan
Turkey (4)
Venezuela (2)

NOT REPORTED (45) (6%)

TOTAL [658]

IX. LIST OF THESES

1972-1973

1) The following theses were submitted to the Nuclear Engineering Department in September 1972.

P.G. Bailey, "Variational Derivation of Modal-Nodal Finite Difference Equations in Spatial Reactor Physics, PhD Thesis.

D.W. Buckley, "Measurement of Secondary Flow Patterns in Non-Circular Channel Turbulent Flow Using Laser Doppler Velocimeter Techniques," SM/SB Thesis.

A.C. Cerne, "Using Reaction Rates to Improve Multigroup Flux Approximations," SM Thesis.

P.L. Doan, "PWR Loss-of-Coolant Accidents by Hypothetical Vessel Rupture," ScD Thesis.

T.J. Flanagan, "Augmentation of Wet Natural Draft Cooling Towers," SM Thesis.

M.W. Goldsmith, "Evaluation of a Gas-Cooled Fast Breeder Reactor for Ship Propulsion," Nucl.E. Thesis.

B.G. Hittner, "Heavy Ion Reactions on Intermediate Nuclei," SM Thesis (joint thesis with Physics Dept.).

P.W. Kolody, "The Feasibility of Liquid Core Fuel Element," SM Thesis.

R.S. Lowder, "MHD Kink Mode Interaction with External Boundaries and Requirements for Feedback Stabilization," PhD Thesis.

A.A. Ott, "Simplified Dynamics of a Portion of the Proposed Nuclear Rocket Engine," SM/SB Thesis.

T. Yarman, "Reactivity and Transient Analysis of MITR-II," PhD Thesis.

A.W. Lippitt, "Heat Transfer Effects from Agitation of Electrolysis Bubbles by an AC Electric Field," SM/SB Thesis.

2) The following theses were submitted in February 1973:

S.T. Brewer, "The Economics of Fuel Depletion in Fast Breeder Reactor Blankets," PhD Thesis.

P. Carajilescov, "A New Approach to the Treatment of Uncertainties in Reactor Thermal Analysis by Expansion of the Method of Correlated Temperatures," SM Thesis.

M.V. Gregory, "Heterogeneous Effects in Fast Breeder Reactors," PhD Thesis.

R. Guida, "Numerical Simulation of the Flow of Real Fluids with Heat Transfer," SM Thesis.

J.C. Hsia, "Submillimeter Plasma Diagnostics," SM Thesis.

J.A. Kee, "A Model for Molten Fuel Movement in an LMFBR Pin," Nucl.E. Thesis.

J.P. Kearney, "Simulation and Optimization of In-Core Nuclear Fuel Management," PhD Thesis.

C.C. Lai, "Light Intensity Correlation Spectroscopy and its Application to Study of Critical Phenomena and Biological Problems," ScD Thesis.

Y.M. Lefevre, "Neutron Scattering Studies of Molecular Dynamics in Pressurized Gases and Liquid Metals," ScD Thesis.

A. Ovi, "Decision Analysis Applied to Nuclear vs. Fossil Alternatives for Electrical Production Systems," SM Thesis.

A. Tagishi, "Investigation and Design of On-Line Digital Noise Analysis System for the MITR," SM Thesis.

H.Y. Watt, "Incremental Cost and Optimization of In-Core Fuel Management of Nuclear Power Plants, ScD Thesis.

3) The following theses were submitted in June 1973.

F.L. Bowman, "Reactor Core Meltdown Containment for Off Shore Applications," SM Thesis (joint thesis with Ocean Eng. Dept.).

W.D. Brown, "Flow Redistribution Around Partially Blocked Coolant Channels in Pressurized Water Reactors," Nucl.E. Thesis.

D. Calabrese, "Development of In-Vivo Radioisotope Tracer Methods for Thrombus Detection in Calves with Prosthetic Heart Assist Pumps," SM Thesis.

L. Cave, "Computer Assited Radionuclide Identification from Gamma Ray Spectra," SM Thesis.

P.F. Deaton, "Utility System Integration and Optimization Models for Nuclear Power Management," PhD Thesis.

L. Deppe, "The Finite Element Method Applied to Neutron Diffusion Problems," Nucl.E. Thesis.

O.L. Deutsch, "A Kinetic Model Calculation of the Incoherent Spectrum of Density Fluctuations in a Maxwell Gas," SM Thesis.

G. Dials, "International Implications of High Level Radioactive Waste Management in Western Europe," SM Thesis (joint thesis with Political Science).

J.K. Edgar, "Nondestructive Testing of High Strength Steel Welds by Neutron Radiography," SM Thesis (joint thesis with Ocean Eng. Dept.).

A.R. Forbes, "Design of a Small Axisymmetric Tokamak," SM Thesis.

J.E. Fox, "Anomalous Skin Effect and Current Penetration in Confined Plasmas," SM Thesis.

J.D. Harris, "Critical Flow Models in LOCA and Modeling of a Condensing Steam Jet," SM Thesis.

S. Jardin, "A Numerical Investigation of Unsteady Magneto Gas Dynamics," SM Thesis (joint thesis with Physics Dept.).

S.C. Jones, "The Production and Use of Carbon-11 Labeled Carbon Dioxide and Glucose," SM Thesis.

M. Kazimi, "Theoretical Studies on Some Aspects of Molten-Fuel-Coolant Thermal Interaction," PhD Thesis.

D. Komm, "Construction of a Fast-Scanning Fabry-Perot Interferometer," SM Thesis.

A.S. Kubo, "Technology Assessment of High-Level Nuclear Waste Management," PhD Thesis.

R. McCrory, "Theory of Drift-University and Drift Cone Modes of Collisionless Plasma in Cylindrical Geometry," PhD Thesis.

S.A. May, "Analysis of Ash Content of Black Mesa Coal by Gamma-Ray Attenuation," SM Thesis.

W. Miles, "Fuel Management Strategies for Pressurized Water Reactors," SM Thesis.

M. Robertson, "The Environmental and Economic Aspects of Wet Cooling Towers," SM/SB Thesis.

P.W. Walsh, "Inelastic Thermal Neutron Scattering from Gaseous Hydrogen at High Pressure," SM Thesis.

G.W. Braun, "Design of a Natural Uranium/Lithium Blanket for a Breakeven Theta Pinch," Nucl.E. Thesis.