MITNE-244

ACTIVITIES IN NUCLEAR ENGINEERING AT MIT

Prepared by the Staff of the
Nuclear Engineering Department
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 1981

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1. INTRODUCTION

Academic:

This report has been prepared by the personnel of the Nuclear Engineering Department at M.I.T. to provide a summary and guide to the Department's educational, research and other activities. Information is presented on the Department's facilities, faculty, personnel, and students. The information has been prepared for the use of the Departmental Visiting Committee, past and present students, prospective students interested in applying for admission to the Department, and others.

The outlook for nuclear power appears to have taken a more positive turn with the new federal administration's encouragement of nuclear development. However, the industry is still faced by two key problem areas. First, the uncertainties in the licensing process must be greatly reduced and, second, the financial condition of the utilities must be improved so that they can raise the capital required for major building projects. The effect of rapid inflation and modest rate relief has left the majority of utilities in too weak a financial condition to fund major projects by either borrowing or capitalization through sale of stock. Since utility rates are controlled by state commissions it will be difficult to solve this problem by action at the national level.

Today about 12% of all U.S. electricity is generated by nuclear plants. In many countries of Western Europe the percentage is higher. However, only France is going full speed ahead with its nuclear development. They have over 30 plants that will be completed by 1985. In other countries, as in the United States, the current public concern over nuclear power and a considerable slowing of the growth of electric demand have slowed down nuclear development.

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

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

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

Employment opportunities have remained excellent for nuclear engineers at all degree levels. There are three basic reasons for this high demand. First, despite the lack of new plant orders, there are currently over 70 plants under construction which need nuclear engineers. Second, as a result of the analysis of the Three Mile Island Unit II accident, operating plants have an increased need for people with nuclear engineering training. And, third, graduates are required to support the national research effort for fusion and advanced reactor concepts.

At a time when many Nuclear Engineering Departments are having difficulty meeting their enrollment goals the Department has been able to maintain its graduate enrollment at its goal of between 150 and 160 students. In this graduate population we have seen an increase in the fraction of students choosing the fusion option. However, the undergraduates choosing nuclear engineering during this year dropped to ten students as compared to 20 last year. The total undergraduate enrollment is currently 42 students, well below our goal of 70 to 80.

The Department awarded 62 advanced degrees including 20 Doctorates, eight Nuclear Engineers, and 34 Masters of Science during the 1980-81 academic year. Ten bachelor degrees were awarded, four of which were joint SM/BS degrees.

Table 1

Enrollment in M.I.T. Nuclear Engineering Department

Fall Semester

1972	113
1973	127
1974	139
1975	200
1976	222
1977	215
1978	218
1979	216
1980	186

Table 2

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

Fall Semester		
	1972	88
	1973	102
	1974	128
	1975	149
	1976	136
	1977	139
	1978	123
	1979	105
	1980	114

Financial

The Nuclear Engineering Department conducts research in the areas of Applied Radiation Physics, Energy and Energy Policy, Reactor Engineering (Chemical Engineering and Fuel Cycles, Materials and Structures, Reliability and Thermal Hydraulics), Reactor Physics (Experimental and Theoretical) and Plasma Fusion (Experimental and Theoretical). During the fiscal year ending June 30, 1980, department faculty supervised a research volume of $2,241,300 including research funded through the Nuclear Engineering Department, as well as the MIT Energy Laboratory, the Harvard/MIT Division of Health, Science and Technology, the Nuclear Reactor Laboratory, the Plasma Fusion Center, and the Research Laboratory of Electronics. The fiscal year 1980 research volume in the Nuclear Engineering Department was $1,021,300.

During this research year approximately 53% of the graduate student body was supported through research assistantships. An additional 12% were supported through department teaching assistantships. Other financial aid is available to graduate students in Nuclear Engineering in the form of MIT endowed tuitionships and fellowships, namely the Sherman R. Knapp Fellowship (Northeast Utilities), the Theos J. Thompson Memorial Fellowship, the Institute of Nuclear Power Operations Fellowships, and the College Work Study Program.

In Section 2 of this report there is a discussion of developments within the Department since January 1980. Section 3 is a detailed discussion of our research and educational activities. Section 4 presents a discussion of our curriculum, including the S.B. program. Section 5 discusses the facilities of the Department. In Section 6 there is a summary of Departmental personnel. Sections 7 and 8 provide statistical information about the Department and its students. The final section, 9, is a listing of theses completed since our last report.

2. SUMMARY OF DEVELOPMENTS SINCE JANUARY 1980

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

During the past year several changes in the academic program have been possible as a result of new faculty. Professor I-Wei Chen joined the staff as an Assistant Professor in January 1980. This and the probable addition of another Assistant Professor in nuclear materials during 1981 has permitted the development of three new subjects in nuclear materials which will replace the two currently offered. These new subjects will permit both an introductory subject for nonmaterial specialists, plus a strengthened program for those pursuing a career in the materials area. In the spring of 1981 Professor Richard Lester offered a new subject on radioactive waste management technology. This is the first subject on nuclear waste management to be taught at the Institute and is offered at a time when waste management issues are of growing interest in the United States and overseas.

The Engineering Internship Program, which offers undergraduates the opportunity to have on-the-job experience as part of their overall education, has been successful since it was initiated in the summer of 1978. A total of 10 students -- 1 graduate, 3 juniors and 6 seniors -- are now in the program. Companies which have placed students from the Nuclear Engineering Department are Brookhaven National Laboratory, Commonwealth Edison, EG&G Idaho, Stone & Webster Engineering Corporation, and Yankee Atomic Electric Company. This program is described in Section 4.8.

During the summer of 1981 the Department offered a Special Summer Program on Nuclear Power Reactor Safety, directed by Professors Norman C. Rasmussen and Neil E. Todreas. This two week program was attended by 189 people representing all segments of the nuclear industry and nine foreign countries. The Summer Session program "Man-Machine Interfacing in Nuclear Power and Industrial Process Control" was offered again in June 1981 jointly with the Mechanical Engineering Department by Professors David Lanning and Thomas Sheridan. The program was very well attended by about 100 people.

In recognition of the need for news media personnel to acquire a deeper understanding of nuclear power-related issues, a special seminar, "Nuclear Power: Challenge for Journalists", was offered in October 1980. The seminar was directed by Professor Richard Lester and was staffed primarily by Nuclear Engineering faculty. It was offered under the auspices of the Seminar Office of the Center for Advanced Engineering Studies. The goal of the seminar was to offer an intensive short course on nuclear technology and policy issues so as to increase the capacity of journalists to analyse, interpret, and seek advice on such issues when reporting nuclear power stories in the future. The program was carefully designed to avoid staff advocacy of one policy position or another. The seminar, which was self-supporting, attracted approximately 35 participants from news organizations throughout the country.

The MIT Student Chapter of the American Nuclear Society hosted the Eastern Regional Student Conference on March 26-29, 1981. These Regional Student Conferences give undergraduate and graduate students an opportunity to develop professionally in technical skills by the exchange of research results and in communication skills through presenting papers. Over 150 students from the nuclear engineering departments of more than 14 colleges and universities from Eastern United States and Canada participated in the Conference. A total of 16 awards was presented, 8 of which were made to MIT nuclear engineering students.

The Nuclear Engineering faculty members continue to be active outside the Department in both MIT non-department activities outside of MIT for professional societies, government and industry.

Professor Rose continues this year as the U.S. representative to the Asia-Pacific Energy Studies Consultative Group, which has included senior representatives from about 20 countries in that area, plus OPEC and several foundations. Professor Rose is a member of the Program Committee of the International Energy Symposia series, an activity preparatory for and related to the 1982 International Energy Exposition in Knoxville, Tennessee. Professor Sow-Hsin Chen was invited as a Visiting Professor of Physics to the University of Guelph in Canada for the month of January 1981. During his visit he gave a series of four lectures on recent results in biophysical applications of neutron and light scattering. Professor Driscoll has completed his term of service as the School of Engineering representative to the Institute's Committee on Educational Policy, and that committee's representative to the Committee on the Humanities, Arts and Social Sciences. He continues to serve as faculty chairman of the MIT Undergraduate Seminar Program. He also continues to serve on the MIT Reactor Safeguards Committee. Professor Golay continued as Chairman of the American Nuclear Society Environmental Sciences Division. In June of 1980 he presented a seminar at the Centre des Etudes Nucleaire of Commissariat a l'Energie Atomique in Grenoble, France. Professor Gyftopoulos continues as an advisor to the National Energy Council of Greece. Professor Kazimi serves as Chairman of the Nuclear Heat Transfer Committee of the AIChE, and a Director of the American Nuclear Society Northeast Section. In March of 1981 he participated in an International Atomic Energy Agency Workshop on Fusion Reactor Safety in Vienna, Austria. He serves on the Review Committee of the Department of Energy Fellowship for Magnetic Fusion Energy Technology. He is President of the Association of Arab-American University Graduates. Professor Lidsky was instrumental in founding and is now Editor-in-Chief of the Journal of Fusion Energy, published by Plenum Press. The first issue of this quarterly publication appeared in January 1981. Professor Todreas serves as chairman of the Technical Working Group on Thermal Hydraulics for the American Nuclear Society. He also is on the editorial board of the thermal design area of the Journal of Nuclear Engineering and Design. Professor Harling continues to serve as Director of the interdepartmental Nuclear Reactor Laboratory. Professor Lanning continued as UROP Coordinator for the Department and served as chairman of the Search Committee for a new Department Head. Professor Heising Goodman is Vice-Chairman (Chairman-Elect) of the Northeastern Section of the American Nuclear Society. She also serves on the National Program Committee of the ANS Reactor Safety Division. She is consultant to the joint NRC-ANS standards committee on probabilistic risk assessment. She is a

member of the Technical Writing Group of the ANS/IEEE Probabilistics Risk Assessment Standards. Professor Meyer serves as Vice Chairman of the Mathematics and Computation Division of the American Nuclear Society. Professor Rasmussen was appointed to the Safety Advisory Board, Three Mile Island Unit-II. He continues to serve as Chairman of the MIT Reactor Safeguards Committee. He serves as Chairman of the EG&G Idaho National Engineering Laboratory Scientific Review Committee at that laboratory. He was appointed a member of the Board of Directors of the Atomic Industrial Forum and a member of the National Committee on Radiation Protection.

Several of the Department faculty were recognized with honors during the past year. Professor Yip received the Outstanding Teacher Award of the MIT Student Chapter of the ANS. Professor Neil Todreas was elected a Fellow of the American Nuclear Society. Professor Norman Rasmussen was elected a Fellow of the American Academy of Arts and Sciences. He also received the Theos J. Thompson Award from the Nuclear Reactor Safety Division of the American Nuclear Society.

During the last year and a half there have been a number of changes in the faculty. Professor Peter Politzer resigned to take a position on the research staff of the Plasma Fusion Center. Professor Alan Nelson was appointed Assistant Professor of Nuclear Engineering. The appointment is joint with Health Sciences and Technology. His activities will be in the biomedical area. Professor Carolyn Heising-Goodman was appointed Assistant Professor of Nuclear Engineering in the area of reactor safety and reliability.

3.   RESEARCH AND EDUCATIONAL ACTIVITIES

3.1 Reactor Physics

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

3.1.1 Subjects of Instruction

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

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

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

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

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

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

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

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

22.22: Nuclear Reactor Dynamics, deals with the formulation of nuclear plant dynamics and methods of analysis and control. Topics covered include point kinetics formalism, Laplace transforms, experimental methods for measuring dynamic characteristics, control of reactor transients; space-time formalism and numerical methods of analysis, xenon oscillations and statistics of reactor noise.

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

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

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

22.43: Numerical Methods in Reactor Engineering Analysis, covers numerical methods used in analysis of nuclear reactor engineering problems studies. Topics include finite difference and finite elements formulations

in solution of heat conduction, fluid dynamics, structural component design, and transient system analysis problems.

3.1.2 Reactor Physics

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

1) Nodal Schemes

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

The computer code QUANDRY developed within the department is one of the most efficient nodal codes currently available. (For a given accuracy QUANDRY is about a thousand times faster than a finite difference code for finding average nodal fluxes in LWR's.) The code has been exported to a number of laboratories and organizations and has been run successfully at (among others) Yankee Electric, Southern California Edison, Los Alamos and the CISE laboratory in Italy. At MIT it is currently being combined with the three dimensional, two-fluid-model thermal-hydraulics code MEKIN (See Section).

2) Application to Graphite and Heavy Water Moderated Cores

QUANDRY was applied to several small, two-dimensional, Cartesian-geometry reactor models composed of assemblies representative of those found in graphite and D_2O moderated thermal power reactors. For these applications it was found necessary to change the iteration parameters to get the code to run efficiently. But when this was done a gain in efficiency (over finite difference schemes) of better than a factor of 20 was achieved.

The assemblies comprising graphite moderated thermal power reactors are often hexagonal in shape. In anticipation of extending the QUANDRY method to

this geometry, a study is underway to represent the reflector of a reactor composed of hexagonal assemblies by a generalized albedo boundary condition so that explicit flux calculations in the reflector will not be necessary.

3) Treatment of the Core Baffle and Rod Cusping Effects

In order to reduce power peaking at the core-reflector interface PWR's usually have a 1-inch thick steel baffle (or shroud) between the core and the water reflector. QUANDRY can accept non-uniform node sizes and hence can represent the shroud as a sequence of non-square nodes. However, since nodal mesh lines must extend through the entire reactor, the extra number of nodes introduced by such an explicit representation increases running time significantly. A similar problem arises with control rods which, as they move in the axial direction through a given node, must be treated as moving "window shades" of homogeneous poison if artificial cusps in the curve of reactivity vs. rod position are to be avoided.

A way has been devised to account for these difficulties by subdividing given QUANDRY nodes into several smaller homogeneous regions having different material properties. (The subdivision is done without extending mesh lines beyond the node being subdivided.) An extension to QUANDRY implementing these methods has been completed and run successfully.

4) Homogenization Methods

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

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

To find the discontinuity precisely is self-defeating since they depend on the average leakage and reaction rates of the heterogeneous core. However it has been found that they are not very sensitive to the current boundary conditions on the nodal surfaces, and this fact suggests that it may be possible to estimate them fairly well by performing local calculations for the heterogeneous node alone or for that node and its nearest neighbors.

The simplest procedure for carrying out such local calculations is to impose zero-net-current boundary conditions on the surface of an isolated node. This method was found in severe test problems representative of BWR's to reduce errors in average nodal power by a factor of three. However for PWR's, for which standard flux-weighting procedures (discontinuity factors equal to 1) produce errors of only 2 to 3% in average nodal power, the use of

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discontinuity factors based on zero-net current assembly calculations led to little improvement and often increased errors slightly. Because of this, and since for the BWR test cases the reduced errors were still uncomfortably large (10% reduced to 3%; 23% reduced to 8%) we have been studying iterative procedures for finding discontinuity factors whereby a first estimate of the discontinuity factors (based on zero-net-current nodal calculations) is used to run a global QUANDRY problem and the resulting average currents across nodal surfaces are used as boundary conditions for local calculations to provide an improved set of discontinuity factors (which are then used in a second global calculation).

For a BWR, with some 400 fuel assemblies in a two dimensional plane of a reactor, having to stop at the end of a global calculation and do a local, fine-mesh, calculation for each heterogeneous node and its nearest neighbors would be extremely expensive even if there were quarter core symmetry. Accordingly we have developed a method of performing local calculations for the discontinuity factors using net nodal-surface currents from a global run along with response matrices for each different kind of node comprising the reactor. Response matrix calculations must still be done for each node at the end of a global run. However they are very fast. The costly, fine-mesh solutions needed to determine the response matrices may be carried out a priori and need be performed for only the four or so different kinds of node making up the reactor. We have worked out a scheme using these response matrices such that errors in node-average power are reduced (over those which result when conventional flux weighting is used) from 10% to 1% (mild case) and from 23% to 3% (extreme case).

5) Extension to Depletion

Since response matrices are now used to determine heterogeneity factors (and also homogenized cross sections) for QUANDRY, it is necessary to work out efficient procedures for updating these matrices as assembly conditions change with thermal hydraulic conditions and depletion. An interpolation scheme is being investigated for this purpose. Interpolation is difficult because it is multidimensional and because there are certain conditions under which the response matrix elements we are using (which are based on net surface currents rather than on partial surface currents) become infinite. Preliminary results indicate that these problems can be overcome.

Investigators: Professor A.F. Henry; Messrs. G. Allard, A. Cheng, D. Griggs, C. Hoxie, H. Khalil, J. Koclas, R. Loretz, K. Parsons, K. Smith, F. Yarman.

Related Academic Subjects:

Recent References:

K.S. Smith, An Analytic Nodal Method for Solving the Two-Group, Multidimensional Static and Transient Neutron Diffusion Equations, NE Thesis, MIT, Department of Nuclear Engineering (June 1979).

G. Greenman, K. Smith and A.F. Henry, "Recent Advances in an Analytic Nodal Method for Static and Transient Reactor Analysis", Proceedings of the ANS Topical Meeting on Computational Methods in Nuclear Engineering, Williamsburg, Virginia (April 1979).

K. Smith, Spatial Homogenization Methods for Light Water Reactor Analysis, PhD Thesis, MIT, Department of Nuclear Engineering, (June 1980).

R.A. Loretz, The Determination of Equivalent Diffusion Theory Parameters by Local Implementation of the Koebke Method, SM Thesis, MIT, Department of Nuclear Engineering (August 1980).

J.D. Koclas, A Subnoding Technique in the Context of the Analytic Nodal Methods, PhD Thesis, MIT, Department of Nuclear Engineering (September 1980).

K. Smith, A.F. Henry and R. Loretz, "Determination of Homogenization Diffusion Theory Parameters for Coarse Mesh Nodal Analysis", ANS Topical Meeting, Sun Valley, Idaho (September 1980).

A.Y. Cheng, C.L. Hoxie, A.F. Henry, "A Method for Determining Equivalent Homogenized Parameters", ANS/ENS Topical Meeting on Advances in Mathematical Methods for Nuclear Engineering, Munich, W. Germany (April 1981).

3.1.3 Fast Reactor Physics and Core Design

During the past year work was completed on MIT projects investigating the physics and fuel design of the Fast Mixed Spectrum Reactor (FMSR) under subcontract to Brookhaven National Laboratory, and the Gas-Cooled Fast Breeder (GCFR), under subcontract to General Atomic. Work has continued on the long term FBR Blanket Project, supported by DOE for over 12 years now.

The latter stages of the FMSR support effort was devoted primarily to modeling of duct wall behavior under irradiation at high temperatures to determine whether advanced materials could withstand the environmental stresses under the extremely high fluence to which an FMSR core could be exposed particularly in some of the long-lived versions under evaluation (10-30 year in-core residencies).

The GCFR project involved evaluation of the use of heterogeneous core designs in this reactor. Heterogeneous and conventional homogeneous cores were separately optimized under comparable ground rules. It was found that there was no particular advantage to the use of radial internal blankets in the GCFR. The results are general enough to suggest that the major incentive for use of such designs in the LMFBR is the reduction in sodium void reactivity, and that other advantages accrue only if one starts with severe constraints such as already-designed core and assembly configurations.

The ongoing LMFBR blanket project has been devoted of late to the evaluation of intra-assembly heterogeneity as an FBR design stratagem. This includes the incorporation of blanket (depleted uranium) fuel pins and/or moderated (zirconium hydride) pins in driver (mixed oxide fueled) assemblies. To date no significant advantages of these designs have been identified. As part of this effort MIT has also participated in the Large Core Code Evaluation Working Group's benchmark calculation program. Thermal-hydraulic and economic analyses of various advanced FBR designs were also carried out as part of this work.

Investigators: Professors M.J. Driscoll, D.D. Lanning and J.E. Meyer; Computer Operations Assistant, R. Morton; Messrs. D. Lancaster, W.T. Loh, M. Plys, S. Ahmad, I.I. Saragossi.

Support: U.S. Department of Energy (approximately $60,000 in 1981).

Related Academic Subjects:

22.212 Nuclear Reactor Physics II
22.213 Nuclear Reactor Physics III
22.313 Advanced Engineering of Nuclear Reactors
22.314J Structural Mechanics in Nuclear Power Technology
22.35   Nuclear Fuel Management

Recent References:

W.T. Loh, An Evaluation of the Fast Mixed Spectrum Reactor, S.M. Thesis, MIT, Department of Nuclear Engineering (December 1979).

D.B. Lancaster and M.J. Driscoll, An Assessment of Internal Blankets for Gas-Cooled Fast Reactors, MITNE-237 (October 1980).

I.I. Saragossi, Assigning a Value to Plutonium: Methodology and Policy Implications, Ph.D. Thesis, MIT, Department of Nuclear Engineering (January 1981).

M.G. Plys, The Neutronics of Internally Heterogeneous Fast Reactor Assemblies, S.M. Thesis, MIT, Department of Nuclear Engineering (June 1981).

D.B. Lancaster and M.J. Driscoll, "An Evaluation of Heterogeneous Cores for Gas-Cooled Fast Reactors", Trans. Am. Nucl. Soc., 38 (June 1981).

3.1.4 LWR Uranium Utilization Improvement

Work continues on a DOE-supported project to investigate innovations in PWR core design and fuel management which would improve uranium utilization on the once-through fuel cycle.

The major accomplishment during the past 18 months was the development of a methodology for making self-consistent comparisons. This step was a crucial one because it has been difficult heretofore to evaluate suggested

improvements on an "all else being equal" basis: differences in core leakage or fuel assembly power history can obscure the incremental advantage of a given modification. This screening technique was then used to evaluate most of the approaches suggested for uranium conservation in PWR units.

A study was completed which confirms the utility of routine pre-planned coastdown as an effective means to increase the energy extracted from a given batch of fuel. Longer coastdowns, up to the economic breakeven point, were shown to roughly double U_3O_8 savings.

Work is currently underway on an evaluation of axial blankets and axial power shaping, and on the optimum use of burnable poison in extended burnup, low-leakage cores.

Investigators: Professors M.J. Driscoll and D.D. Lanning; Messrs. J.A. Sefcik, A. Kamal, W.T. Loh, L. Lobo, M.A. Malik, P.E. Cavoulacos, M.A. de Fraiteur, D.C. Cambra; Computer Operations Assistant, R. Morton.

Support: U.S. Department of Energy via MIT Energy Laboratory ($80,000 in FY-1981).

Related Academic Subjects:

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

Recent References:

A. Kamal, The Effect of Axial Power Shaping on Ore Utilization in PWRs, S.M. Thesis, MIT, Department of Nuclear Engineering (January 1980).

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A. de Fraiteur, Correlating Economic Optimum Burnup for Light Water Reactors, S.M. Thesis, MIT, Department of Nuclear Engineering (December 1980).

L. Lobo, Coastdown in Light Water Reactors as a Fuel Management Strategy, S.M. Thesis, MIT, Department of Nuclear Engineering (December 1980).

J.A. Sefcik, M.J. Driscoll, D.D. Lanning, "Evaluation of Core Designs and Fuel Management Strategies for Improved Uranium Utilization", Trans. Am. Nucl. Soc., 35 (November 1980).

J.A. Sefcik, M.J. Driscoll and D.D. Lanning, Analysis of Strategies for Improving Uranium Utilization in Pressurized Water Reactors, MIT-EL-80-032, (January 1981).

M.J. Driscoll, J.A. Sefcik, A. Kamal, D.D. Lanning, "Using Annular Fuel to Save Uranium in PWRs", Trans. Am. Nucl. Soc., 38 (June 1981).

3.1.5 Advanced Control System

It has been recognized for some time that improvements can be made in the reactor control instrumentation in the area of fault detection and identification (FDI). Some potential improvements in this area are being studied as a joint program between the Charles Stark Draper Laboratory and MIT. The goal of the program is to utilize fault detection technology that has been developed for aerospace control systems and apply it to reactor control instrumentation.

The principal features of the method involve comparison of sensors and the use of analytic models to provide an analytic redundancy for an independent check on the sensor values. Although the general techniques exists for taking these inputs and detecting faults, the real time analytic models for the nuclear plant systems are not available. Thus the MIT studies at this time largely involve development of the real time analytic models and the Draper program carries over all applications of the methods for sensor validation together with fault detection and identification. Future considerations involve the potential for diagnostic information developed from the fault detection and eventually there is a possibility of more closed loop controls.

In addition to the Nuclear Engineering Department, the MIT group effort involves some people from both the Mechanical Engineering Department and the Electrical Engineering and Computer Science Department. In particular, the control display systems are being studied for human factor engineering considerations at the man-machine interfaces by the participants from the Mechanical Engineering Department. This work has led to a one-week Summer Session Program presented jointly by the Mechanical Engineering Department and the Nuclear Engineering Department entitled Man-Machine Interfacing in Nuclear Power and Industrial Process Control.

Draper IR&D funded task areas include reactor core modeling, plant component modeling, steam generator FDI application, MIT Reactor Feasibility Study, decision analysis technology transfer, alternate diagnostic concepts, computer utilization concepts, and a 1-D fusion plasma code.

Investigators: Professors D.D. Lanning, J.E. Meyer, T.B. Sheridan; Drs. P. Nicholson, P.A. Bergeron (Yankee Atomic Electric Company); Messrs. R. Ornedo, C. Geffray, W. Strohmayer, J. Molina, G. Nakayama, R. Vilim, J. Bernard, C. Antonini, L. Gulko, J. Borghese, J. Novak, G. Baltra (MIT); Drs. A. Ray, J. Deyst, J. Hopps, C. Whitney and Mr. R. Geiger (Draper Laboratory).

Support: Internal Draper Funds (IR&D) and self supporting students with NED computer funding.

Related Academic Subjects:

    22.22   Nuclear Reactor Dynamics Numerical Methods
    22.32   Nuclear Power Reactors
    22.43   Numerical Methods in Reactor Engineering Analysis

Recent References:

C. Geffray, _Nuclear Reactor (PWR) Pressurizer Real Time Modeling for Sensor Validation_, S.M. Thesis, MIT, Department of Nuclear Engineering (July 1980).

J. Molina, _Analysis of the Feedwater System for a Pressurized Water Reactor_, S.M. Thesis, MIT, Department of Nuclear Engineering (April 1981).

G. Nakayama, _Linearized Model Real Time Reactor Simulation_, S.M. Thesis, MIT, Department of Nuclear Engineering (April 1981).

R. Ornedo, _Development and Assessment of a Pressurized Water Reactor Core Model for Real Time Diagnostics_, S.M. Thesis, MIT, Department of Nuclear Engineering (May 1981).

P.J. Nicholson, and D.D. Lanning, "Requirements and Concepts for a Nuclear Plant Surveillance and Diagnostics System (NPSDS)", _Proceedings IAEA Specialists Meeting on Distributed Systems for Nuclear Power Plants_ (May 1980).

G. Baltra, _Design of A Coordinated Plant Control System for a Marine Nuclear Propulsion Plant_, NE/SM Thesis, MIT, Department of Nuclear Engineering and Department of Ocean Engineering (March 1981).

3.2   Reactor Engineering

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

3.2.1   Subjects of Instruction

    A total of seventeen subjects of instruction are offered under the category of reactor engineering by the Department. The following paragraphs present a description of all of the subjects in reactor engineering.

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

22.031: <u>Engineering Analysis of Nuclear Reactors</u>, topics covered include power plant thermodynamics, reactor heat generation and removal (single-phase as well as two-phase coolant flow and heat transfer) and structural mechanics. Engineering considerations in reactor design. Lectures are in common with 22.312, homework, exams, and recitation are separate.

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

22.311: <u>Engineering Principles for Nuclear Engineers</u>, is intended primarily for students who did their undergraduate work in physics or other fields which did not provide much instruction in engineering principles. Topics dealt with include fundamentals of engineering thermodynamics, transport phenomena and structural mechanics, with examples of applications to nuclear power systems.

22.312: <u>Engineering of Nuclear Reactors</u>, emphasis is on applications in central station power reactors. Power plant thermodynamics; energy distribution and transport by conduction and convection of incompressible one- and two-phase fluid flow in reactor cores; mechanical analysis and design.

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

22.314J: <u>Structural Mechanics in Nuclear Power Technology</u>, deals with techniques for structural analysis of nuclear plant components. It is a joint subject with five other engineering departments (Civil, Mechanical, Materials, Ocean, and Aero/Astro) since nuclear plant components illustrate applications of these disciplines. The structural aspects of plant components are discussed in terms of functional purposes and operating conditions (mechanical, thermal, and radiation). A designers view is adopted, emphasizing physical rationale for design criteria and methods for executing practical calculations. Application topics include fuel performance analysis, reactor vessel safety, flow induced vibrations, and seismic effects.

22.32: <u>Nuclear Power Reactors</u>, is a descriptive survey of engineering and physics aspects of current nuclear power reactors. Design details are discussed including requirements for safety of light and heavy water reactors, high temperature gas-cooled reactors, fast reactors both liquid-metal and gas-cooled, and fast breeder reactors. Reactor characteristics are compared both in class and by individual student projects. Development problems are discussed and potentials for future improvements are assessed.

22.33: <u>Nuclear Engineering Design</u>, is a group design project involving integration of reactor physics, control, heat transfer, safety, materials, power production, fuel cycle management, environmental impact, and economic optimization. The subject provides the student with the opportunity to synthesize knowledge acquired in the reactor design field. The subject meets concurrently with 22.033 but assignments differ.

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

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

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

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

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

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

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

22.915: Seminar in Reactor Safety, surveys the general considerations and methodology of safety analysis as applied to commercial and advanced reactor designs. Specific topics are selected for review and discussion by the participant students. Invited speakers lecture on the status of current safety research.

3.2.2 Coolant and Energy Mixing in Rod Bundles

An experimental and analytical program has been continued under DOE 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 effort in this program has been split between forced convection and mixed convection studies. In the forced convection area, the relevant conservation equations can be decoupled and adequate solutions developed by solving only the energy equation. Mass and momentum effects are accounted for by experimentally determining the flow distribution and providing it as an input condition. For this reason salt conductivity measurements of flow mixing effects are sufficient in this flow regime and are used in place of heated pin tests. In contrast in the mixed convection region, the relevant conservation equations must be solved in a coupled manner. Our supporting mixed convection experiments utilize heated pins with a water coolant and measurements of velocity and temperature are made. An additional major focus of this effort is the gathering and analysis of sodium mixed convection data from other laboratories so that Prandtl numbers effects will be included in the models developed.

A) Forced Convection Area - Recent accomplishments have been:

   a) completion of tests of several bundles with varied geometries to fill in gaps in the data base,
   b) completion of models for input parameters of MIT codes of flow distribution and mixing factors for the entire Reynolds number range,
   c) completion of friction factor models for the entire Reynolds number range,
   d) completion of a test of a shaved wire bundle (the shaved wire concept reduces the peripheral channel flow area thereby forcing more flow to the central heated area of the bundle).

B) Mixed Convection Area - Recent accomplishments have been:

   a) means to predict shape factors have been developed,
   b) a criteria for onset of mixed convection has been tested,
   c) a 3D code to predict local clad temperature has been written,
   d) a test section with 16 heater rods in square array for mixed convection testing in water has been built and the instrumentation developed,
   e) analytic solution of the isolated subchannel case has been completed.

Investigators: Professors N.E. Todreas, W.M. Rohsenow (Department of Mechanical Engineering); Messrs. T. Greene, P. Symolon, S.F. Wang, K. Burns, J. Hawley, Y.N. Chan, S.N. Kim, A. Efthimiadis, S. Cheng.

Support: U.S. Energy Research and Development Administration, ($120,000/year for coolant and energy mixing in rod bundles).

Related Academic Subjects:

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

Recent References:

S.F. Wang, W.M. Rohsenow, N.E. Todreas, "Steady, Laminar, Fully-Developed Mixed Convection in Finite Rod Arrays", COO-2245-73TR, MIT, (February 1981).

K.J. Burns, N.E. Todreas, "A Comparison Between the SIMPLE and Energy Code Mixing Models," DOE/ET/37240-78TR, (July 1980).

J.T. Hawley, C. Chiu, W.M. Rohsenow, N.E. Todreas, "Correlations for Subchannel and Bundle Friction Factors and Flowsplit Parameters for Laminar, Transition, and Turbulent Longitudinal Flows in Wire Wrap Spaced Hexagonal Arrays", DOE/ET/37240-79TR, (December 1980).

J.T. Hawley, C. Chiu, N.E. Todreas, "M.I.T. Extraction Method for Measuring Average Subchannel Axial Velocities in Reactor Assemblies", DOE/ET/37240-80TR, (July 1980).

K.J. Burns, W.M. Rohsenow, N.E. Todreas, "Laminar/Transition Sweeping Flow Mixing Model for Wire Wrapped LMFBR Assemblies", DOE/ET/37240-81TR, (July 1980).

P.D. Symolon and N.E. Todreas, "Fluid Mixing Studies in a Hexagonal 217 Pin Wire Wrapped Rod Bundle," DOE/ET/37240-84TR, (February 1981).

S.F. Wang, W.M. Rohsenow, and N.E. Todreas, "Flow Split, Pressure Drop, and Mixing Experiments in a 61 Pin Shaved Wire Blanket Assembly, DOE/ET/37240-86TR, (February 1981).

S.F. Wang, N.E. Todreas, "Computer Model for MIT Correlations for Friction Factors, Flow Split, and Mixing Parameters in LMFBR Wire-Wrapped Rod Assemblies," DOE/ET/37240-87TR, (February 1981).

S.F. Wang and N.E. Todreas, "Experimental Investigations of Laminar Mixed Convection in a Square Array of Bare Rods," Report No. DOE/ET/37240-88TR, (February 1981).

J.T. Hawley, Y.N. Chan and N.E. Todreas, "Input Parameters to Codes which Analyze LMFBR Wire Wrapped Bundles," COO-2245-17TR, (Revision II), December 1980).

P.D. Symolon and N.E. Todreas, "Fluid Mixing Studies in a Hexagonal 61 Pin Wire Wrapped Rod Bundle," COO-2245-51TR, (Revision I), (February 1981).

Y.N. Chan and N.E. Todreas, "Turbulent Sweeping Flow Mixing Model for Wire Wrapped LMFBR Assemblies," COO-2245-55TR, (Revision II), (December 1980).

Y.N. Chan and N.E. Todreas, "Turbulent Flow Split Model and Supporting Experiments for Wire Wrapped Core Assemblies," COO-2245-56TR, (Revision I), (December 1980).

T.E. Greene and N.E. Todreas, "WARD Blanket Assembly Pre-Test Predictions by SUPERENERGY," COO-2245-40TR, (Revision I), (April 1981).

J.T. Hawley, C. Chiu, W.M. Rohsenow and N.E. Todreas, "Subchannel and Bundle Friction Factors and Flow Split Parameters for Laminar, Transition and Turbulent Longitudinal Flows in Wire Wrap Spaced Hexagonal Arrays," Proceedings ANS/ASME NRC Int'l Topical Mtg. on Nuc. Reactor Thermal Hydraulics NUREG/CP-0014, 3, pp. 1766-1788, (October 1980).

S.F. Wang, W.M. Rohsenow and N.E. Todreas, "Subchannel Friction Factors for Bare Rod Arrays under Mixed Convection Conditions", in Decay Heat Removal and Natural Convection in Fast Breeder Reactors, A.K. Agrawal and J.G. Guppy, Eds., Hemisphere Publishing Corp., N.Y., pp. 95-109, (1981).

C. Chiu, J.T. Hawley, W.M. Rohsenow, and N.E. Todreas, "Parameters for Laminar, Transition and Turbulent Longitudinal Flows in Wire-Wrap Spaced Hexagonal Arrays", Accepted for presentation at the Topical Meeting on Nuclear Reactor Thermal Hydraulics, Saratoga, NY, (October 5-8, 1980).

3.2.3 Hydrodynamic Prediction of Single- and Two-Phase Flow in Rod Arrays

Advanced thermal-hydraulic codes have recently been developed for design and operational performance analysis of energy generating devices such as steam generators, heat exchangers, and nuclear reactor cores. All these devices utilize multidimensional flow over rod arrays. Several examples of these advanced codes are THERMIT developed at MIT, TRAC developed at Los Alamos Scientific Laboratory, and URSULA developed by EPRI.

The basic inputs of thermal hydraulic codes, aside from the problem specific geometry and boundary conditions, are the constitutive laws. These laws provide closure of the general conservation equations. The new advanced codes are developed for three-dimensional, multiphase flow analysis. Although constitutive laws have been well formulated for one-dimensional flow fields, the constitutive laws for two- and three-dimensions have not received extensive attention. Moreover, the current multidimensional constitutive laws used are unsubstantiated extensions of one-dimensional models. More appropriate models would be those based on a foundation of experimental observations in multidimensional flow geometries.

The focus of this research is to develop comprehensive constitutive corrrelations for the hydrodynamics of multidimensional flow through rod arrays. The constitutive correlations will be based on physical considerations and experimental observations of flows at inclined angles through rod arrays. Specifically, this work will develop constitutive correlations for the fluid-structural flow resistance and relative motion between phases.

Investigators: Professors N.E. Todreas and P. Griffith (Department of Mechanical Engineering); Mr. D.B. Ebeling-Koning

Support: Unsponsored research, proposal submitted to U.S. Department of Energy.

Related Academic Subjects:

    22.313 Advanced Engineering Nuclear Reactors
    22.36J Two-Phase Flow and Boiling Heat Tranfer

Recent Publications:

Y. Coeffe and N.E. Todreas, "Formulation of the Fluid-Solid Interaction Force for Multidimensional, Two-Phase Flow within Tube Arrays," Nuclear Engineering and Design, 58, pp. 383-391, (December 1980).

3.2.4 Theoretical Determination of Local Temperature Fields in LMFBR Fuel Rod Bundles

The objective of this work is to obtain the local velocity and temperature fields in wire wrapped LMFBR rod bundles. Better knowledge of the velocity and temperature fields will improve the prediction of the location and the value of the hot spot temperature in the reactor under any circumstances. It also provides valuable information for future multi-

dimensional structural analyses of the rod cladding and the hexagonal bundle walls. The outcome of these analyses, of course, will reduce the design margin due to over-conservatism.

In the present U.S. LMFBR design, helical wire-wraps are widely used to maintain spacing between fuel pins. However, the addition of these wires also introduces some complicated hydrodynamic and heat transfer problems. The purpose of the wire is to induce substantial swirl flow around the pins and some cross-flow between flow channels. Since there is contact between the wires and the pins, the hot spot temperature may increase. To understand the whole situation, one has to solve a three-dimensional hydrodynamic and heat transfer problem.

Because of the complicated geometry due to the helical wire wrap, a technique which is developed from the MAC method and ICE technique, called DICE (Direct Implicit Continuous Eulerian), is being employed to solve this three-dimensional nonlinear hydrodynamics and heat transfer problem. This technique involves formulating an implicit elliptic pressure equation and applying an efficient direct method to solve this pressure equation to obtain an updated pressure distribution. Once, the pressure field is known, the new velocities and temperature can be found easily by solving the discretized momentum and energy equations. The only restriction in this technique is that in order to maintain stability, the Courant condition has to be satisfied because of the explicit nonlinear terms in the momentum equation. This technique is designed to be fast and efficient. A computer code, called HEATRAN, using this methodology has been written. In order to verify this computer code, it has been systematically checked against many standardized problems. The typical problems that have been checked are, circular pipe flow with uniform inlet condition or with a small vortex at the entrance, a circular duct with a twisted tape, and the interior cell of a bare rod bundle. The on-going work is to apply this computer code HEATRAN to solve the wire-wrapped rod bundle heat transfer problem.

Investigators: Professors L. Wolf and N. Todreas; Mr. C.N. Wong.

Support: U.S. Department of Energy ($30,000/year out of the Coolant Mixing Project)

Related Academic Subjects:

    22.312   Engineering of Nuclear Reactors
    22.313   Advanced Engineering of Nuclear Reactors
    22.33   Nuclear Engineering Design

Recent References:

None to date

3.2.5   Voiding in Bypass Flow Channels in Boiling Water Reactors

The purpose of this research was to investigate the thermal hydraulic characteristics of the bypass flow in Boiling Water Reactors with specific

emphasis on the onset of voiding. The term "bypass" refers to those flow paths in the reactor between the assemblies and external to the channel walls.

Models were developed which estimate the energy addition to the bypass flows from three sources; 1) the conduction heat transfer between the hot fluid in the active region of the assembly and the cooler fluid in the bypass, 2) The energy generated in the control material due to the absorption of neutrons, and 3) The energy deposited in the bypass region due to neutron moderation and gamma attenuation. Additional models were developed to predict the flowrate in the bypass regions as a function of percent total reactor power, percent total reactor flow, power level in the active regions surrounding each bypass channel, and the geometry of the assemblies from which the bypass flow originated.

The primary tools used in the investigation were the computer codes FIBWR (Flow in Boiling Water Reactors) and COBRA IIIC/MIT. The trends predicted by the calculations performed for this analysis tend to indicate that a small degree of voiding in the bypass region is normal. At operating conditions, void fractions as large as 8% were calculated. About 45% of the bypass channels had some degree of voiding under these operating conditions. The effects of such voiding on the neutronics in the upper regions of the core must be assessed and design decisions made as to the degree of voiding which can be tolerated.

Investigators: Professor N. Todreas; Mr. J. Jackson

Support: Electric Power Research Institute

Related Academic Subjects:

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

Recent References:

J.W. Jackson, Thermal Hydraulic Analysis of the Bypass Flow in Boiling Water Reactors, S.M. Thesis, MIT, Department of Nuclear Engineering, (June 1981).

3.2.6 Fluid Dynamic Modeling of Forced-Buoyant Flow in Reactor Vessel Plenums

Analytical and experimental work is being pursued with the goal of improving understanding of, and models for, behavior of turbulent mixing of buoyant flows. The specific problem examined concerns development of models for flow mixing in the LMFBR outlet plenum. To do this the influence of different turbulence models upon predicted mixing patterns are being investigated. These results are to be compared to measured velocity and temperature fields, and measured velocity and temperature correlation functions, with the

aim of developing an appropriate turbulence model for use in design calculations. In a broader sense this work permits an investigation into the nature of turbulent mixing in buoyant flows, which has application in a wide range of practical problems.

In recent work it has been seen for many important reactor design problems that truncation error effects (inherent in numerical simulation methods) can be of equal magnitude to important physical transport phenomena. This can lead to flawed design analyses.

In an effort to improve upon this situation an examination of alternative numerical treatments of fluid flow problems has been performed in order to identify and improve upon methods providing low error, stable predictions.

Current work is concerned with turbulence in three-dimensional highly anisotropic flows.

Investigators: Professor M.W. Golay, Messers. S.H. Chang, and R. Sawdye.

Support: U.S. Department of Energy ($35,000)

Related Academic Subjects:

    22.312   Engineering of Nuclear Reactors
    22.313   Advanced Engineering of Nuclear Reactors
    22.43   Numerical Methods in Reactor Engineering Analysis
    19.65J   Turbulence and Random Processes in Fluid Mechanics

Recent References:

D.R. Boyle and M.W. Golay, Transient Effects in Turbulence Modelling, PhD Thesis, MIT, Department of Nuclear Engineering, (1979).

S.H. Chang and M.W. Golay, Buoyancy Effects in Mathematical and Numerical Turbulence Modeling, SM Thesis, MIT, Department of Nuclear Engineering, (1979).

3.2.7   Sodium Boiling in LMFBR Fuel Assemblies

The objective to this program is to contribute to the development of an improved understanding of sodium voiding behavior under postulated LMFBR accident conditions. The program consists of development of multi-dimensional computer models under low flow, low power conditions. The experimental study is being conducted in the Mechanical Engineering Department and is not reported here.

Under the computer model development effort two codes are being developed in parallel. The first will use a two-fluid (6 equation) model which is more difficult to develop but has the potential for providing a code with the utmost in flexibility and physical consistency for use in the long term.

The other will use a "mixture" (≤6 equation) model which is less general but may be more amenable to interpretation and use with available experimental data. Therefore, it may be easier to develop for application in the near term. Both codes are being developed using the existing transient thermal-hydraulic analysis code, THERMIT, as a basis. A major effort has been the modification of the numerical scheme originally developed for water application to one that is suitable for sodium application. To assure that the codes being developed are not design dependent, geometries and transient conditions typical of both foreign and U.S. designs are being considered for the process of code testing and application.

An effort has been made to maintain close communication with DOE contractors and laboratories in order to: (1) assure that maximum use is made of data and information available from related programs and, (2) facilitate their eventual acquisition and use of the codes.

Activities on the mixture model code was initiated about a year ago. A four equation drift flux approach will be utilized. All necessary two phase correlations as well as the specific numerical technique which will be utilized are now being identified. The two-fluid model code has been under development for two years. The objective of this effort is to develop calculational models for sodium boiling in fast reactor assemblies based on the two-fluid approach. In particular, two codes will be pursued: two dimensional model (NATOF-2D) and a three dimensional code based on the LWR code THERMIT-TF. The models will be verified by comparison to existing experimental results on sodium boiling. Where needed, additional experimental results will be defined.

The NATOF-2D and THERMIT-TF codes are now at an advanced state of development. The importance of the 2D effects under some transient conditions imply that development of these models should be pursued at the same time so that comparison of the 1D and 2D and 3D models will be helpful in verification of the appropriate scaling laws of small bundles usually employed in experiments.

The codes are in a relatively primitive state as regards physical realism. Thus, implementation of the correlations necessary to bring realism into the code is pursued. This means examining all sodium boiling data and creating models and correlations appropriate to the two fluid formalism, including:

1) description of relative motion of the phases via interphase and wall friction correlations;

2) flow boiling heat transfer models;

3) flow regime description accounting for both heat transfer and fluid dynamics;

4) optionally (if super heat is important), interphase heat and mass transfer rate models.

The development of these multi-dimensional models will allow the study of the sensitivity of sodium boiling consequences to the geometrical effects

of different designs. Assessment of such effects will define the design conditions that need to be factored in fast reactor assemblies in order to intensify the inherent safety features.

Investigators: Professors M. Kazimi, P. Griffith, N. Todreas; Dr. W.D. Hinkle, Messrs. M. Granziera, G. Wilson, A. Schor, A. Levin, H.C. No

Support: U.S. Department of Energy (approximately $100,000/year).

Related Academic Subjects:

    22.36J   Two-Phase Flow and Boiling Heat Transfer
    22.43   Numerical Methods in Reactor Engineering Analysis

Recent References: (Sodium Boiling in LMFBR Assemblies)

A. Levin and P. Griffith, "Development of a Model to Predict Flow Oscillations in Low Flow Sodium Boiling", MIT-EL-80-006, (April 1980).

M.R. Granziera and M.S. Kazimi, "A Two-Dimensional Two Fluid Model for Sodium Boiling in LMFBR Assemblies", MIT-EL-80-011, (May 1980).

G. Wilson and M.S. Kazimi, "Development of Models for the Sodium Version of the Two-Phase Three Dimensional Thermal Hydraulics Code THERMIT", MIT-EL-80-010, (May 1980).

3.2.8 Optimal Modeling of a PWR Steam Generator

    A small research project on steam generator thermal hydraulic modeling has been supported by some utilities in the Northeast area. The objectives of the project are to look for the minimum acceptable nodes to be used in the system codes such as RETRAN for the steam generator representation. Also to compare two fluid thermal hydraulic calculations with the homogeneous model. These studies are being made by using the THERMIT Code for both steady state and transient calculations.

Investigators: Professors D.D. Lanning, N.E. Todreas, Messrs. B. Rhee, D. Ebeling-Koning, F. Bamdad, and H. Da Silva.

Support: Several electric utilities through the MIT Energy Laboratory Electric Utility Program ($38,800)

Related Academic Subject:

    22.312   Engineering of Nuclear Reactors

Recent Publications:

None to date

3.2.9 Core Water Level Measurement in a PWR

A direct measurement of the core water level for the PWR system has not been incorporated into the original designs. It is desirable to have such information for safe operation of these reactors. One method of accomplishing this would be to utilize a "heated-thermocouple" technique. In this technique a probe consisting of two thermocouples is used, one thermocouple is embedded near a small electric heater and the other is away from the heater but nearby. When the two thermocouple systems are surrounded by water, the reference temperature difference is measured. If the water is removed or changed to steam, a higher value of the temperature difference is measured due to the reduced heat transfer coefficient near the heated thermocouple. In this project, several experiments have been made with such probes to study the response under simulated PWR thermal hydraulic conditions. Encouraging results have been obtained in that an easily detected response is found. A search for possible anamolous responses is being made.

Investigators: Professors D.D. Lanning, P. Griffith (Mechanical Engineering), Mr. G. DeWitt.

Support: Several electric utilities through the MIT Energy Laboratory Electric Utility Program, ($63,155)

Related Academic Subject:

22.312 Engineering of Nuclear Reactors

Recent Publications:

None to date

3.2.10 Improvement of COBRA-IIIC/MIT

The objectives of this project are: (a) to make several improvements to the currently available version of the COBRA-IIIC/MIT code and (b) to further assess the code's capability for use in LWR thermal hydraulic analysis.

The specific tasks to be completed are the following:

1. Addition of a new fuel pin conduction model which includes temperature dependent properties and burnup dependent gap heat transfer coefficient.

2. Addition of a new heat transfer package which covers a broad range of flow regimes and contains more consistent logic.

3. Addition of a quality dependent mixing model for two-phase flow.

4. Addition of new correlations for BWR, CHFR and CPR calculation.

5. Addition of new options for using transverse momentum coupling parameters for use in the single-pass method.

The improvements have been tested individually and during application of the improved code to PWR and BWR test cases. Testing mainly involved comparison of the predictions of different modeling options and in some instances, comparison of predications with experimental measurements. MDNBR, MCPR and MCHFR predictions showed only small sensitivities to the fuel rod and heat transfer modeling options used for the PWR and BWR transient test cases analyzed. Differences in predictions of the old and new heat transfer models resulted in different clad temperature predictions. Clad temperature varies more smoothly in the axial direction when the new heat transfer model is used. The new heat transfer model predictions vary more smoothly from one time step to the next with changing coolant conditions. Discontinuous change in old heat transfer model predictions caused failure of the flow solution to converge during transient BWR analysis. Fuel rod surface heat flux predictions of the old and new fuel rod models were close even though fuel rod temperature predictions showed some differences. The new mixing model did not improve subchannel flow and enthalpy predictions for BWR conditions. However, some improvement was seen in predictions for subcooled conditions. The CISE-4 MCPR predictions were in agreement with experimental CHF measurements. Hench-Levy MCHFR predictions were conservative for the CHF test cases. The new transverse momentum parameters had no significant effect on steady state hot channel predictions of the single pass method.

Additionally a final report and updated user's manual for the code have been completed. The updated code has been designated COBRA IIIC/MIT-2. The first version (Bowring/ Moreno) is now referred to as COBRA IIIC/MIT-1.

<u>Investigators</u>: Dr. W. Hinkle, Prof. N. Todreas, Messrs. J. Loomis and J. Jackson.

<u>Support</u>: $37,000 for one year. Sponsored by Consolidated Edison Company of New York, Consumers Power Company, Florida Power & Light Company, Long Island Lighting Company, Public Service Electric & Gas Company and Yankee Atomic Electric Company under the Energy Laboratory Electric Utility Program.

<u>Related Academic Subjects</u>:

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

<u>Publications</u>:

J.N.Loomis, <u>Reactor Thermal-Hydraulic Analysis Improvement and Application of the Code COBRA-IIIC/MIT</u>, N.E. Thesis, MIT, Department of Nuclear Engineering, (November 1980).

J.W. Jackson, <u>Thermal-Hydraulic Analysis of the Bypass Flow in Boiling Water Reactors</u>, S.M./S.B. Thesis, MIT, Department of Nuclear Engineering, (May

3.2.11 Development of the Two-Fluid Three-Dimensional THERMIT for LWR Applications

This effort involves the development and assessment of the two-fluid computer code THERMIT for light water reactor core and subchannel analysis. The developmental effort required a reformulation of the coolant to fuel rod coupling, found in the original THERMIT code, as well as an improvement in the fuel rod modeling capability. With these modifications, THERMIT now contains consistant thermal-hydraulic models capable of traditional coolant-centered subchannel analysis. As such this code represents a very useful design and transient analysis tool for LWR's.

The advantages of THERMIT are that it contains the sophisticated two-fluid, two-phase flow model as well as an advanced numerical solution technique. Consequently, mechanical and thermal non-equilibrium between the liquid and the vapor can be explicitly accounted for and, furthermore, no restrictions are placed on the type of flow conditions. However, the formulation of the two-fluid model introduces interfacial exchange terms which have a controlling influence on the two-fluid equations. Therefore, the models which represent these exchange terms must be carefully defined and assessed.

In view of the importance of these interfacial exchange terms, a systematic evaluation of these models has been undertaken. This effort has been aimed at validating THERMIT for both subchannel and core-wide applications. The approach followed has been to evaluate THERMIT for simple cases first and then work up to more complex flow conditions. Hence, the evaluation effort consists of performing comparison tests in the following order:

a) Steady-state, one-dimensional cases,
b) Steady-state, three-dimensional cases,
c) transient, one-dimensional cases, and
d) transient, three-dimensional cases.

For these comparison tests, experimental measurements have been used including tests performed by G.E. and at Ispra.

As a result of these comparisons, the following conclusions can be made. First, it is found that THERMIT can adequately predict the void fraction for a wide range of flow conditions.

A second conclusion is that the newly formulated post CHF heat transfer is capable of reasonable predictions of wall temperatures.

A third conclusion is that the turbulent mixing model must be added to THERMIT in order to accurately predict the flow and enthalpy distribution in subchannel geometry. Both single-phase and two-phase measurements illustrate this point. Without such a model, the mass flux and quality predictions are poorly predicted. The application of this model is particularly needed in BWR analysis. The high pressure in the PWR operating conditions leads to diminishing effects for the turbulent mixing.

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A new task has been initiated to couple the three dimensional neutronic code QUANDRY and THERMIT. This coupled capability should greatly improve the capability to analyze the LWR fast transients.

Investigators: Professor M.S. Kazimi, A.F. Henry, Messrs. J. Kelly, D. Griggs, and P. Kao.

Support: Energy Laboratory Electric Utility Program ($95,000/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:

J.E. Kelly and M.S. Kazimi, "Development of the Two-Fluid Multi-Dimensional Code THERMIT for LWR Analysis", in AIChE Symposium Series 76, 99, R.P. Stein, Editor, (August 1980).

J.E. Kelly and M.S. Kazimi, "THERMIT, A Three-Dimensional Two-Fluid Code for LWR Transient Analysis", Trans. AM. Nucl. Soc. 34, p. 893, (June 1980).

J. Kelly, "Development of a Two-Fluid, Two-Phase Model for Light Water Reactor Subchannel Analysis", Ph.D. Thesis, MIT, Department of Nuclear Engineering, (1980).

P. Kao, Post-Critical Heat Transfer and Critical Heat Flux Predictions for Light Water Reactors, S.M. Thesis, MIT, Department of Nuclear Engineering, (1981).

3.2.12 Thermal Phenomena in LMFBR Safety Analysis

This program was started in June, 1977 to study the processes of thermal exchange between two fluids when either or both of them are in a liquid-vapor two-phase state. Such phenomena are of interest in analysis of fast reactor accidents. In particular, better definition of the interaction rate of two-component two-phase systems is needed in the computer models that are being developed to describe the integral behavior of reactor materials under severe accident conditions.

The interaction processes of interest under accident conditions are those that can lead to significant early cooling of the molten fuel and hence decrease the potential for high mechanical energy release. The phenomena are studied by experimental and analytical models. The interaction modes of interest in this program can be divided into two categories:

1. In-Core Phenomena: This includes the rate at which heat can be transferred from molten fuel and/or vaporized fuel to the non-fuel components in the reactor core. In this regard the modes of heat transfer are those between fuel and steel within a molten pool as well as from the pool to the surrounding structures.

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2. Out-of-Core-Phenomena: This includes the rates of mixing and heat transport from molten core materials and above core sodium in the vessel as the former is ejected into the latter following hypothetical meltdown conditions.

The analysis developed to describe the interaction phenomena will be tested against results of experiments using simulant materials. The predictive models will then be applied to the fast reactor fuel/steel/sodium conditions.

The progress made in the last year can be summarized as follows:

A model of the volumetric heat transfer coefficient from fuel to steel has been formulated. The model is based on an extension of the single bubble behavior in a sea of liquid to multi-bubble behavior in a sea of liquid to multi-bubble behavior. The heat transfer is correlated as a function of the dispersed phase (steel) drop size and volumetric fraction. The model is in agreement with published data on two-phase two-component heat transfer. An experiment has been designed and constructed to test the model. Several tests were performed and the results were used for model verification.

Investigators: Professors M.S. Kazimi, W.M. Rohsenow; Messrs. R. Smith, R. Bordley.

Support: Nuclear Regulatory Commission (approximately $32,000/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
22.915 Seminar in Reactor Safety

Recent Publications:

R.A. Rothrock and M.S. Kazimi, "On the Potential for Plugged Core". "Pressurization Following a Hypothetical Accident in the LMFBR", Nuclear Engineering and Design, 53, pp. 197-205, (1979).

R.C. Smith, W.M. Rohsenow and M.S. Kazimi, "Modeling of Fuel-to-Steel Heat Transfer in Core Disruptive Accident", MITNE-233, (June 1980).

P.W. Bordley, A Photographic Study of a Direct-Contact Boiler, B.S. Thesis, MIT, Department of Nuclear Engineering, (1980).

3.2.13 Transient Code Sensitivity Studies: MEKIN Code

The computer code MEKIN provides an analysis of space-dependent transients in light-water cooled and moderated nuclear reactor cores. Specifically, MEKIN models thermal, hydraulic, and neutronic phenomena in boiling water and pressurized water reactor cores. These models treat three-dimensional configuration space (Cartesian geometry) and time. MEKIN also performs the static calculations required to establish initial reactor conditions.

The computer code MEKIN (an acronym for MIT - EPRI - Kinetics) was developed for the Electric Power Research Institute (EPRI) by the Nuclear Engineering Department of the Massachusetts Institute of Technology (MIT) and EPRI subsequently has approved funding for MIT to make sensitivity studies and further improvements in the code. In addition to the sensitivity results, these sensitivity studies have led to many code corrections and improvements, particularly in the thermal-hydraulics area. These studies are being continued with special emphasis on the potential application of two-fluid, two-phase models to reactor core transients.

The MEKIN code was first completed in September of 1975 and since then many code tests and studies have been completed including integrated tests with variations in the feedback effects and studies of the sensitivity of the calculated results to various assumptions in the model. The results of the sensitivity studies have been reported in monthly reports and student theses.

These studies are now essentially completed. The final projects have been related to the thermal-hydraulic section of the code and the feedback effects for the neutronic calculations. Specifically, the following sections are under investigation:

- Formulation of improved thermal-hydraulic methods utilizing the two-fluid two-phase models.
- Benchmark calculations made by using the MEKIN Code.

Investigators: Professors D.D. Lanning, A.F. Henry, J.E. Meyer, N.E. Todreas, Messrs. C. Barbehenn, D. Dube, S. Kim, L.T. Rodack, L. Tan, M. VanHaltern, F. Rodriguez, MS. E.S. Gordon.

Support: Electric Power Research Institute ($410,000 over 4 years)

Related Subjects:

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

Recent References:

D.A. Dube, _Development of a Fully Implicit Two-Fluid Thermal-Hydraulic Model for Boiling Water Reactor Transient Analysis_, PhD Thesis, MIT, Department of Nuclear Engineering, (1980).

E.S. Gordon, _Improved Fuel Pin Conductance Model for Use in the MEKIN Code_, SM Thesis, MIT, Department of Nuclear Engineering, (1980).

L. Tan, _MEKIN Numerical Modeling and Simulation of the Spert III E-Core Transient Tests_, SM Thesis, MIT, Department of Nuclear Engineering, (1980).

M. Van Haltern, _A Sensitivity Study of Thermal-Hydraulic Correlations in the Computer Code MEKIN_, SM Thesis, MIT, Department of Nuclear Engineering, (1980).

3.2.14 The Impact of Periodic Testing on the Availability of Standby Safety Systems

The major strength of the FRANTIC-2 code is its ability to model the impact of component testing on time-dependent system unavailability. However, its potential has not yet been fully explored because it has not been applied to actual systems. The capabilities of the code need to be assessed considering the data base available to the systems engineer and the practical range of options that can be employed.

This research is focused on relating the FRANTIC-2 code's modeling capabilities to failures that could occur in actual systems. FRANTIC-2 can model time-dependent failure modes represented by a Weibull distribution and a comprehensive set of test and repair effects. Therefore this effort will emphasize as many of these options as possible. To accomplish this goal we will:

1. Develop an engineering interpretation of the failure modes of standby components subject to periodic inspection and repair and relate the code's input parameters to these failure modes.

2. Develop an understanding of the sensitivity of FRANTIC-2's predictions to the various failure modes and test parameters that can be modeled. Use these results to suggest simplifying assumptions which could be used to derive input without impacting the predictions of the code.

3. Analyze several reactor systems using FRANTIC-2 as one of the tools and derive methods of optimizing component test and maintenance schedules to minimize system unavailability. Trade-offs available to the operator will be identified as well as their impact on system unavailability.

Investigators: Professor N. Rasmussen, Mr. Andrew Dykes

Support: Brookhaven National Laboratories ($16,000).

Related Academic Subject:

22.38 Reliability Analysis Methods

Recent Publications:

None to date.

3.2.15 Reliability Analysis of the Control Rod Drive Scram System of the Vermont Yankee Nuclear Power Plant

This research uses the fault tree analysis method to estimate the unavailability of the control rod drive system (or generally called reactor protection system) of Vermont Yankee Nuclear Power Plant. The main structure of the fault tree in WASH-1400 is followed. Various common mode failures are identified and they are quantified by statistical method using all the operation experience data that are available and applicable. The computer code UNRAC is then used to analyze the fault tree.

The scram failure probability is estimated to be 1.77×10^{-5} per demand, with the 90% confidence interval between 3.4×10^{-6} per demand and 2.2×10^{-4} per demand. This result is conservative because, for cases where no failures have been observed, it is assumed that a failure will occur in the next dt. Though we believe, based upon our engineering knowledge of the system, that the scram failure probability should be substantially smaller than this estimated value, it is the best estimate we can get by the statistical method. More experience data are needed to demonstrate more accurately the failure probability of a highly redundant system like the reactor protection system if a purely statistical approach is used. However a careful study of various potential common mode failures mechanisms may give enough understanding so that reasonable estimates of the likelihood of common mode failures can be made in the absence of statistical data.

Investigators: Professor N. Rasmussen, Mr. Y.-H. Yang

Support: Yankee Atomic Company and self-supporting

Related Academic Subjects:

22.38 Reliability Analysis Methods

Recent References:

Y.-H. Yang, Reliability Analysis of the Control Rod Drive Scram System of the Vermont Yankee Nuclear Power Plant, MS and NE Thesis, MIT, Department of Nuclear Engineering, (May 1981).

3.2.16 Analyzing the Safety Impact of Containment Inerting at Vermont Yankee

This research analyzes the public risk-benefits of containment inerting, particularly for the Vermont Yankee plant. Occupational health risks will be examined as well. We will examine the technical alternatives to nitrogen inerting (e.g., controlled burning of hydrogen, etc.) that may reduce occupational hazards while ensuring the same degree of control over hypothetical hydrogen releases. This analysis should provide the basis upon which conclusions can be drawn concerning the value of containment inerting as a safety device.

Investigators: Professors N. Rasmussen, C. Heising-Goodman, Mr. J. Lepervanche-Valencia

Support: Yankee Atomic Company ($11,000).

Related Academic Subject:

22.38 Reliability Analysis Methods

Recent References:

C.D. Heising-Goodman and J. Lepervanche-Valencia, "An Evaluation of Containment Inerting and Air Dilution Systems as Methods for Post-Accident Hydrogen Control in BWRs" Nuclear Engineering and Design, 64, No. 3, (April 1981).

3.2.17 Extensions of the Modular Analysis of Fault Trees

In the Reactor Safety Study (WASH-1400), reduced fault trees were derived by eliminating those basic events which contribute to the top tree event only through minimal cut-sets of high order, say quadruple or quintuple event cut-sets. This reduction process has, however, never been automated.

After the basic development of PLOD, it was realized that this code is particularly suited as a tool for automatically deriving reduced fault trees since the following two criteria for cutting off portions of a tree were made available in the code:

(a) Modular events, rather than basic events, contributing to the top tree event only through minimal cut-sets of an order larger than a given N may be deleted.

(b) Once an upper limit has been chosen, the Vesely-Fussell modular importances calculated by PL-MOD can be used to further reduce the tree by cutting off modules whose importances are smaller than a pre-selected cut-off value.

Option (b) has been fully verified in the meantime and proved to be a valuable and sensitive tool for practical fault tree analysis. In order to take advantage of Option (a) the minimal cut-set information must be derived from the modules first. Efforts in this direction have shown that all cut-set information is contained in the modules. Thus, cut-sets of order 60 have been generated for special cases.

Given the efficient recursive computational procedure, the inclusion of a time-dependent tree analysis capability was thought to be justified. This has already led to the development of the extended version PL-MODT, which allows the determination of time-dependent point unavailabilities for a system comprising nonrepairable, repairable, tested and maintained components. PL-MODT has been sucessfully tested against the standard PREP and KITT package, as well as against the newly released FRANTIC code. The latter is considered very fast by present standards in evaluating a given system function and yet, PLODT is computationally more effective by both analyzing and evaluating the sample trees in a shorter time. The latest accomplishment with PL-MOD concerns the coupling of the steady-state version with a Monte Carlo package which enables the user to assign uncertainties to the input values for the failure rates and to propagate those to the top event. It is obvious that the modular concept is especially beneficial here to save computer time. This code, PL-MOD-MC, will be extended in the near future to time-dependent analysis.

In order to handle more effectively fault trees which include common cause failures, the following two capabilities will be incorporated into the PLOD code:

(a)   In its present version, PL-MOD can only handle sophisticated modular gates. In general, however, replicated gates may exist which do not represent a supercomponent event. Eliminating this restriction could significantly enhance the code's capabilities. At the same time, this comprises the first step towards an effective qualitative common cause failure analysis.

(b)   Similarly, PL-MOD allows the appearance of explicit symmetric K-out-of-n gates, only if the inputs to these gates are non-replicated components or supercomponent events. In order to be more general, symmetric gates will be allowed to operate an input event which are replicated elsewhere in the fault tree.

Besides the major efforts concerning common cause failure analysis, a program package was issued in 1979 which comprised PL-MOD, PL-MODT, and PL-MOD-MC.

Investigators: Professors N.C. Rasmussen, L. Wolf; Mr. M. Modarres

Support: Nuclear Regulatory Commission ($35,000)

Related Academic Subject:

    22.38 Reliability Analysis Methods

Recent References:

M. Modarres, Reliability Analysis of Complex Technical Systems Using the Fault Tree Modularization, Ph.D. Thesis, MIT, Nuclear Engineering Department (1980).

3.2.18   Test Interval Optimization of Nuclear Power Plant Safety Systems

Technical specifications call for the periodic testing of the majority of the engineered safety systems in nuclear reactor power plants. These systems are usually in a standby mode during normal operations of the plant. It is a well known fact that periodic testing of these systems and their components will substantially improve their availabilities per demand by detecting system failures whose existence would otherwise not have been revealed.

An interesting problem, especially for the utilities, is to determine the optimum test interval which minimizes the unavailability of standby engineered safety systems.

The purpose of this research was to study the effect of the diesel generator test interval upon the unavailability of an emergency power bus of a specific nuclear power plant.

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First, an assessment of failure rate data was performed with special consideration to diesel generators. This study indicated that overall more recent data still display the same trend as published in WASH-1400. In a second step, several published procedures for the selection of an optimum test interval for a single component system were reviewed. The various results were compared and a sensitivity study was performed for those procedures which were allowed to change certain parameters such as test efficiency. After these preliminary studies the whole emergency power system was analyzed because it was argued that the optimum test interval for the diesel generator should be determined such that the unavailability of the emergency power system becomes minimum. Unfortunately, no explicit formulas exist for complex systems. Therefore a code had to be used for the analysis of the fault tree and its evaluation. For the latter part the NRC code FRANTIC has been applied which evaluates time dependent and average unavailabilities for any system consisting of any arbitrary combinations of non-repairable components, monitored components and periodically tested components. During this research FRANTIC has been successfully coupled to the minimal cut set generator, BIT. This enables now even a nontrained person to perform probabilistic system analysis.

The results of this study clearly indicate the importance of the probabilistic methodology for the engineering decision process. At the same time the limitations of explicit analytic procedures became obvious.

Investigators: Professors L. Wolf, N.C. Rasmussen; Mr. R. Karimi.

Support: Boston Edison Co. under Energy Laboratory Electric Utility Program

Recent References:

R. Karimi, Qualitative and Quantitative Reliability Analysis of Safety Systems, ScD Thesis, MIT, Department of Nuclear Engineering. (May 1980).

3.2.19 Common-Cause Analysis: A Review and Extension of Existing Methods

The research consists of developing a quantification method for common-cause failures and updating existing qualitative common-cause analysis codes with this method. Three codes are being tested and compared for their efficiency: COMCAN-II (EG&G) BACFIRE-II (Fussell of U. of Tenn.), and MOCUS-BACFIRE (developed by Vesely and Fussell; combined at MIT). So far, a user's manual for MOCUS-BACFIRE has been written, and the code has been tested on several reactor systems. Work is continuing to compare the three codes, and extend one of them for quantitative analysis.

Investigators: Professors N.C. Rasmussen, C. Heising-Goodman, Messrs. C. Mak, P. Cavoulacos

Support: Electric Utility Program at MIT ($107,000 until January 1983)

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Related Academic Subjects:

    22.38   Reliability Analysis
    22.40   Advanced Reliability Analysis

Recent References:

C. Mak, User's Manual for MOCUS-BACFIRE, MIT (March 1981).

C. Heising, C. Mak, P. Cavoulacos, and M. Modarres, "Application and Extension of the MOCUS-BACFIRE Common Cause Analysis Code to Reactor Safety Systems", submitted to American Nuclear Society Topical Meeting on Probabilistic Risk Assessment, Long Island, NY (September 1981).

3.2.20 Modifications to the Meltdown Accident Response Characteristics Code (MARCH): Modes of Vessel Failure and Melt-Concrete Interactions

This research extends the engineering models used in the MARCH code for reactor vessel failure during a meltdown accident in a LWR, and the subsequent melt-concrete interactions as the melt continues through the concrete basemat. This work is funded by the Electric Power Research Institute as part of its larger effort to improve the MARCH code. The work is expected to last approximately one year. The field of degraded core analysis is expected to expand in the department over the next few years.

Investigators: Professors M. Kazimi, C. Heising-Goodman, G. Brown.

Support: Electric Power Research Institute ($75,000 until July 1982).

Related Academic Subjects:

    22.311   Engineering Principles for Energy Engineers
    22.312   Engineering of Nuclear Reactors
    22.313   Advanced Engineering of Nuclear Reactors
    22.38   Reliability Analysis
    22.40   Advanced Reliability Analysis

Recent References:

None to date.

3.2.21 Generic Nuclear Safety Issues: Methods for Analysis

During the past year, a study was completed for the Nuclear Safety Analysis Center (NSAC) related to methods of analysis for generic nuclear safety issues. The problems analyzed include

    (i)   anticipated transient without scram (ATWS) frequency estimates;

    (ii)   containment inerting of BWRs -- cost-risk-benefit analysis;

(iii)   hydrogen control in PWR containments -- methods for calculating
        pressure response due to burn or explosion, and comparison of
        control methods; and

(iv)   estimate of core-melt frequency after TMI.

Ongoing extensions of the work include an analysis of filtered-vented
containment strategies for large, dry PWR containments. A PhD dissertation
is being written on this topic. Another outgrowth of this project is a hand-
book on reliability methods for nuclear engineers. This handbook is also
undergoing additional development. Another followup is an engineer's thesis
related to reactor protection system (RPS) availability.

Investigators: Professors N.C. Rasmussen, C. Heising-Goodman, Messrs. J.
Lepervanche-Valencia, A. Dykes, R. Schechtman, Y.H. Yang, Ms. E.S. Gordon.

Support: Electric Power Research Institute (1/1/79-1/1/80; $75,000)

Related Academic Subjects:

    22.311 Engineering Principles for Energy Engineers
    22.312 Engineering of Nuclear Reactors
    22.32   Nuclear Power Reactors
    22.38   Reliability Analysis
    22.40   Advanced Reliability Analysis

Recent References:

C.D. Heising, Generic Nuclear Safety Issues: Methods of Analysis,
MIT-NE-241, Final Report, NSAC, (September 1980).

C.D. Heising-Goodman, J. Lepervanche-Valencia, "A Probabilistic Assessment of
Containment Inerting in BWRs", IAEA-CN-39/212, International Conference on
Current Nuclear Plant Safety Issues, Stockholm, Sweden (October 1980).

C.D. Heising-Goodman, J. Lepervanche-Valencia, "An Evaluation of Containment
Inerting and Air Dilution Systems as Methods for Post-Accident Hydrogen
Control in BWRs", Nuc. Eng. and Design (1981).

J. Lepervanche-Valencia, Safety Analysis of Containment Inerting in Boiling
Water Reactors, Engineer's Thesis, MIT, Department of Nuclear Engineering
(June 1980).

A. Dykes, C. Heising, "Applying Bayes Theorem to Update the Estimate of the
Reactor Core Melt Frequency After TMI", submitted to ANS Conference on
Probabilistic Risk Assessment, Long Island, NY (September 1981).

R. Schechtman, C. Heising, "Analysis of Filtered Venting as a Mitigation
Safety Feature in PWRs with Large, Dry Containments", submitted to ANS
Conference on Probabilistic Risk Assessment, Long Island, NY (September
1981).

3.2.22 Emergency Planning of Reactor Accidents

The research consists of determining methods for including "real-time" considerations in reactor accident emergency planning. The work is funded by the Nuclear Regulatory Commission (NRC) through the Fuel Cycle Risk Analysis group at Sandia National Laboratory. Work is being done on four tasks:

1. Review current status of existing emergency response plans planning guidelines and organizations.

2. Determine information that will be available to an operator during several "key" potential accident sequences, and when that information will be available.

3. Formulate guidelines for incorporating plant status information into offsite emergency response plans

4. Evaluate methods in terms of potential consequence mitigation using CRAC-2 consequence model.

This work is expected to significantly impact on the NRC guidelines for emergency planning, and is a research area of potential growth in the department.

Investigators: Professor C. Heising-Goodman, Messrs. P. Burke, S. Dinsmore.

Support: U.S. NRC through Sandia National Laboratory ($50,000 through April 1982).

Related Academic Subjects:

22.37 Environmental Impact of Electric Power Production
22.38 Reliability Analysis
22.40 Advanced Reliability Analysis

Recent References:

R. Burke, C. Heising, and D. Aldrich, "Methods for Incorporating Real-Time Considerations in the Emergency Planning for Reactor Accidents", submitted to American Nuclear Society Meeting on Probabilistic Risk Assessment, Long Island, NY, (September 1981).

3.2.23 Structural Mechanics

Nuclear power plants contain components requiring applications of a wide variety of structural mechanics analysis techniques. These range from fusion reactor first wall design (untested, high radiation field, high magnetic field, within view of a plasma at hundreds of millions of degrees) to stress analysis of tubes in heat exchangers (widely used, vital from a plant reliability standpoint, no radiation field).

Investigators: Professor J.E. Meyer, R.O. Racana, and W.T. Loh.

<u>Support</u>: Partial funding from other research topics (e.g., Sections. 3.1.3, Fast Reactor Physics and 3.3.11 The Development of Advanced Primary First Wall Alloys).

<u>Related Academic Subjects</u>:

      22.314J   Structural Mechanics in Nuclear Power Technology
      22.43   Numerical Methods in Reactor Engineering Analysis
      22.75J   Radiation Effects to Reactor Structural Materials

<u>Recent References</u>:

R.O. Racana, <u>Stress Analysis Techniques in Fusion Reactors</u>, PhD Thesis, MIT, Department of Nuclear Engineering, (January 1980).

W.T. Loh, <u>Duct Wall Dilation, Special Problem</u>, MIT, Department of Nuclear Engineering, (October 1980).

3.2.24 <u>Analysis of Forces on Core Structures During a Loss-of-Coolant Accident</u>

Safety calculations must be performed to estimate the amount of damage to a nuclear reactor core if it were subjected to a hypothetical loss-of-coolant accident (LOCA). One possible cause for damage occurs from the forces imposed from the coolant on the core and associated structure during the very early (blowdown) stage of a LOCA. Work in this area is aimed at determining the state-of-the-art in performing such calculations and in assessing various assumptions employed. The project has not been continued beyond this point.

<u>Investigators</u>: Professor J.E. Meyer, Messrs. D.P. Griggs, R.A. Heft, R.B. Vilim and C.H. Wang.

<u>Support</u>: Several electric utilities under the MIT Energy Laboratory Electric Utility Program.

<u>Related Academic Subjects</u>:

      22.312   Engineering of Nuclear Reactors
      22.314J   Structural Mechanics in Nuclear Power Technology

<u>References</u>:

D.P. Griggs, R.B. Vilim, C.H. Wang and J.E. Meyer, <u>Analysis of Forces on Core Structures During a Loss-of-Coolant Accident</u>, MIT Energy Laboratory Report No. MIT-EL80-029, (August 1980).

3.3 <u>Nuclear Materials and Radiation Effects</u>

The nuclear materials program has four major objectives: (1) to provide students in the Department with sufficient background in the principles of physical metallurgy and physical ceramics to incorporate a fuller con-

sideration of reactor structural and fuel materials in their thesis programs;
(2) to advance reactor materials technology in the areas of materials selec-
tion, component design, irradiation behavior modeling, safeguards analysis,
quality assurance, and reliability assessment; (3) to conduct instructional
and research programs into both the fundamental nature of radiation effects
to crystalline solids and the interrelationships between radiation-induced
structural problems on an interdepartmental and interdisciplinary manner in
the general fields of energy conversion, energy transmission, and environ-
mental technology as related to power production.

3.3.1 Subjects of Instruction

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

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

22.71J: Physical Metallurgy Principles for Engineers, is the intro-
ductory course in this sequence of study and is intended for students who did
their undergraduate work in engineering and science fields which did not pro-
vide formal instruction in metallurgy or materials science. This course
emphasizes the following topics: crystallography and microstructure; defor-
mation mechanisms and the relationship of mechanical properties to
metallurgical structure; thermodynamics and rate processes to include phase
equilibria, recovery and transformation mechanism, diffusion, corrosion, and
oxidation; mechanical property testing methods, strengthening mechanisms,
fracture mechanics, fatigue and creep. 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 including

temperature and stress distributions, the mechanism of fuel restructuring, creep, swelling, fission gas release, energy and mass transport, and fuel-clad interactions are discussed in detail.

22.73J: Radiation Effects in Crystalline Solids, is designed for graduate students of nuclear engineering, materials science and physics desiring a detailed background in the physics of radiation damage and the characteristics of crystal defects and defect interactions. Topics include the collision theory of displacement damage; displacement processes, energy dissipation, and crystallographic effects. Evolution of damage state; primary damage state, recovery of damage related to mobility and structure of crystalline imperfection, defect configurations. Rate processes enhanced by radiation; solute redistribution, phase transformaions, gas bubbles, void swelling and phase stability. Mechnaical properties; deformation resistance, irradiation creep, irradiation growth and fracture.

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

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

3.3.2 The Anisotropic Mechanical Behavior of Zirconium Alloys

An investigation is being made into the effect of crystallographic anisotropy on the mechanical behavior of zirconium alloys. The investigation is considering short time (creep) behavior. The experimental program is also looking at the effect of plastic strain on texture rotation in these alloys. The program will help develop a more thorough understanding of material behavior thus allowing more accurate modeling of the complex mechanical histories which occur in nuclear fuel applications.

Investigators: Professor R.M.N. Pelloux; Messrs. R. Ballinger, G. Alberthal, S.A. El Khider.

Support: Exxon Nuclear Company

Related Academic Subjects:

    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

Recent References:

E.-K. Si Ahmed, <u>Crystallite Orientation Analysis for Zircaloy Application of Three Dimensional Representation of Textures</u>, MS and Engineer Thesis, MIT, Department of Nuclear Engineering, (February 1981).

3.3.3   Hydrogen Embrittlement and Corroison Fatigue of Nickel-Base Alloys for Nuclear Steam Generator Applications

An investigation is being conducted to investigate the effect of hydrogen and other environmental factors on the cracking susceptibility of Inconel-600, X-750 at room temperature and at nuclear steam generator operating conditions. This investigation will aid in the understanding of several phenomena, including denting, and stress corrosion cracking, which have led to a loss in availability of many nuclear electric generating stations.

Investigators: Professors R.M. Latanision, R.M.N. Pelloux; Messrs. R. Ballinger, W.C. Moshier and Ms. K. Siedein.

Support: Electric Power Research Institute

Related Academic Subjects:

    22.71J   Physical Metallurgy Principles for Engineers
    3.54   Corrosion -- The Environmental Degradation of Materials

Recent References:

R.M. Latanision, R.M.N. Pelloux, R. Ballinger, W. Moshier, "The Role of Uncertainty in Measurement of Crack Lengths in the Role of Compliance," Presented at the <u>IAEA Specialists Meeting on Subcritical Crack Growth</u>, Frieburg, W. Germany, (May 13-15, 1981).

3.3.4   Precipitation Mechanisms and Sequences in Rapidly Cooled Ni-Nb Alloys

Rapid cooling from the melt (splat cooling) is capable of producing highly non-equilibrium microstructures -- especially regarding solute supersaturation and crystal structure. Irradiation may push the system further into irreversibility, and in conjuction with rapid cooling may give phases and precipitation sequences never before observed. We have prepared amorphous and microcrystalline samples of 60-40 Ni-Nb and microcrystalline samples of 85-15 Ni-Nb which are being irradiation with 3 MeV Ni+ ions in the Argonne National Laboratory accelerator. The temperature (600°C), atomic

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displacement rate (10^{-3}, displacements/atom sec) and dose (20 displacement/atom) were chosen to optimize irradiation altered phase stability. The irradiated samples and samples reacted thermally will be studied by electron microscopy -- TEM and STEM -- in the CMSE facility to determine the nature and distribution of phases and determine rules for phase stabilities.

Investigators: Professor K.C. Russell; Messrs. R.S. Chernock, and B. Liebowitz

Support: National Science Foundation ($30,000/year).

Related Academic Subjects:

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

Recent References:

K.C. Russell and H.I. Aaronson, Editors of "Precipitation Processes in Solids", TMS-AIME, New York, (1979).

H.I. Aaronson, J.K. Lee and K.C. Russell, "Mechanisms of Diffusional Nucleation and Growth", in Precipitation Processes in Solids, edited by K.C. Russell and H.I. Aaronson, TMS-AIME, New York, (1979).

3.3.5 Defect Aggregation in Irradiated Metals

This is a combined theoretical and experimental study of defect aggregation in irradiated metals. A theoretical study is being conducted of the stabilities of incoherent precipitates under irradiation. Model systems correspond to TiC or Al_2O_3 in austenitic stainless steel. A modelling study is being made of void nucleation and growth under conditions of continuous helium generation, as in neutron irradiation. An experimental study is in progress on nucleation of graphite precipitates in irradiated undersaturated Fe-Ni-C solid solutions.

Investigators: Professor K.C. Russell, Dr. H. Frost, Ms. S. Best, Messrs. C. Parker and C. Tong.

Support: National Science Foundation ($75,000/year).

Related Academic Subjects:

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

Recent References:

S.I. Maydet and K.C. Russell, "Numerical Simulation of Void Nucleation in Irradiated Metals", J. Nuclear Mats. 82, pp. 271-285 (1979).

K.C. Russell, "The Theory of Phase Stability Under Irradiation", J. Nuclear Mats. 83, pp. 176-185 (1979).

S.A. Seyyedi, M. Hadji-Mirzai, and K.C. Russell, "Void Nucleation at Hetero-
geneities," in Proceedings of International Conference on Irradiation
Behaviour of Metallic Materials for Fast Reactor Core Components, Gif Sur
Yvette, France, VD pp. 101-106 (1979).

3.3.6   Embrittlement in Ferritic Stainless Steels

Research is being conducted to understand the extend and the nature of
embrittlement due to phase precipitation in ferritic stainless steels which
are increasingly used in nuclear applications. Phase diagram at low tem-
perature is determined using diffusion couples of Fe and Cr analyzed by Auger
electron spectroscopy. Effects of ion irradiation which causes enhanced
diffusion and solute redistribution are studied by electron microscopy.
Microstructure and mechanical properties of rapidly solidified alloys are
also investigated to explore the possible benefit of toughening derived from
this technique.

Investigators: Professor I-W. Chen, Messrs. C-H Yeh and B. Lou.

Support: National Science Foundation

Related Academic Subjects:

    22.71J   Physical Metallurgy Principles for Engineers
    22.73J   Radiation Effects in Crystalline Solids

Recent References:

None to date.

3.3.7   Failure Mechnisms of Fiber-Epoxy Composite Materials for Magnet Applications

An investigation is being conducted to determine the failure mechanisms
of fiber-epoxy composite materials which in thin sheets are proposed for
insulator applications in fusion magnets. Compression fatigue tests were
carried out on irradiated and unirradiated samples followed by fractography
examination. It was found that failure is controlled by the plastic flow of
the epoxy matrix which, under compression with interfacial friction, is
effectively suppressed to give rise to the outstanding performance of the
components. These observations are in accord with theoretical calculations of
the elastic-plastic response using model configurations.

Investigators: Professor I-W. Chen, Dr. H. Becker, and Mr. C. Tong.

Support: U. S. Department of Energy

Related Academic Subject:

    22.71J   Physical Metallurgy Principles for Engineers

Recent References:

None to date.

3.3.8   Intergranular Cavitation in Creeping Alloys

Growth of cavities on grain boundaries in the presence of surface diffusion, grain-boundary diffusion, and creep in the surrounding matrix is investigated. A growth law which incorporates all the above effects can now be analytically stated using a simple model which handles the coupling by the boundary-layer technique. The failure criterion obtained following this development compares favorably with experimental results and should be directly applicable in front of a creep crack. Attention is now directed to the consequence of inhomogeneous cavitation which is typical for structural components in long-term service of power plants. The technique developed here should be also useful for other physical phenomena such as irradiation creep and fuel swelling.

Investigators: Professors I-W. Chen, A.S. Argon

Support: U.S. Department of Energy

Related Academic Subjects:

    22.71J   Physical Metallurgy Principles for Engineers
    22.73J   Radiation Effects in Crystalline Solids

Recent References:

None to date

3.3.9. Experimental and Theoretical Studies of Radiation Damage In Future Fusion Reactors

The fast neutron radiation fields in future controlled thermonuclear reactors (CTR's) will adversely affect the mechanical properties of first wall structural material. Development of the required understanding of damage effects and a design data base are needed prior to the design of the experimental power and demonstration power reactors (EPR and DPR). Facilities used to test materials for fusion reactor applications are inadequate, since the gas production associated with displacement damage in the CTR cannot readily be simulated in a fast fission reactor, a need has developed for CTR damage simulation. Our research effort in this project has been directed (1) toward the development of simulation techniques for synergistic helium and damage production and (2) toward improving the understanding of the effects of near surface damage and gas implantation upon the mechanical properties of the first wall of fusion reactors. In the first task area, techniques are under development for homogeneous alloy doping with ^{10}B, to permit simultaneous generation of helium and displacement damage during reactor irradiations. In the second task area an in-core fatigue cracking experiment is under design and construction. This experiment is expected to simulate much of the environment expected at the fusion reactor

first wall. Surface bombardment, bulk irradiation damage and strain cycling are all incorporated into this experiment.

Investigators: Professors O.K. Harling, I-W. Chen, A.S. Argon; Drs. N. Kanani, M. Lee, H. Frost; Messrs. H. Andresen, G. Kohse, S. DiPietro. O. Boydas

Support: U.S. Department of Energy

Related Academic Subjects:

    22.612   Plasmas and Controlled Fusion
    22.73.J Radiation Effects in Crystalline Solids
    22.75J   Radiation Effects in Reactor Structural Materials

Recent References:

S.E. Best, Characterization of the MIT Research Reactor for Fusion Reactor Related Studies, S.M. Thesis, MIT, Department of Nuclear Engineering (February 1979).

S.E. Best, A. Fadaii and O.K. Harling, "Initial Results Using Splat Cooling in the Development of Boron Doping for the Simulation of Fusion Reactor Helium Embrittlement", First Topical Meeting on Fusion Reactor Materials, Bal Harbour, Fla. January 29-31, 1979), invited paper; J. Nucl. Mats. 85 & 86 pp. 835-838 (1979).

H. Andresen and O.K. Harling, "A New Approach to Simulation of Helium and Simultaneous Damage Production in Fusion Reactors - In Reactor Tritium Trick", First Topical Meeting on Fusion Reactor Materials, Bal Harbour, Fla. (January 29-31, 1979), invited paper; J. Nucl. Mats. 85 & 86 pp. 485-489 (1979).

E.G. Daxon, R. Pirek, M. Saiedfar, S. Seyeddi, K.C. Russell and O.K. Harling, "Low Fluence Radiation Damage and Helium Effects on the Microstructure and Mechanical Properties of Type 316 Stainless Steel", First Topical Meeting on Fusion Reactor Materials, Bal Harbour, Fla. (January 31, 1979), invited paper.

S. Best, G. Dansfield, H. Frost, J. Megusar, O. Harling and K. Russell, "Boron Doping of Stainless Steel by Rapid Quenching", DAFS Quarterly Report, USDOE (January-March 1979).

M.S. Saiedfar and K.C. Russell, "Oxide Dispersoid in Irradiated Alloys", DAFS Quarterly Report, USDOE (April-June 1979).

K.C. Russell, "Void Swelling in Irradiated Metals", DAFS Quarterly Report, USDOE (April-June 1979).

S. Best, G. Dansfield, H. Frost, J. Megusar, O. Harling and K. Russell, "Boron Doping of Stainless Steel by Rapid Quenching", DAFS Quarterly Report, USDOE (April-June 1979).

O.K. Harling, "Effects of Near Surface Damage and Helium on the Performance of the First Wall", DAFS Quarterly Report, USDOE (April-June 1979).

M.V. Tsakonas, The Influence of Boron Doping and the Effect of Specimen Size on the Mechanical Properties of Austenitic Stainless Steel, SB Thesis, MIT, Department of Nuclear Engineering (September 1979).

O.K. Harling, "Effects of Near Surface Damage and Helium on the Performance of the First Wall", DAFS Quarterly Report, USDOE (January-March 1980).

K.C. Russell, "Phase Stability Under Irradiation", DAFS Quarterly Report, USDOE (January-March 1980).

L. Arnberg and O. Harling, "Characterization of Rapidly Solidified Boron Doped Stainless Steel for Synergistic Helium Production", DAFS Quarterly Report, USDOE (January-March 1980).

H. Andresen (MIT/Hahn-Meitner-Institute) and O.K. Harling, "Fusion Reactor First-Wall Performance Under Ion Bombardment and Cyclic Stresses", ANS Annual Meeting, Las Vegas, Nevada (June 8-12, 1980), invited paper.

G. Kohse, S.G. DiPietro and O. Harling, "Effects of Near Surface Damage and Helium on the Performance of the First Wall", DAFS Quarterly Report, USDOE (January-March 1981).

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

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

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

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

Related Academic Subjects:

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

3.3.11 The Development of Advanced Primary First Wall Alloys

The severe environment of future fusion reactors is expected to drastically limit the lifetime of the first wall structures if currently available

materials are used in reactor construction. In this recently funded research effort a broad ranging interdisciplinary approach is being applied to the development of improved structural alloys for the first walls of fusion reactors. The approach used in this project includes:

1. a determination of the structural alloy requirements based on an analysis of fusion reactor design,

2. production of carefully chosen test lots of alloy by rapid solidification from the melt,

3. development of critical mechanical property tests designed to limit the required test matrix,

4. mechancial property testing of unirradiated material,

5. modeling of mechanical behavior, and

6. irradiation, testing, and modeling of the best candidate alloys.

Investigators: Professors O.K. Harling, N.J. Grant, A.S. Argon, J.E. Meyer, and J.B. Vander Sande; Drs. J. Megusar, L. Arnberg, N. Kanani, M. Lee and D. Imeson; Messrs. A. Adegbulugbe, K. Genssler, M. Manahan, E. Testart and G.P. Yu.

Support: U.S. Department of Energy

Related Academic Subjects:

    22.612   Plasmas and Controlled Fusion
    22.73J   Radiation Effects in Crystalline Solids
    22.75J   Radiation Effects in Reactor Structural Materials

Recent Reference:

J.E. Meyer and A.O. Adegbulugbe, Functional Requirements for Fusion Reactor First Walls - A Status Report, Report No. MITNRL-002, prepared for USDOE, (March 1980).

K. Gennsler and N.J. Grant, "Properties of Rapidly Solidified Nuclear Grade 316 Stainless Steel," ADIP Quarterly Report, USDOE, (June 30, 1980).

J. Megusar, L. Arnberg, J.B. Vander Sande and N.J. Grant, "Optimization of Structure and Properties of Prime Candidate Alloy (PCA) by Rapid Solidification", ADIP Quarterly Report, USDOE (June 30, 1980); to be published in J. Nucl. Mats.

H.J. Frost and K.C. Russell, "Particle Stability with Recoil Resolution", submitted to Acta Metall., (March 1980).

G.-P. Yu, Relationship of Material Properties to the Design of a Fusion Reactor First Wall, ScD Thesis, MIT, Department of Nuclear Engineering, (May 1981).

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A.O. Adegbulugbe, <u>Structural Design Limits for Fusion First Walls</u>, ScD Thesis, MIT, Department of Nuclear Engineering, (May 1981).

3.3.12 Light Water Reactor Fuel Performance Analysis

The fuel rods in light water reactors must perform to permit reasonable time between refuelings, rapid enough rates for plant power changes to fit utility dispatching requirements, and sufficiently low failure rates to retain low fission product activity levels. Techniques to be used in fuel performance analysis require models for material behavior in a high temperature and radiation field environment; model evaluation by comparison to experimental data; and approaches to be used in performing design/operations calculations. Recent efforts have included:

a) Establish design/operating criteria for light water reactor fuel rods with stainless steel clad;

b) Determine the effect of fuel/clad friction in establishing proper boundary conditions for detailed analysis;

c) Obtain methods to combine effects of heat transfer and thermal expansion during fuel rod transients;

d) Review techniques for adopting clad anisotropy in creep treatment of Zircaloy clad.

<u>Investigators</u>: Professor J.E. Meyer; Dr. S. Harriague; Messrs. J.S. Marks and J.E. Rivera.

<u>Support</u>: Partial support from utilities under the MIT Energy Laboratory Electric Utility Program.

<u>Related Academic Subjects</u>:

> 22.314J Structural Mechanics in Nuclear Power Technology
> 22.43   Numerical Methods in Reactor Engineering Analysis
> 22.72J   Nuclear Fuels
> 22.75J   Radiation Effects to Reactor Structural Materials

<u>Recent References</u>:

J.E. Rivera and J.E. Meyer, <u>Stainless Steel Clad for Light Water Reactor Fuels</u>, MIT Energy Laboratory Report No. MIT-EL80-021, (July 1980).

J.S. Marks, <u>Computational Methods for Thermal and Mechanical Analysis of Nuclear Reactor Fuel Rod Transients</u>, MS Thesis, MIT, Department of Nuclear Engineering and BS Thesis, MIT, Department of Chemical Engineering (July 1980).

J.E. Rivera, <u>Performance of Light Water Reactor Fuel Rods During Plant Power Changes</u>, Engineer Thesis, MIT, Department of Nuclear Engineering, (January 1981).

3.4 Nuclear Chemical Technology

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

3.4.1 Subject of Instruction

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

3.4.2 Extraction of Uranium from Seawater

Based upon results obtained in a project supported by seed money from the MIT Energy Laboratory, DOE funding was obtained for a more ambitious evaluation of the prospects of uranium recovery from seawater. The Rohm and Haas Corporation is collaborating in this research, in the role of subcontractor, providing several batches of advanced ion exchange resins for testing by MIT at the Woods Hole Oceanographic Institute.

As part of this investigation an international conference on uranium from seawater was held at MIT in December, 1980. Over forty investigators from six of the major national programs participated.

The MIT work involves evaluation of overall system designs in addition to performance testing of candidate sorber materials. Both actively-pumped and passive current-intercepter concepts are under consideration. Delayed neutron and fission track each counting following irradiation in the MIT Reactor are being evaluated to provide the sensitive uranium assay techniques needed. Small experimental facilities have beeen assembled to make hydraulic measurements of key parameters characterizing the sorber beds under study and to perform uranium uptake test using natural seawater. Fianlly, a computer program has been developed to permit overall economic optimization of the entire recovery process.

Investigators: Professor M.J. Driscoll and Dr. F.R. Best; Mses. C.K. Nitta and E.A. Thompson, Messrs. L.G. Riniker, J.L. Whaley, C.T. Graves, R.L. Coxe, D.C. Surber and D.A. Medek.

Support: U.S. Department of Energy via MIT Energy Laboratory ($139,000 in FY- 1981).

Related Academic Subjects:

22.76J   Introduction to Nuclear Chemical Engineering

Recent References:

F.R. Best and M.J. Driscoll, Prospects for Uranium Recovery form Seawater, MIT-EL-80-001, (January 1980).

F.R. Best and M.J. Driscoll, Proceedings of a Topical Meeting on the Recovery of Uranium from Seawater, MIT-EL-80-031, (includes two MIT papers), (December 1980).

F.R. Best and M.J. Driscoll :The Prospects for Uranium Recovery from Seawater", Trans. AM. Nucl. Soc., 34   (June 1980).

F.R. Best and M.J. Driscoll, "Uranium from Seawater: An update on World-wide Progress", Trans. Am. Nucl. Soc., 38, (June 1981).

F.R.Best , M.J. Driscoll, C. Nitta, "Recovery of Uranium from Seawater" in AIChE Conference 74th Annual Meeting, New Orleans, Louisiana, (November 8-12, 1981).

3.5   MIT Reactor

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

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

The modification makes use of all of the existing reactor components except the reactor tank, fuel elements, control rods and drives and top

shield plugs. Parts of the former reactor that remain include the graphite reflector, thermal shield, biological shield, beam ports, heat exchangers, pumps, cooling towers and containment building.

Engineering studies and experiments on aspects of the new core have provided many opportunities for student research and participation and give unique practical training. Topics investigated by students include reactor physics calculations, neutron transport measurements in a mock-up of the new beam port and reflector configuration, fluid flow measurements on a hydraulic mock-up, heat transfer measurement and theoretical calculations on finned plates, safety analysis and fuel management studies, and construction, start up and checkout operation of the modified reactor. Recent studies are in the area of experimental-facility design, fuel management, advanced control systems and in the use of waste heat from the reactor for heating a significant part of the MIT building complex.

Investigators: Professors M.J. Driscoll, S-H. Chen, I-W. Chen, F. Frey, O.K. Harling, D.D. Lanning, N.E. Todreas, G.L. Brownell, A.S. Argon, C.G. Shull; Drs. M. Janghorbani, G. Ting, B. Ila, N. Istfan, A. Nahapetian; Messrs. L. Clark, Jr., H. Andresen, M. Manahan, J. Bernard, W. Fecych, K. Kwok, G. Kohse, O. Boydass S. DiPietro, M. Izenson, J. Kirsch, C.Y. Chen, L. Gulen, W. Pergram, G. Ray, M. Roden, T. Sando, H. Stockman, M. Christensen, P. Sirichakwal, T. Takala, D. Atwood, J. Arthur, T. Beatty; Mses. M. Ashtari, R. Hickey, A. Sundaresan, P. Sirichakwal.

Support: MIT Reactor Depreciation Account and Reactor Operating Research Account

Related Academic Subjects:

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

Recent References: (reactor engineering and reactor physics only):

G.D. Dooley, The Application of Three Dimensional Reactor Physics Calculations Utilizing Synthesis Techniques, MS Thesis, MIT, Department of Nuclear Engineering (1979).

A.O. Adegbulugbe, Radioactive Waste Handling and Shipment for MITR-II, MS Thesis, MIT, Department of Nuclear Engineering (1979).

J.A. Bernard, Jr., MITR-II Fuel Management, Core Depletion, and Analysis: Codes Developed for the Diffusion Theory Program Citation, MS Thesis, MIT, Department of Nuclear Engineering (1979).

NOTE: References shown here emphasize reactor physics and engineering and do not include a large number of papers, reports and theses in research areas such as beam tube research in physics and chemistry, trace analysis and

radiochemistry studies in nutrition, geochemistry, nuclear medicine, etc.
Much more comprehensive information about research activities at the MITR-II
is contained in references such as MITNRL-001, Report of Educational and
Research Activities for Academic Years 1975-76, 1976-77, 1977-1978.

3.6 Applied Radiation Physics

This program is concerned with the utilization of nuclear and atomic
radiations in applications which are not specifically connected with the
technology of nuclear power production. Four faculty members are presently
engaged in teaching applied nuclear physics, radiation interactions, and
biological effects of radiations. Research activities are primarily in the
areas of materials science and health science.

3.6.1 Subjects of Instruction

The following subjects of instruction are offered:

22:02: Introduction to Applied Nuclear Physics, is an introductory sub-
ject to nuclear physics and neutron physics with emphasis on those aspects of
the subject which are applied in nuclear engineering. Topics covered include
elementary results of quantum theory and special relativity, detection of
atomic and nuclear particles, properties of atomic nuclei: isotopes and iso-
topic masses; nuclear reactions; natural and artifically induced radio-
activity; cross sections for nuclear reactions; alpha-, beta- and
gamma-decay; nuclear models; shell-models; liquid-drop model; nuclear fission
properties of fission and their relation to the feasibility of nuclear power
and to its problems; slowing down and diffusion of neutrons; neutron induced
chain reactions.

22.04: Radiation Effects and Uses, deals with 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 measure-
ments at the MIT Reactor.

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

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

22.112: **Nuclear Physics for Engineers II**, is a continuation of 22.211 with emphasis on detailed studies of nuclear reactions, electromagnetic and charged particle interactions. Cross section calculations using optical models. Neutron thermalization, inelastic scattering and radiative capture. Charged particle emissions, photonuclear reactions. Fusion reactions. Availability and accuracy of current nuclear data files.

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

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

22.55J: **Biological and Medical Applications of Radiation and Radioisotopes I**, covers the principles of radiation production and interactions. Radiation dosimetry with emphasis on applications and health hazards. Shielding of beta, gamma and neutron radiation from isotope and machine sources. Detection and spectroscopy of beta, gamma, and neutron radiation. Neutron activation analysis. Production of radioisotopes and radiopharmaceuticals. Principles of nuclear medicine.

22.56J: **Principles of Medical Imaging**, is a subject which deals with the principles of medical imaging including X-ray, nuclear medicine, ultrasound, NMR, emission and transmission-computed tomography, and other modalities. Fundamentals of image formation, physiology of image perception, physics of radiation and ultrasound interaction and detection, and physics of NMR, medical applications, biological hazards and cost-benefit analysis of imaging modalities are covered.

3.6.2 **Neutron Spectrometry and Molecular Dynamics in Solids and Fluids**

Density fluctuations occur in all forms of matter because of thermal motions of the atoms and molecules. Since these fluctuations result in space- and time-dependent inhomogeneities in the system, they can be observed directly by thermal-neutron scattering. In this way one has a powerful tech-

nique for studying molecular dynamics on a microscopic level (frequencies and wavelengths of the order of 10^{15}Hz and one Angstron).

A three-axis crystal spectrometer has been constructed at the MIT reactor and put into operation in 1971. The principle study conducted during the period, 1971-1976, was a series of measurements of incoherent scattering in hydrogen gases pressurized up to 200 atmospheres. The density dependence of the self-diffusion coefficient was studied through the observed quasielastic line width, and the data confirmed the recent prediction (based on computer molecular dynamics simulation results) of correlation effects in dense fluids. The wave number dependence of the observed line width clearly showed deviations from behavior characteristics of hydrodynamic fluctuations. Such effects have been analyzed using kinetic theory as well as results obtained from computer simulation experiments (see Section 3.6.4).

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

The program described above can be resolved into two major branches -- the experimental (acquisition of neutron-scattering spectra) and the computational (generation of calculated spectra and refinement of potential functions). On the experimental side, we have just completed a neutron-scattering spectrometer at the MIT reactor. This spectrometer directs a beam of monochromatic neutrons (2.1 - 107 meV) onto the sample. An array of graphite crystals in the analyzer focuses onto the detectors all neutrons up- or down-scattered to an energy of 2.4 meV (the instrument is thus of the variable-incident-energy, fixed-final-energy design). Computationally, we have evolved a rather complex program (LATDYN) which carries out lattice dynamics calculations within the frame-work of Born-von Karman theory. A number of less ambitious computer codes have been used to study individual molecules and single-chain polymers.

Investigators: Professor S.-H. Chen, Dr. C.V. Berney, Mr. Z. Djorgevic.

Support: National Science Foundation

Related Academic Subject:

   22.51   Radiation Interactions and Applications

Recent References:

C.V. Berney and S. Yip, "Inelastic Neutron Scattering Spectroscopy", Chapter 3.4 in Volume of Polymer Physics (R.A. Fava, ed.) in the series Methods of Experimental Physics (L. Marton, editor-in-chief), Academic Press, New York, (1980).

Z.B. Djordjevic and S.H. Chen, "Regularity of the Stage Sequence in Graphite Intercalation Compounds", in Synthetic Metals, 2, No. 17 (1980).

3.6.3 Kinetic Theory of Dense Fluids and Its Experimental Tests

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

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

The kinetic equation conventionally used to discuss transport properties of dense gases is the Boltzmann-Enskog equation. This equation is characterized by a collision operator which treats molecular interactions as uncorrelated binary collisions. Recent studies of correlated collision processes have led to the derivation of a generalized transport equation which is believed to be a significant improvement beyond the level of the Enskog-Boltzmann equation. The new equation is still tractable computationally because it involves only binary collisions, but correlations are now included so that the theory is qualitatively correct even at high densities.

The most direct tests of kinetic theories in describing fluctuations at molecular wavelengths and frequencies are thermal neutron inelastic scattering measurements and computer molecular dynamics simulations. In this project explicit solutions of the generalized kinetic equation will be obtained and applied to the analysis of neutron and computer data, some of which will be generated in-house.

Investigators: Professors S.-H. Chen and S. Yip; Mr. K. Touqan.

Related Academic Subjects:

    22.51 Radiation Interactions and Applications

Recent References:

S. Ranganathan and S. Yip, "Space-Time Memory Functions of Simple Kinetic Models", _Physica_, 100A, P.127, (1980).

J.-P. Boon and S. Yip, _Molecular Hydrodynamics_, McGraw-Hill, New York, (1980).

L. Letamendia, J.P. Chabrat, G. Nouchi, J. Rouch, C. Vaucamps and S.H. Chen, "Light Scattering Studies of Moderately Dense Gas Mixtures I. Hydrodynamic Regime", _The Physical Review_ A, in press.

L. Letamendia, P. Jourbert, J.P. Chabrat, J. Rouch, C. Vaucamps, C. Boley, S. Yip and S.H. Chen, "Light Scattering Studies of Moderately Dense Gases II. Non-Hydrodynamic Regime", _The Physical Review_ A, submitted.

L. Letamendia, S.H. Chen, J.P. Chabrat, J. Rouch and C. Vaucamps", Dynamics of Two-Component Gas Mixtures: Effects of Mode Couplings in Rayleigh-Brillouin Spectra", paper presented at the _International Conference on Thermophysical Properties_, June 15-19, (1981), to appear in the Proceedings.

W. Goetze, E. Leutheusser, S. Yip, "Dynamical Theory of Diffusion and Localization in a Random Static Field", _The Physical Review_, A 23, p. 2634, (1981).

W. Goetze, E. Leutheusser, S. Yip, "Correlation Functions of the Hard Sphere Lorentz Model", _The Physical Review_ A, in press.

W. Goetze, E. Leutheusser, S. Yip, "Diffusion and Localization in Two-Dimensional Lorentz Model", _The Physical Review_ A, in press.

S. Yip, W.E. Alley, B.J. Alder, "Evaluation of Time Correlation Functions from a Generalized Enskog Equation", _Journal of Statistical Physics_, in press.

L. Letamendia, E. Leutheusser, S. Yip, "Modification of a Kinetic Model of the Generalized Enshog Equation", _The Physical Review_ A, in press.

3.6.4 Computer Molecular Dynamics Studies

The purpose of this project is to investigate basic materials properties and behavior by exploiting the unique capabilities of molecular dynamics and Monte Carlo simulation to handle highly nonlinear processes and provide detailed results on atomic structures and motions. In molecular dynamics one numerically integrates the Newton's equations of motion for a system which typically contains several hundred atoms and obtains the system properties or responses by appropriate analysis of the atomic positions and velocities thus generated. In a Monte Carlo simulation system properties are obtained as ensemble averages with the phase-space configurations generated by allowing each atom random moves and thereby sampling stochastically certain prescribed probability distributions functions.

Several fundamental processes in materials science are being studied by molecular dynamics simulation, atomic diffusion in grain-boundary solids,

plastic deformation at crack tips, thermal ignition in a system undergoing self-heating by exothermic chemical reactions, and dynamical structures of nonlinear lattices. The Monte Carlo method is being used to compute the thermodynamic properties of crystalline solids with defects. Each problem is an area of thesis research for a graduate student in the Department.

1. Grain-Boundary Structure and Diffusion

Atomic diffusion in solids often occurs by the vacancy jump mechanism. For grain boundary structures determination of dominant diffusion mechanism is difficult because of lack of a method to directly observe such processes. In an extensive molecular dynamics study of a tilt boundary ($\Sigma=5$) in b.c.c. iron we have demonstrated the feasibility of observing vacancy migration at various temperatures. The simulation results constitute explicit evidence that the vacancy mechanism dominates over interstitial migration. The data also provided a wealth of information on thermal defect generation and the effects of local structure on diffusion kinetics.

The work has been carried out in collaboration with Professor R.W. Balluffi and co-workers in the Department of Materials Science, and with Dr. P.S. Ho of IBM Watson Research Center.

2. Crack Propagation

Molecular dynamics simulations provide a means to obtain atomistic details of the deformation processes that govern crack propagation. We are presently studying the structure and properties of a crack tip embedded in a lattice under tensile stress (mode I fracture). It is essential to use a flexible boundary condition in the simulation system so that dislocations may be freely generated at the crack tip and allowed to migrate away. Dislocations have been observed in the simulation results for copper, confirming the well-known ductile nature of this material. In the case of α-iron the results show brittle behavior; however, the crack propagates along the [110] direction instead of the known cleavage direction of [100]. The origin of this apparent discrepancy is under investigation.

This work is being carried out in collaborations with Professor A. Argon of the Mechanical Engineering Department.

3. Thermal Ignition

A simulation program has been developed which is capable of treating a two-dimensional system of reacting hard sphere particles in contact with rigid walls acting as a thermal reservoir. The particles undergo elastic and exothermic reaction collisions, the latter occuring when the relative kinetic energy at impact exceeds a prescribed threshold value. A critical state is reached when the reactions release more energy than can be transferred to the reservoir, then the system temperature will spontaneously jump to a high value. This characteristic behavior of thermal ignition has been observed in simulation. Detailed comparison with the predictions of the theory of thermal explosion shows the importance of surface heat transfer, particularly for small size systems.

4. Nonlinear Lattices

The dynamics of atoms moving in double-well single-particle potentials while also experiencing normal dispersive forces in a harmonic lattice is of interest because such a system can sustain excitations characteristic of nonlinear media. The so-called soliton excitations play an important role in the current understanding of structural phase transitions nonlinear transport phenomena in condensed matter physics. Our interest is focused on the dynamics of kink configuration in a one-dimensional lattice, configurations in which half the atoms are localized in the left well of the double-well potential while the other half are localized in the right well. Both the discrete lattice and its continuous counterpart are studied, and pertubation theory calculations are carried out in conjunction with molecular dynamics simulation.

5. Thermodynamic Properties of Defect Solids

The Monte Carlo technique of sampling the various configurations of an atomic system makes it particularly appropriate for the calculation of thermodynamic properties. We are interested in developing a method to obtain the free energy of a grain boundary solid based in the (N,P,T) ensemble. The basic approach is to start with an appropriate reference system and exploit the idea of umbrella sampling. Results will also provide useful information as the stability of grain boundary structures at elevated temperatures.

Investigators: Professor S. Yip; Messrs. D.P. Chou, A. Combs, B. deCelis, T. Kwok, R. Najafabaki, and F. Cattion.

Support: Army Research Office - Durham (continuing support since July 1974, current contract period extends to September 1981)

Related Academic Subjects:

22.51	Radiation Interactions and Applications
2.332	Physics of Deformation and Fracure of Solids I
2.333	Physics of Deformation and Fracture of Solids II
2.281	Reacting Gas Dynamics

Recent References:

D.P. Chou, "Molecular Dynamics Simulation of Self-Diffusion in Hard-Disk Fluids", NE Thesis, MIT, (June 1980).

B. deCelis, "Molecular Dynamics Simulation Studies of Fracture in Two Dimensions", NE Thesis, MIT, (May 1980).

G.H. Bishop, R.J. Harrison, T. Kwok, S. Yip, "Simulation of Grain Boundaries at Elevated Temperatures by Computer Molecular Dynamics", in Progress in Materials Science, Bruce Chalmers Volume, J.W. Christian, ed. Pergamon Press (1981), p. 49.

T. Kwok, P.S. Ho, S. Yip, R.W. Balluffi, P.D. Bristowe, A. Brokman, "Molecular Dynamics Simulation of Grain Boundary Diffusion of Vacancies in bcc Iron", _Physical Review Letters_, submitted.

R.W. Balluffi, T. Kwok, P.D. Bristowe, A. Brokman, P.S. Ho, S. Yip, "Determination of Vacancy Mechanism for Grain Boundary Self-Diffusion by Computer Simulation", _Scripta Metallurgia_, in press.

D.P. Chou and S. Yip, "Computer Molecular Dynamics Simulation of Thermal Ignition in a Self-Heating Slab", _Combustion and Flame_, submitted.

3.6.5 Quasielastic Light Scattering Studies of Motility of Cells and Aggregation of Macromolecules

A new technique for determining the Doppler frequency shifts in the scattered laser light from slowly moving particles has been developed. This so-called "photon correlation spectoscopy" is a completely digital technique in the time domain whereby the intensity correlation function of the scattered light $\langle I(t) \, I(t+\tau) \rangle$ can be simultaneously measured at 256 values of the delay time τ by using a delay coincidence method. The accessible range for τ in this instrument is from 1 sec to 1 μsec which covers a useful range of fluctuation phenomena from neutron population in a reactor core to flow of particles in turbulent fluids. The method has been applied to the study of slow fluctuations of the concentration in a binary liquid mixture near the critical point with a great deal of success. Recently this technique has been applied to measurement of isotropic random motion of bacteria in liquid media and also to directed biased motions when a chemotactic agent is present. The usefulness of the method for study of macromolecular aggregation kinetics in solution has also been demonstrated.

Investigators: Professor S.-H. Chen; Mr. Paul Wang

Support: National Science Foundation (Biophysics Section): February 1, 1979 - July 31, 1984 ($252,000).

Related Academic Subjects:

22.51 Radiation Interactions and Applications
8.442 Statistical Optics and Spectroscopy

Recent References:

M. Holz and S.-H. Chen, "Spatio-Temporal Structure of Migrating Chemotactic Band of E. coli, I. Traveling Band Profile" _Biophy. J._ **26**, 243 (1979).

M. Kotlarchyk, S.-H. Chen, S. Asano, "Accuracy of RGD Approximation for Computing Light Scattering Properties of Diffusing and Motile Bacteria", _Appl. Opt._ **18**, 2470 (1979).

J.P. Yangos and S.H. Chen, "Simple Low-Cost Digital Events Analyser", _Rev. Sci. Instr._, **51**, 344, (1980).

P.C. Wang and S.H. Chen, "Quasi-elastic Light Scattering From Migrating Chemotactic Bands of E. coli II: Analysis of Anisotropic Bacterial Motions", to appear in Biophys. J., (1981).

R.E. Tanner, B. Herpigny, S.H. Chen and C. Rha, "Conformational Change of Protein/SDS Complexes in Solution - A Study by Dynamic Light Scattering", to appear in J. Chem. Phys., (1981).

W.J. Glantschnig and S.H. Chen, "Light Scattering From Water Droplets in the Geometrical Optics Approximation", to appear in Appl. Opt., (1981).

3.6.6 Characterization of Block Copolymers by Small-Angle Neutron Scattering

Small-angle X-ray scattering (SAXS) has previously been used to estimate domain size and interphase thickness in AB diblock copolymers. Small-angle neutron scattering (SANS) is potentially a more powerful tool for this kind of investigation since deuteration of one of the two components (A or B) greatly increases the contrast between domains as seen by SANS, while no comparable staining procedure exists for SAXS. Several polystyrene-polybutadiene copolymers have been synthesized using deuterated butadiene, and SANS data have been acquired at the National Center for Small-Angle Scattering Research at Oak Ridge. These data provide interesting information about the structure of the samples, including evidence that the polybutadiene spheres form a body-centered cubic lattice in the polystyrene matrix. Current work is directed toward getting information about the composition gradient between the styrene and butadiene microphases.

Investigators: Dr. C.V. Berney

Support: National Science Foundation-DMR ($137,500)

Related Academic Subjects:

22.51 Radiation Interactions and Applications

Recent References:

None to date.

3.7 Biological and Medical Applications of Radiation and Radiosotopes

3.7.1 Subjects of Instruction

22.55J: Biological and Medical Applications of Radiation and Radiosotopes I, principles of radiation production and interactions. Radiation dosimetry with emphasis on applications and health hazards. Detection and spectroscopy of beta, gamma and neutron radiations. Neutron activation analysis. Production of radioisotopes and radiopharmaceuticals. Principles of nuclear medicine.

22.56J: Principles of Medical Imaging. This new course includes a broad range of topics in Medical Imaging, including radiological imaging, nuclear medicine, CT, ultrasound, NMR and other modalities. Topics in image processing and medical decision theory are also included.

3.7.2 Boron Neutron Capture Therapy

An extensive program of preclinical studies of BNCT continues. Studies are aimed at the demonstration of successful therapy of brain tumors in an animal model. Studies include the dosimetry of boron capture and other radiation, radiobiological aspects of BNCT radiation in brain and brain tumor and autoradiography.

Investigators: Professor G.L. Brownell; Ms. M. Ashtari, Mr. J. Kirsh, and J. Fox (Division of Laboratory Animal Medicine, MIT).

Support: National Institutes of Health

Related Academic Subject:

22.55J   Biological and Medical Applications of Radiation and
         Radioisotopes I

Recent References:

J. Kirsh, G.L. Brownell, "Neutron Induced Track Etch Autoradiography of the Therapeutic Compound $Ne_2B_{12}H_{11}SH$", Medical Physics $\underline{8}$, No. 5, (September - October 1981).

M. Ashtari, G.L. Brownell, "Boron Neutron Capture Therapy In the Treatment of Glioblastoma", Medical Physics, $\underline{8}$, No. 5 (September - October 1981).

3.7.3 Collaborative Projects with MGH

1) Medical Imaging: Medical imaging is a scientific area of considerable interest in the Department of Nuclear Engineering. Much of this work is carried out in conjunction with the Massachusetts General Hospital (MGH). An area of particular interest is transverse section imaging using short-lived cyclotron produced isotopes. This area includes isotope production, radiopharmaceutical preparation, instrument development, computer techniques, and physiological modeling. Areas of interest include heart, lung and brain.

2) CT Scanner Development: MGH and MIT are engaged in the development of a fan beam CT scanner system. The system will be used to investigate fundamental aspects of computerized tomography. In particular, we are investigating the possibility of obtaining images of average atomic number as well as electron density. Other studies include applications to heart imaging and the imaging of animals for research programs.

3) Computers in Nuclear Medicine: A joint project in conjuction with MGH includes an investigation of the role of computers in radiology and

nuclear medicine. This includes image processing from scintillation cameras, preparation of parametric images, and biological modeling.

Investigators: Professor G. Brownell; Mr. D. Laning, T. Miller, Ms. K. Kearfott.

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

Related Academic Subjects:

22.55J   Biological and Medical Applications of Radiation and Radioisotopes I
22.56J   Principles of Medical Imaging

Recent References:

G.L. Brownell, C.A. Burnham, J.A. Correia, D.A. Chesler, "Transverse Section Imaging with the MGH Positron Camera", IEEE Trans. Nucl. Sci., NS26, pp. 2698-2703, (1979).

G.L. Brownell, "Current Status and Future Development in Radionuclide CT" published in Japan Symp. on Phys. & Techn. Aspects of Trans. & Em. Compt. Tom., January, Tokyo, Japan, (1979).

G.L. Brownell, "Computed Tomography in Biological and Medical Research" Published in Journal of Computer Assisted Tomography, 1980, Presented at Intl. Sypm. and Course on Computed Tomography, Las Vegas (1980).

3.8   Radiation Biophysics

3.8.1   Subjects of Instruction

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

22.57J: Radiation Biophysics, this is an area of science which has not previously been taught at MIT. This year's first trial of the new subject covered radiobiology, in vivo models for radiation effects on tumors, mathematical models of cell survival radiation chemistry, diagnostic radiology and radiation therapy. The contents of the course will evolve as new information becomes available for analysis.

3.8.2   Tumor Strangulation

Studies are being conducted on the combined effects of ionizing radiation and hyperthermia on tumor vasculature. A novel approach of plastic injection into treated tumor vasculature and subsequent analysis under high

resolution scanning electron microscopy is being tested. The results should provide new insights into tumor treatment.

Investigator: Professor Alan C. Nelson

Related Academic Subjects:

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

Support: Whitaker Health Sciences Fund

Recent References:

S. Koichi, et al., Structure of Ocular Vessels, Igaku-Hoin Press, N.Y. (1978).

3.8.3   Magnetic Field Effects on Biomaterials

Basic research on the effects of high magnetic fields and high field gradients on biological materials is being conducted at the Francis Bitter Magnet Lab and the Whitaker College Laboratory of Microscopy. Current interests focus on the orientation of fibrin fibres and collagen fibres in magnetic fields with a view to the synthesis of new high strength biomaterials for use in artificial skin, for example. Magnetic field effects on living cells is also being examined.

Investigators: Professors B. Frankel and A.C. Nelson

Related Academic Subjects:

22.111   Nuclear Physics for Engineers
22.51   Radiation Interactions and Applications

Support: Naval Research Laboratory

Recent References:

J. Torbet, et al., "Oriented Fibrin Gels Formed by Polymerization in Strong Magnetic Fields", Nature, 289, p. 91 (Jan. 1981)

3.8.4   Microstructural Cell Damage Due to Heavy Ion Radiation

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

Investigators: Professors A.C. Nelson and S. Penman.

Related Academic Subjects:

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

Support: Lawrence Berkeley Laboratory

Recent References:

A.C. Nelson, <u>Theoretical and Observational Analysis of Individual Ionizing
Particle Effects in Biological Tissues</u>, Ph.D. Thesis, Univ. of California,
Berkeley, Department of Biophysics (1980).

A. Ben-Ze'ev, <u>et al</u>., "The Outer Boundary of the Cytoskeleton", <u>Cell</u>, <u>17</u>, p.
859, (August 1979).

3.9   Quantum Thermodynamics

Professor Elias P. Gyftopoulos and Dr. George N. Hatsopoulos of the
Mechanical Engineering Department continued their research on the foundations
of quantum thermodynamics. The emphasis of this research has been on the
general equation of motion of quantum thermodynamics and mathematical forms
that distinguish between quantal and nonquantal uncertainties. Significant
progress was made in both these efforts. A nonlinear quantum equation of
motion was conceived that satisfies the requirements of: (a) energy
conservation; (b) nondecrease of entropy; and (c) leading from a none-
quilibrium to a thermodynamic equilibrium state.

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

3.9.1   Subjects of Instruction

22.571J: <u>General Thermodynamics I</u>, presents the foundations of ther-
modynamics in a general way, followed by the application of thermodynamic
principles to energy conversion systems and industrial processes. First
part: the first and second laws are introduced together with the defini-
tions of work, energy, stable equilibrium, available work, entropy, ther-
modynamic potentials, and interactions (work, nonwork, heat, mass transfer).
Second part: thermodynamic analyses of stable equilibrium properties of
materials, bulk flow, energy conversion processes, chemical equilibria,
combustion, and industrial manufacturing processes.

22.572J: <u>General Thermodynamics II</u>, is a continuation of the applica-
tion of thermodynamic principles to practical problems, followed by a presen-
tation of quantum statistical foundations of thermodynamics. First part:
thermodynamic analyses of ideal and nonideal solutions, electrolytes, surface
phenomena, and gas-solid interfaces; linear rate processes and phenomenologi-

cal equations. Second part: Gibbsian and quantum probabilities and corresponding definitions of states. Derivations of canonical distributions, and Bose-Einstein, Fermi-Dirac, and Boltzmann statistics, and quantum-statistics of semiperfect and perfect gases, including one-particle systems, and Einstein and Debye theories of crystals.

3.10   Energy: Policy and Environmental Issues

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

These activities continued to grow rapidly during the past year and have had substantial influence both at M.I.T. and elsewhere.

3.10.1   Subjects of Instruction

22.08: Energy, this subject deals with energy from a holistic point of view: provision, rational utilization and conservation, regulation, environmental effects, and impact on other societal sectors. Resources of petroleum, natural gas, coal, nuclear and other energy forms. Technologies of providing energy from these forms. Utilization of energy in various sectors: transportation, industrial, commerical, and domestic, including especially opportunities for increased efficiency and energy conservation. Regulatory, tax, and other institutional arrangements that affect production and use patterns. Environmental costs and opportunities associated with exercising various energy strategies, both existing and proposed. Domestic and international political, strategic, and economic implications.

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

22.37: Environmental Impacts of Electric Power Production, assesses the various environmental impacts of producting thermal and electric power with currently available technology. Impacts compared throughout both the fossil and nuclear fuel cycles. Topics include fuel resources and extraction, power

station effluents, waste heat disposal, reactor safety, and radioactive waste disposal.

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

22:80 <u>National Socio-Technological Problems and Responses</u>, is a subject designed to acquaint the student with large socio-technological problems and our capabilities regarding them, in ways beyond discipline oriented research. The structure and content of national problems; connectivity between problems and sectors. Review of present organizations at the working level (universities, national laboratories, industrial laboratories, etc.) the extent to which they relate to decision-making levels, and to the extent to which they match or mismatch their programs to the true scale of problems. Recent efforts to make new organizations or to re-orient present ones. Recent debates, programs, and proposals related to energy and the environment used as particular examples.

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

22.83J: <u>The Finite Earth: Agendas for a More Just Sustainable and Participatory Society</u>, this course is given jointly with three other departmetns in the schools of Engineering and Humanities, was organized in the Nuclear Engineering Department to combine a number of major issues in ways that do not correspond to normal curriculum paths. Problems such as food supply, energy, material resources, global environment, and rapid changes in third world countries often tend to be looked on as separate; but each affects the other, and the connective tissue between then is too often lost. This subject explores several of these issues (especially food, energy, technology transfer, world security and the views from alternative social systems) in context. Each topic cannot be developed in depth; the purpose of the subject is to introduce interested students to these issues and the ways in which they interactively influence the quality of social life for many in today's world, and to assess choices and directions for the future.

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

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3.10.2 Energy Policy Study

In collaboration with the Energy Division of the Oak Ridge National Laboratory and the Institute for Energy Analysis (at Oak Ridge, Tennessee) we are studying national and global energy prospects with a view to assessing the energy options available to the United States. This joint study involves several tasks: (1) Evaluating the prospects for reduced energy consumption in the transportation, commercial/domestic, and industrial sectors via increased efficiency and more rational utilization. This work will build on various recent and realistic analyses (e.g., the National Academy of Science Committee on Nuclear and Alternative Systems Study), and incorporate new work proceeding here. (2) Similar but less sure assessments for "conservation" potentials in other industrialized and non-industrilized parts of the world, and in centrally planned economies (e.g., the U.S.S.R.). (3) Evaluating the projections for future energy demand in those global regions. (4) Estimating the consequence of future fossil fuel use, under several assumptions about global adoption of "conservation" strategies. (5) The projections for (a) global availability of fossil fuels, especially to developing countries; and (b) for atmospheric carbon dioxide increase with time, and the climatological consequences thereof. (6) The implications for U.S. energy policy, especially in relation to the use of fossil fuels and nuclear power, and in relation to the U.S. energy use and policy vis-a-vis the rest of the world.

Investigators: Professors E.P. Gyftopoulos, R.K. Lester, D.J. Rose; Dr. M.M. Miller; Messrs. K. Araj, H. Bazerghi, R. Marlay.

Support: $175,000 subcontract from the Oak Ridge National Laboratory.

Related Academic Subjects:

    22.37 Environmental Impacts of Electric Power Production
    22.80 National Socio-Technological Problems and Responses
    22.81 Energy Assessment

Recent References

D.J. Rose, "Toward a Sustainable Energy Future", Proceedings of World Council of Churches Conf. on Faith, Science and the Future. Held at MIT, (July 1979).

D.J. Rose, "Views of the U.S. Nuclear Energy Option", Proceedings of Inst. for Foreign Policy Analysis Conf. on the Future of Nuclear Power, Hawaii (October-November 1979).

D.J. Rose, "Energy", Chapter 5 of Science and Technology: A Five-Year Outlook, report of National Academy of Sciences as a part of White House message to Congress, W.H. Freeman Co., San Francisco (1979).

3.10.3 Retrospective Study of the U.S. Breeder Program

The U.S. has spent more time and money on developing breeder reactors than any other country, yet the program has, at least until very recently,

been in an uncertain state. This is a historical technology assessment of the trends, decisions, and actions prior to Spring 1977: factors affecting the decision of private vs. public development; many vs. few technical options; emphasis on light water reactors vs. breeders; decision surrounding each major construction project; interactions between the Congress and the Atomic Energy Commission (later the Energy Research and Development Administration). Study of this complex task is expected to give insight into how such activities get carried out, and how to foresee future problems.

Investigators: Professor D.J. Rose; Mr. M Stiefel.

Support: U.S. Department of Energy ($22,500).

Related Academic Subjects:

22.80	National Socio-Technological Problems and Responses
22.81	Energy Assessment
22.84	Nuclear Energy Policy Analysis
ST5 413J	Public Controversies on the Control of Technology
17.226	The Domestic and International Politics of Energy

Recent References:

None to date.

3.10.4 Nuclear Policy Studies

In conjunction with the Energy Division of the Oak Ridge National Laboratory and the Institute for Energy Analysis, we are carrying out a study for the Department of Energy of energy options, particularly with respect to fossil and nonfossil energy use in the U.S. and globally, if particular limits on carbon dioxide releases to the atmosphere are not to be exceeded. The study takes into account: recent projections of global energy demand, recent estimates by climatologists regarding the effects of increasing CO_2 in the atmosphere, the opportunity for and likilihood of further, more effective use of energy (often called conservation), and other factors. Using these data, the global rates of shift from fossil to nonfossil sources in order to satisfy specified asymptotic CO_2 levels have been derived. The rates of installation of nonfossil systems and the required manufacturing capacity to produce those systems have also been estimated; some of the numbers are disturbingly large, and the time needed for the shift is disturbingly short. To assess the energy conservation potential, the response of the U.S. industrial sector to energy price and other stimuli has been studied. Calculations made to date indicate that the response consists mainly of price-stimulated shifts from energy intensive industries to less-intensive ones, and that technical innovation stimulated by government policies may have a large effect in the long term, but has not had much effect yet.

Investigators: Professor E.P. Gyftopoulos, R.K. Lester, D.J. Rose; Dr. M.M. Miller, Messrs. K. Araj, H. Bazerghi, M. Marley.

Support: Oak Ridge National Laboratory ($175,000)

Related Academic Subjects:

22.37   Environmental Impact of Electric Power Production
22.80   National Socio-Technological Problems and Responses
22.81   Energy Assessment
22.83J The Finite Earth: Agendas for a More Just, Sustainable and
        Participatory Society
 2.84   Nuclear Energy Policy Analysis
10.39   Energy Technology

Recent References:

D.J. Rose, "On the Global CO_2 Problem", U.S. Senate Committee on Energy and
Natural Resources Hearings, (April 3, 1980).

D.J. Rose, "Toward a Sustainable Energy Future" in the Great Ideas Today,
published by Encyclopedia Britannica, (1980).

D.J. Rose, "Rational Energy Prospects for the Long Term", in Proc. Amer.
Phil. Soc., to be published.

3.10.5 Nuclear Power, Nuclear Weapons Proliferation, and International Security

Exploration of the relationships between nuclear power and the spread of
nuclear weapons has continued over the past year. The emphasis has been on
the assessment of the ongoing International Nuclear Fuel Cycle Evaluation
(INFCE) and the review of international nuclear policy alternatives for the
United States after INFCE is concluded in February 1980.

An assessment of the economic prospects and proliferation implications
of laser isotope separation processes for uranium enrichment has been
performed.

Investigators: Professors R. Lester, D. Rose, C. Heising-Goodman; Dr. M.M.
Miller.

Support: MIT General

Related Academic Subjects:

22.003J In Pursuit of Arms Control
22.08   Energy
22.81   Energy Assessment
17.841J The Technology and Politics of Nuclear Weapons and Arms Control
17.851   The Domestic and International Politics of Energy

Recent References:

P. Lellouche and R. Lester, "The Crisis of Nuclear Energy", Washington
Quarterly (Summer 1979).

R. Lester, The "Back-end" of the Nuclear Fuel Cycle in the Industrialized World: U.S. Policy after INFCE, Proc. Conference on Next Steps after INFCE, Center for Strategic and International Studies, Georgetown University, Washington, D.C. (December 1979).

R. Lester, Laser Isotope Separation for Uraninum Enrichment, PhD Thesis, MIT, Department of Nuclear Engineering (September 1979).

3.10.6 Nuclear Waste Management Technology

During the past year, a new research effort has been initiated in the area of nuclear waste management technology. The outlook for civil nuclear power in the United States and several other countries throughout the world is closely linked to the resolution of problems at the back end of the nuclear fuel cycle, including, especially, the management and disposal of nuclear wastes. The successful performance of mined geologic repositories for final disposal of reprocessed high level wastes or spent fuel is of central importance to the overall effectiveness of the national nuclear waste management program. Analysis of the thermo-mechanical and thermal hydraulic responses of the host medium to waste emplacement is a key element of waste repository design. Recent efforts in this area have included:

(1) The development of analytical approximations for the radioactivity and radiogenic heat decay behavior of spent fuel and reprocessed high level waste from various fuel cycles.

(2) The development of models to predict the far-field temperature, stress and displacement profiles in waste repository host rock.

Investigators: Professors R.K. Lester, J.M. Deutch (Department of Chemistry).

Support: MIT General and U.S. Department of Energy Contract ($130,000).

Related Academic Subjects:

    22.76 Nuclear Chemical Engineering
    22.77 Nuclear Waste Management

Recent References:

C. Malbrain, R. Lester, and J.M. Deutch, "Analytical Correlations for Decay Behavior of High-Level Wastes", (March 1981).

R.K. Lester, "Nuclear Waste Management: Some Scale Considerations", in Proceedings of the Annual Scientific Meeting of the Radiation Research Society, Minneapolis, (May 1981).

C. Malbrain, Analytical Characterization of Spent Fuels and High-Level Wastes and Application to the Thermal Design of a Geological Repository in Salt, SM Thesis, MIT, Department of Nuclear Engineering, (May 1981).

R. Baradaran, Risk Analysis of High-Level Waste Management at West Valley, NY, SM Thesis, MIT, Department of Nuclear Engineering, (August 1980).

3.10.7 <u>International Cooperation in Energy Technology Research,</u>
<u>Development and Demonstration</u>

Incentives for energy cooperation among the industrialized nations arise
from a collective interest in the broad economic and political benefits of
successful national energy policies and programs, from the economies that may
result from cooperative programs, and from reciprocal constraints on the
formulation and implementation of such programs. A key area of international
cooperation involving both the public and the private sectors is that of new
energy technology development, commercialization and control. During the
past year, a research project has been initiated with the objective of
assessing previous experience in and the future prospects of U.S. -Japanese
cooperation in three technological areas: synthetic fuels technology
development; nuclear reactor and fuel cycle technology development and com-
mercialization, and nuclear fusion research and development. In each area,
the relative roles of independent research, development, and demonstration
(r.d.&d.), cooperative r.d.&d., and the transfer of commercialized technology
are being studied.

<u>Investigator</u>: Professor R.K. Lester

<u>Support</u>: Japanese Ministry of Foreign Affairs Endowment through MIT Center
for International Studies.

<u>Related Academic Subjects</u>:

22.08   Energy
22.81   Energy Assessment
17.851   The Domestic and International Politics of Energy

<u>Recent References</u>:

None to date.

3.10.8   <u>Bouyant Atmospheric Plume Modeling</u>

Over the past four years an effort concerned with numerical similation
of atmospheric buoyant plume behavior has been underway. The motivation for
this work is to develop a plume-model which is sufficiently fundamental and
general that it can be applied to many different situations, but which is
sufficiently simple that its use is not prohibitively expensive. In the
spectrum of available plume models such a gap exists which our model is
intended to fill.

Use of the model requires knowledge of atmospheric velocity, temperature,
humidity, turbulence kinetic energy, and eddy diffusivity data; the model
provides a three dimensional prediction of the plume velocity, temperature,
pollutant concentration, moisture, and turbulence fields. The method adopts
a mixed Eulerian-Lagrangian coordinate system in which a two-dimensional
grid -- oriented perpendicular to the downwind vector -- is translated
downwind. In this grid the transient two-dimensional fluid flow field is
simulated, and by interpolation between the results at different grid posi-

tions the three-dimensional plume field is obtained. In this case time acts as a surrogate third spatial variable.

Results with the model to date have been very good, with many laboratory and field plume cases having been simulated successfully. Current efforts are directed toward more complete code validation, elaboration, and efficiency improvement.

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

Support: Northeast Utilities and Consolidated Edison ($42,000 per year).

Related Academic Subjects:

22.312   Engineering of Nuclear Reactors
22.37   Environmental Impact of Power Production
22.43   Numerical Methods in Reactor Engineering Analysis
 2.283   Fluid Physics of Pollution
10.39   Energy Technology
19.46   Numerical Weather Prediction
19.65J   Turbulence and Random Phenomena in Fluid Mechanics
19.66   The Planetary Boundary Layer and Cumulus Convection

Recent References

R.G. Bennett, and M.W. Golay, Numerical Modeling of Buoyant Plumes in a Turbulent, Stratified Atmosphere," Atmos. Environ.

3.11 Applied Plasma Physics

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

The Department's Fusion Research Group is engaged in experimental research via participation in the Alcator projects, in several plasma physics and diagnostic development projects funded by the National Science Foundation, and in a new divertor simulation study as part of the Fusion Center's overall responsibility for the national divertor program. Our fundamental theoretical studies of plasma turbulence are continuing and are

adding expertise in "device oriented" theoretical analysis. The Technology Group has played an important role in the National Magnet Laboratories High Field Tokamak Reactor Design and is engaged in an EPRI funded study of comparative reactor economics. The methodology of the Reactor Safety Study of fission reactor safety has been applied to questions of fusion reactor safety and some particularly important questions raised in theis effort have been singled out for further research.

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

3.11.1 Subjects of Instruction

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

22.069: Undergraduate Plasma Laboratory, deals with the basic engineering and scientific principles associated with experimental plasma physics. Topics include investigation of vacuum pumping phenomena and gauge operation, normal and superconducting magnetic field coils, microwave interactions with plasmas, laboratory plasma production including electrical breakdown phenomena, Langmuir probe characteristics and spectroscopy.

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

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

22.611J: Introduction to Plasma Physics, is an introduction to plasma phenomena, the occurrence and generation of plasmas with applications to thermonuclear fusion, gas lasers and astrophysics. Motion of charged particles

in electric and magnetic fields; drifts; adiabatic invariants. Plasma
models: kinetic equations, MHD and fluid approximations. Wave propagation in
cold and warm plasmas; Landau damping. Simple equilibrium and stability
analysis. Introduction to collisions and transport processes.

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

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

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

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

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

22.64J: **Plasma Kinetic Theory**, content varies from year to year.
Typical subjects: the linearized Vlasov equation, Fokker-Planck and dif-
fusion approximations for the average distribution function, autocorrelation
functions, resonant and nonresonant diffusion, free energy, energy and momen-

tum conservation, resonsant wave coupling, non-linear Landau damping, strong
turbulence theories. Selected applications to enhance diffusion, stochastic
acceleration, turbulent resistivity, shock waves, radio emission.

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

22.66: Transport Phenomena in Toroidal Systems, presents the plasma
phenomena pertaining to the various loss channels, and their synthesis in
reactor transport codes modeling the approach to ignition. Attempts are
made to compare predictions of transport theory and results from the major
tokamak and stellarator experiments. The theoretical phenomena surveyed
include both classical and neo-classical collisional transport of hydrogen
and impurity ions in a toroidal magnetic field, finite beta anomalous
electron transport due to magnetic islands and stochastic field lines caused
by tearing and resistive ballooning modes and drift modes, and anomalous
alpha particle transport due to Alfven modes driven by the strong spatial
gradient of the alpha pressure in the plasma core and by the non-Maxwellian
alpha distribution in velocity space including the loss effects due to large
orbits and field ripple.

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

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

3.11.2 Fusion Reactor Environmental and Safety Studies

The overall objectives of these studies are the development of a meth-
odology suitable for safety and environmental analysis of proposed fusion
reactor power plants and the development of criteria to guide designs in order
to ensure admissible environmental risks.

This effort was initiated in October 1976. Several sub-tasks have been
addressed. The major achievements of the last two years can be summarized as
follows:

1. The lithium combustion model (LITFIRE) has been applied to the conditions of the scoping experiments performed at the Hanford Engineering Development Laboratories (HEDL). The comparison between the predicted and observed results led to few adjustments in the description of heat and mass transfer functions. In general the initial model was overpredicting the rate of heating of the atmosphere in the building confining the lithium fire.

The LITFIRE model has also been extended to describe the physical and chemical processes occurring during an accidental contact of water and a lithium compound (the tritium breeding material). This has been applied to investigate the consequences of hypothetical reactions in the NUWMAK reactor design. Various breeding materials were considered. The results indicate that pure lithium leds to a higher temperature generation within the blanket than the other materials. Li_2Pb_7 and LiO_2 lead to the lowest heating rates. This model will be further refined in the future to account for the pressurization of the interior of the blanket accompanying the exothermic reactions.

2. The environmental and economic acceptability of presently conceived D-T fueled fusion power plants will depend in large part on the ability to contain and handle tritium within the reactor building and to control tritium releases to the environment without incurring exorbitant costs. In order to analyze the time evolution (from reactor start-up) of the inventories, a transient tritium permeation model was developed based on a simplified conceptual fusion reactor design. The major design constraints employed in the model for the fusion plant were the use of a solid breeder blanket, a low pressure purge gas in the blanket and a high pressure (helium) primary coolant. Both diffusive hold-up and solubility considerations were found to be important contributors to the solid breeder tritium inventory, while the fluid resistance to permeation offered by the primary coolant in the heat transfer loop, although included in the model, was found to be negligible compared to the resistance offered by the primary containment metal. Using the STARFIRE-Interim Reference Design system parameters as input, the model predicted a total tritium inventory of approximately 4.5 kg after 18 days for the Li_2O breeder. The addition of oxygen (up to a partial pressure of 10^{-13} torr) to the primary coolant loop was required in order to keep the tritium losses through the heat exchanger (and, hence, to the environment) to within the design goal of 0.1 Ci/day.

3. An assessment has been made of the total risk to human life implied by all the activities associated with electricity generation from fusion. This includes the expected mining, manufacturing and construction activities related to the power plant as well as the operation and maintenance of the plant. The results were compared to published risk assessments for electricity generation from other sources. The total power cycle risk from fusion was found to be comparable to (if not less than) the lowest risk imposed by the alternative energy sources.

4. A major effort has been undertaken to compare the safety impact of alternate material choices for fusion reactor blankets. The consideration will include expected routine and accidental releases of radioactivity to the environment.

Investigators: Professors M.S. Kazimi L.M. Lidsky; Messrs. S. Piet, M. Tillack, V. Gilberti and Ms. D. Hanchar

Related Academic Subjects:

    22.38   Reliability Analysis Methods
    22.621   Thermonuclear Reactor Design

Recent Publications:

A.J. Piet and M.S. Kazimi, "Implications of Uncertainties in Modeling of Tritium Releases from Fusion Reactors", Proc. Tritium Technology in Fission, Fusion and Isotopic Applications, (April 1980).

M.S. Tillack and M.S. Kazimi, "Development and Verification of the LITFIRE Code for Predicting the Effects of Lithium Spills in Fusion Reactor Containments", PFC/RR-80-11, MIT, (July 1980).

M.S. Kazimi and R.W. Sawdye, "Radiological Aspects of Fusion Energy", J. Fusion Energy, 1, No. 1, pp. 87-101, (January 1981).

P.J. Krane, Safety Aspects of Thermonuclear Reactor Designs Employing Use of Lithium Lead Alloys, SM Thesis, Department of Nuclear Engineering MIT, (1980).

D.R. Hanchar, Tritium Permeation Modeling of a Conceptual Fusion Reactor Design, SM Thesis, Department of Nuclear Engineering MIT, (1981).

3.11.3 Fusion Reactor Blanket and First Wall Design

Earlier work on the development of a design limit approach to optimizing fusion blankets is being applied to tube array first walls and divertor target plates. In this approach, desired parameters and constraints are used to define the allowed range or design window for the remaining free variables.

In the first wall analysis, the possibility of continued operation with failed tubes is an interesting feature included in the analysis.

A simple model has been developed for heat transfer in fusion reactor blankets with liquid breeding regions, allowing for natural circulation and the presence of strong magnetic fields. The results have been compared with the limited information available.

For typical fusion blanket dimensions and temperature differences, natural circulation can be the dominant heat transfer mechanism in the molten salt flibe even over 10 Tesla magnetic field strength; it will increase heat transfer appreciably in the liquid lithium-lead mixture $Li_{17}Pb_{83}$ for magnetic field strengths less than about 10 Tesla; and can be neglected in liquid lithium if the magnetic field is over 1 Tesla.

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Investigators: Professors N.E. Todreas, B. Mikic (Department of Mechanical Engineering); Mr. P. Gierszewski.

Support: U.S. Department of Energy

Related Academic Subjects:

22.312   Reactor Engineering
22.313   Advanced Engineering of Nuclear Reactors
22.36J   Two-Phase Flow
22.621   Thermonuclear Reactor Design

Recent Publications:

P. Gierszewski, B. Mikic, N. Todreas, "Property Correlations for Lithium, Sodium, Helium, Flibe and Water in Fusion Reactor Applications", PFC/RR80-12, MIT, (August 1980).

P. Gierszewski, B. Mikic, N. Todreas, "Natural Circulation in Fusion Reactor Blankets", ASME Paper 80-HT-69, 1980 National Heat Transfer Conference, Orlando, Florida, (July 1980)

P. Gierszewski, B. Mikic, N. Todreas, "Natural Circulation of Electrically Conducting Liquids in Fusion Reactor Blankets", PFC/JA 81-7, MIT, (April 1981).

3.11.4   Theory of Magnetically Confined Toroidal Plasma

One purpose of this activity is to determine the important MHD equilibrium and stability limits (both ideal and resistive) of magnetic confinement systems, in particular tokamaks, torsatrons, EBT and the tandem mirror. Specifically, one needs to calculate b limits and current limits for MHD stability to determine whether or not extrapolations of reactor size and economics are favorable. Equally important, one must learn how the critical plasma parameters (i.e., b, q, helical current, etc.) scale with basic geometries and technological constraints (i.e., aspect ratios, ring current, beam energy, etc.) in order to optimize the design of future experiments and possible reactors. The approach to be used consists of solving the ideal and resistive MHD equilibrium and linear stability equations primarily by analytic, asymptotic techniques. The calculations will be carried out for special simple profiles as well as for general diffuse profiles. Small to moderate computations will be required for evaluation purposes. Another purpose of this activity is to develop a self-consistent microturbulence theory for magnetic confinement systems, primarily toroidal (tokamak and stellarator) systems. Such turbulence often gives rise to anomolous transport which can far exceed the classical collional transport. Successful reactor designs will depend largely on our ability to predict and/or scale these anomalous transport processes theoretically. Although our present understanding of the anomalous loss processes in tokamaks is minimal (the mechanism of anomalous losses is not known), several recent developments appear to be converging on the solution to this problem. They are: (a) appreciation of the importance of very small magnetic perturbations in electron transport, (b) experimental

evidence (through understanding the soft X-ray anomaly) from Alcator and T10 that magnetic fluctuations are the <u>mechanism</u> of anomalous heat loss, and (c) development of a self-consistent turbulence theory for the magnetic fluctuations associated with the universal drift instability in a screw pinch.

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

<u>Investigators</u>: Professors J.P. Freidberg, K. Molvig, Dr. A.B. Rechester, M. Gerver; Messrs. K. Swartz, K. Huzinides, K. Cogswell, D. Thayer, and W.H. Chou.

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

<u>Related Academic Subjects</u>:

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

<u>Recent References</u>:

None to date.

3.11.5 <u>Theory of Nonlinear and Turbulent Fluctuations in Plasma</u>

Most plasmas of laboratory or astrophysical interest contain a non-thermal spectrum of fluctuations. These fluctuations are generally non-linear and turbulent and play a major role in determining the important properties of the plasma. For example, in plasmas of thermonuclear interest, such fluctuations can transport heat and particles across the magnetic field lines at a rate greatly in excess of the collisional rate. Also, non-linear fluctuations can enhance the rate of plasma heating for a given current in the plasma. The study of these fluctuations is not only worthwhile from the point of view of practical applications, but is an important problem in many-body physics. For example, our work is closely related to problems in fluid turbulence and the dynamics of self-gravitating systems. Generally speaking, non-linear and turbulent fluctuations are the end result of linear instabilities, which have grown past the linear stage. Unfortunately, the resulting fluctuations frequently bear little resemblance to the linearly unstable waves which drive them. Our research is concerned mainly with discovering and identifying the types of nonlinear excitations that can exist and studying their properties. This research relies on two basic approaches, that of analysis and of numerical simulation. Although the numerical simulation is expensive, it provides unlimited diagnostic information concerning

the microscopic properties of the system. Such information is not available in laboratory experiments. The analytic portion of the research consists of three parts: (1) deriving and solving kinetic equations which predict the time evolution of the fluctuations, (2) the extension of statistical mechanical arguments to apply to nonequilibrium situations, and (3) the deduction of exact nonlinear time independent solutions to the Vlasov equation in the hopes that such solutions might approximate turbulent fluctuations in some cases.

Investigators: Professor, T.H. Dupree; Drs. J.J. Tetreault, R.H. Berman and T. Boutros-Ghali.

Support: U.S. Department of Energy and National Science Foundation

3.11.6 Torsatron/Stellarator Studies

The now four year old torsatron reactor design study carried out as a class design project in subject 22.622, Special Topics in Thermonuclear Reactor Design has had significant impact on both MIT and the national fusion program.

The T-1 reactor design study, funded by the Office of Fusion Energy, was the first result of that class project. Various technological issues are still under study, most notably issues relating to reactor modularity, but recent work in our Department has concentrated on various physics issues raised by the original reactor design. The most significant work is our research on alpha particle confinement and thermal conductivity in moderate aspect ratio systems. The first results of these studies were surprising, and at variance with previously well-accepted theoretical models. In particular, we showed that alpha particles are well contained in reasonably designed torsatron systems and that the ionic thermal conductivity is orders of magnitude below that predicted by the overly simplified theory then in use. We identified unique features of diffusion in toroidal devices with strong helical ripple and thus defined the regime of applicability of earlier theoretical models. Insights gained in this work were included in K. Molvig's rigorous reformulation of neoclassical theory that is helping to clarify our understanding of neoclassical effects in tokamaks.

The torsatron research group is currently involved in a wide range of related studies. A fundamental goal is the development of a classification scheme and subsequent analysis of various helico-symmetric magnetic field configurations. We are trying to develop design criteria necessary to insure "good" flux surfaces in such systems, investigating advanced modular coil structures, computing the effect of distributed alpha particle energy deposition on thermal stability, and investigating the use of fixed superconducting coil systems in maintainable reactors. These advanced field configurations require the use of asymmetric, three-dimensional coil structures. Analysis of structural loads in such systems is extremely complex and the relationship of technological constraints to achievable magnetic field surfaces is not well understood. We are developing extensive computational tools to aid us in the visualization of these complex field structures and magnetic surface shapes. We are also beginning a study of possible next-step

torsatron experiments with particular attention given to large low-field superconductor devices.

Investigators: L.M. Lidsky, J. Aspinall, D. Baker, J. Johnson, M. McQuade, R. Potok, P. Roemer

Support: U.S. Department of Energy (approximately $80,000/year).

Related Academic Subjects

22.621   Thermonuclear Reactor Design
22.622   Special Topics in Thermonuclear Reactor Design
22.63   Engineering Principles for Fusion Reactors

Recent References:

R.E. Potok, et al., "Ion Thermal Conductivity in a Helical Toroid", Phys. Rev. Lettl, 45, No. 16, (October 20, 1980).

T. Uchikawa, "Design Study of Torsatron Power Reactors on the Basis of Maintenance Requirements", PFC/RR-80-20, (May 1980).

J. Johnson, "The Effect of Non-Local Alpha Energy Deposition on Torsatron Reactors" SM Thesis, MIT, (May 1981).

R.E. Potok, et al., "Particle Confinement and Diffusion in Torsatrons", MIT PFC Report RR-80-15 (August 1980).

L.M. Lidsky, et al.,""T-1" A Self-Consistent Torsatron Reactor Point Design", MIT PFC-IR-81-1, (1981).

K. Molvig, et al., "Breakdown of Onsager Symmetry in Neoclassical Transport Theory", MIT PFC Report JA-81-9, (May 1981).

P.A. Politzer, et al., "Torex-A, A Torsatron Proof of Principle Experiment", MIT PFC-TR-79-2, (March 1979).

3.11.7   Bundle Divertor Analysis

Steady-state or long burn operation of fusion reactors requires continuous processing of the plasma to remove helium ash and impurities. Bundle divertors are a particular class of devices which perform this function by removing a bundle or loop flux from the main plasma between the toroidal field coils. Here the plasma strikes divertor target plates and becomes a neutral gas which can be pumped out and chemically processed to separate fuel from ash. Heat transfer, surface sputtering, and gas pumping are difficult engineering problems in the bundle divertor chamber. Present effort is based on 1) determining the possible operation ranges for conventional water-cooled target plates under relatively pessimistic assumptions regarding heat flux and erosion rates; 2) determining the energy and particle fluxes in the bundle divertor more accurately than presently understood; 3) exploring novel concepts for resolving the engineering problems.

This work concentrated on actively-cooled solid targets using a design window approach to define operating regions. The major constraints on survivability are heat removal, surface erosion and fatigue life. Eight solid materials with high-pressure water cooling in tube or plate geometries were considered, in a general environment of 1 kw/cm^2 heat flux, 1.67×10^{22} ions/ m^{2}s, 1.3 keV ions, 10^5, 90 second plasma burn cycles per year.

A combination of the Rousar and Lowdermilk Critical Heat Flux correlations was developed to include all relevant engineering parameters and CHF data in the 1kW/cm^2 range. Subcooled nucleate boiling heat transfer was generally avoided because of the lack of pressure drop data and correlations, but swirl flow heat transfer was considered.

The stated conditions produce a very severe environment for operation of a divertor target plate. Operation for even one year (at 100% capacity factor) is difficult. Generally, the results show that reliable operation of water-cooled solid targets under the given conditions is only possible for times on the order of a few months maximum, much less for most materials.

Better performance can be obtained if the present assumptions on heat and particle flux, particle energy, fatigue life and sputtering rates prove conservative (there are possible order-of-magnitude uncertainties in fatigue life, for example), or if the environment is softened by other engineered approaches such as gas blankets in front of the target plates.

Accurate engineering design of heat transfer and particle pumping systems for bundle divertors requires knowing the plasma ion and neutral particle behaviour in the bundle divertor ducts. Their behaviour is complicated by the presence of strongly varying magnetic fields, reasonably strong interactions between ions and neutrals, on electrostatic potential developed by the ions and electrons in the divertor, and generally complicated geometry.

We are developing single (1-D single species) analytical models based on "average-ion" properties to determine the scaling of particle and energy fluxes down the divertor duct. These calculations are being backed up by a more sophisticated code that can account for the ion energy distribution.

Related Academic Subjects:

22.312   Reactor Engineering
22.313   Advanced Engineering of Nuclear Reactors
22.36J   Two-Phase Flow
22.621   Thermonuclear Reactor Design

Recent Publications:

J. McMurray, <u>Investigation of Tokamak Solid Divertor Target Options</u>, SM
Thesis, MIT, Department of Nuclear Engineering, (May 1981).

4. CURRICULUM

4.1 Degree Programs

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

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

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

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

The objectives of the doctoral program are to provide an advanced education in nuclear engineering and to challenge the student to become a leading and original contributor to her or his professional field. Students in this program are required to pass a general examination and then to complete a major research investigation of sufficient scope and originality to constitute a contribution of permanent value to science and technology. Although no set time is specified for completion of the doctoral program,

most students require from three to five years. Students completing the Doctor's program in Nuclear Engineering are prepared and motivated to work on the frontiers of nuclear technology.

4.2 Fields of Study

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

1. Reactor Physics
2. Reactor Engineering
3. Nuclear Fuel and Power Management
4. Applied Plasma Physics
5. Nuclear Materials Engineering
6. Applied Radiation Physics
7. Applied Fusion Technology
8. Nuclear Energy Systems and Policy Analysis
9. Medical Radiological Physics
10. Reactor Safety Analysis

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 ten 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 ten fields.

4.3 Subjects of Instruction

Subjects of instruction currently offered by the Nuclear Engineering Department are listed below. The subjects are divided into different areas for convenience. The introductory subjects 22.89 Basic Electronics, 22.311 Engineering Principles for Energy 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. Aeronautics and Astronautics, Chemical Engineering, Civil Engineering, Electrical Engineering and Computer Science, Health Science and Technology, Materials Science and Engineering, Mechanical Engineering, Metallurgy, Ocean Engineering, Physics, and Political Science.

Undergraduate Subjects

22.U.R.	Undergraduate Research Opportunities Program
22.001	Seminar in Nuclear Engineering
22.002	Management in Engineering
22.003J	In Pursuit of Arms Control
22.006	Computer Models of Physical and Engineering Systems
22.02	Introduction to Applied Nuclear Physics
22.021	Nuclear Reactor Physics
22.03	Engineering Design of Nuclear Power Systems
22.031	Engineering Analysis of Nuclear Reactors
22.033	Nuclear Systems Design Project
22.04	Radiation Effects and Uses
22.069	Undergraduate Plasma Laboratory
22.07	Basic Plasma Physics
22.070J	Materials for Nuclear Applications
22.071J	Physical Metallurgy Principles for Engineers
22.08	Energy
22.081	The Profession of Engineering: Past, Present and Future
22.084	Inventions and Patents
22.085	Introduction to Technology and Law
22.09	Introductory Nuclear Measurements Laboratory
22.091	Special Topics in Nuclear Engineering
22.092	Engineering Internship

Graduate Subjects

Nuclear Physics

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

Nuclear Reactor Physics

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

Nuclear Reactor Engineering

22.311	Engineering Principles for Energy Engineers
22.312	Engineering of Nuclear Reactors
22.313	Advanced Engineering of Nuclear Reactors
22.314J	Structural Mechanics in Nuclear Power Technology
22.32	Nuclear Power Reactors
22.33	Nuclear Engineering Design
22.34	Economics of Nuclear Power
22.35	Nuclear Fuel Management
22.36J	Two-Phase Flow and Boiling Heat Transfer

22.37	Environmental Impact of Electric Power Production
22.38	Reliability Analysis Methods
22.39	Nuclear Reactor Operations and Safety
22.40	Advanced Reliability Analysis

Numerical and Mathematical Methods

22.41	Numerical Methods of Radiation Transport
22.42	Numerical Methods of Reactor Analysis
22.43	Numerical Methods in Reactor Engineering Analysis
22.571J	General Thermodynamics I
22.572J	General Thermodynamics II

Applied Radiation Physics

22.51	Radiation Interactions and Applications
22.55J	Biological and Medical Applications of Radiation and Radioisotopes I
22.56J	Principles of Medical Imaging
22.57J	Radiation Biophysics

Plasmas and Controlled Fusion

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

Nuclear Materials

22.70J	Material for Nuclear Applications
22.71J	Physical Metallurgy Principles for Engineers
22.72J	Nuclear Fuels
22.73J	Radiation Effects in Crystalline Solids
22.75J	Radiation Effects in Reactor Structural Materials
22.76J	Introduction to Nuclear Chemical Engineering
22.77	Nuclear Waste Management

General

22.80	National Socio-Technological Problems and Responses
22.81	Energy Assessment
22.82	Engineering Risk Benefit Analysis
22.821	Engineering Systems Analysis

22.83J	The Finite Earth: Agendas for a More Just, Sustainable and Participatory Society
22.84	Nuclear Energy Policy Analysis
22.86	Entrepreneurship
22.87J	Current Issues in Engineering
22.88J	Cases and Projects in Engineering Management
22.89	Basic Electronics
22.901 to	Special Problems in Nuclear Engineering
22.904	Special Problems in Nuclear Engineering
22.911	Seminar in Nuclear Engineering
22.912	Seminar in Nuclear Engineering
22.913	Graduate Seminar in Energy Assessment
22.914	Graduate Seminar in Energy Assessment
22.915	Seminar in Reactor Safety
22.92	Advanced Engineering Internship
22.93	Teaching Experience in Nuclear Engineering

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

Civil Engineering

1.143J	Mathematical Optimization Techniques
1.146	Engineering Systems Analysis
1.502	Structural Analysis and Design
1.581	Structural Reliability
1.77	Water Quality Control
1.78	Water Quality Management

Mechanical Engineering

2.032	Dynamics
2.06J	Mechanical Vibration
2.092	Methods of Engineering Analysis
2.093	Computer Methods in Dynamics
2.14	Control System Principles
2.151	Advanced Systems Dynamics and Control
2.155	Dynamics and Control of Thermofluid Processes and Systems
2.20	Fluid Mechanics
2.25	Advanced Fluid Mechanics
2.301	Advanced Mechanical Behavior of Materials
2.41J	Thermodynamics of Power Systems
2.55	Advanced Heat Transfer
2.56	Conduction Heat Transfer

Materials Science and Engineering

3.14	Physical Metallurgy
3.144J	Deformation and Fracture Mechanics of Engineering Alloys
3.25J	Physics of Deformation and Fracture of Solids I
3.26J	Physics of Deformation and Fracture of Solids II
3.37	Deformation Processing

3.38	Behavior of Metals at Elevated Temperatures
3.39	Mechanical Behavior of Materials
3.54	Corrosion

Electrical Engineering and Computer Science

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

Physics

8.312	Electromagnetic Theory
8.321	Quantum Theory I
8.322	Quantum Theory II
8.341	Mathematical Methods of Physics I
8.342	Mathematical Methods of Physics II
8.511	Theory of Solids I
8.512	Theory of Solids II
8.641	Physics of High Temperature Plasmas I
8.642	Physics of High Temperature Plasmas II

Chemical Engineering

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

Ocean Engineering

| 13.21 | Ship Power and Propulsion |
| 13.26J | Thermal Power Systems |

Economics

| 14.22 | Energy Economics |
| 14.281 | The Energy Industries |

Management

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

Aeronautics and Astronautics

16.551	MHD Power Generation

Mathematics

18.085	Methods of Applied Mathematics for Engineers
18.175	Theory of Probability
18.275	Numerical Analysis

4.4 Independent Activities Period

In January 1981, the Nuclear Engineering Department offered 13 activities. Professor Sow-Hsin Chen offered an activity related to neutron spectroscopy, "Fingernail Analysis: Analyze the Heavy Elements in Your Fingernail by Neutron Activation" and Professor Sidney Yip offered an activity in radiation physics entitled "Observations of Fundamental Processes in Materials Behavior by Computer Simulation". Messrs. Steven Piet, Thomas Charis and Professor Carolyn Heising-Goodman offered "Why Choose Nuclear Engineering As a Career?", designed to increase undergraduate interest in the Department. Five members of the nuclear industry gave a one-hour panel discussion on career opportunities. The "Fusion Safety Seminar" was again offered by Professor Mujid Kazimi and Mr. Steven Piet. The student Chapter of the American Nuclear Society organized several activities including a tour of the General Dynamics Shipyard, a program on cardiopulmonary resuscitation and a series on Building an Energy Exhibit. Professor Norman Rasmussen offered a session on "Wise Astute Guesses (WAGs)" designed to challenge engineering minds by teaching how to use rough approximations to get answers quickly. An activity jointly organized by Professors C. Heising-Goodman and Ted Greenwood (of Political Science) was again offered after its successful first offering in 1979. Entitled "Issues in Nuclear Energy Policy-Making", a four-day set of two hour seminars dealt with safety, proliferation and waste disposal. Professors George Rathjens (also of Political Science) and Richard Lester were guest lecturers in the well attended series (approximately 250 people).

Professor Michael Driscoll organized a lecture "Is Nuclear Power Economical" where several utility leaders presented their views on the economic future of nuclear power and investor-owned utilities. "Nuclear Reactor Safety Parameter Display System", an activity related to advanced control room design was offered by Professor David Lanning. Professor Alan Nelson and Ms. Manzar Ashtari, a graduate student, organized "Biomedical Applications of Research Reactors" to explore applications of the MIT research reactor to biomedical nuclear engineering problems. A tour of the research

reactor was given among other activities coordinated with the Nuclear Reactor Laboratory and Plasma Fusion Center.

4.5   Undergraduate Research Opportunities Program

The undergraduate Research Opportunities Program is a special program to provide undergraduate students with research experience in the various laboratories and departments throughout MIT. The seminars are under the direction and support of the MIT Education Research Center. Professor D.D. Lanning is the Nuclear Engineering Department Coordinator.

The program has provided an excellent vehicle for undergraduates to learn about the research activities in the Department. During the 1980-1981 academic year, twenty-three undergraduates were engaged in projects within the Department.

4.6   Description of New and Revised Subjects

Since the spring of 1980 thirteen new subjects have been added to the curriculum. These subjects are described below.

A.   New Subjects

22.002 <u>Managemnt in Engineering</u>, is an introductory subject which deals with the concepts of management of the engineering function, as found in a variety of industrial and nonindustrial settings. Topics covered include financial principles, management of innovation, engineering project planning, scheduling and control, human factors, career planning, contracts, patents, and technical strategy for firms. (This subject is an Engineering School-wide elective.)

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

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

22.084 <u>Inventions and Patents</u>, deals with the history of private and public rights in scientific discoveries and applied engineering leading to the

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development of worldwide patent systems. The classes of invention protectable under the patent laws of the United States, including the procedures in protecting inventions in the Patent Office and in the courts. Reviews of the past cases involving inventions and patents in (a) the chemical process industry and medical field, (b) devices in the mechanical, ocean exploration, civil, and/or aeronautical fields, (c) the electrical and electronic areas including key radio, solid-state, and computer inventions. (This subject is an Engineering School-wide elective.)

22.085 Introduction to Technology and Law, covers the basic principles and functions of law, using legal cases and materials arising from scientific and technical issues. The subject provides an understanding of the law and legal processes as they impact upon work of engineers and scientists. (This subject is an Engineering School-wide elective.)

22.40 Advanced Reliability Analysis, deals with extended application and use of reliability and probabilistic risk analysis methods. Topics include advanced reliability analyses; methods for common mode failure analysis and treatment of dependencies; bayesian statistics applied to reactor safety problems; error sensitivity analysis; application of selected reliability analysis computer codes. Case studies of safety analyses performed in nuclear and non-nuclear areas: LWR safety, fusion reactor safety and aerospace/chemical engineering applications.

22.57J Radiation Biophysics, deals with the effects of ionizing radiation, ultraviolet radiation, and heat on biological materials, cells and tissues of mammals. In vivo and in vitro mammalian systems will be examined in detail, and mathematical models for cell survival is explored with particular emphasis on prediction. Microstructural damage to cell components such as membranes, organelles, enzymes, and DNA is studied thoroughly. Radiation syndromes in man, mutagenesis, and carcinogenesis is also investigated. The course concludes with discussion on new directions for cancer therapy using heavy ion radiation.

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

22.77 Nuclear Waste Management, is a general introduction to the scientific and engineering aspects of the management of spent fuel, reprocessed high-level waste, mill tailings and transuranic and low-level wastes and retired nuclear facilities. Topics include fundamental processes and governing equations of radiation and radionuclide transport; selection criteria for multibarrier system components for long-term waste storage; analysis of interim storage, processing and transportation technologies; analytical methods for risk assessment of waste management and disposal.

22.821 Engineering System Analysis, covers the analytic procedures for the identification and selection of optimal systems. The subject reviews the

economic framework for analysis, and provides a systematic survey of theory and applications of mathematical optimization to engineering problems. The application of this material to real problems in planning and design is stressed throughout the term. (This subject is an Engineering School-wide elective.)

22.87J **Current Issues in Engineering**, reviews a selection of technological developments of great significance to industrialized societies, choosing from current areas such as electronic materials and microprocessors, conventional and new energy technology and practical aspects of cell manipulation. Key features of the technologies, and their relationships to social, economic and managerial issues that development implies.

22.88J **Cases and Project in Engineering Management**, is a continuation of Current Issues in Engineering with a shift from macro-level of technologies toward micro-level of projects. Case studies and student projects involving several real engineering and scientific programs in industrial firms and government agencies are examined. Cases chosen from new ventures as well as mature firms, in both product and process development. All aspects of projects assessed.

22.93 **Teaching Experience in Nuclear Engineering**, is a subject for qualified graduate students interested in teaching as a career. Classroom, laboratory or tutorial teaching under the supervision of a faculty member. Students selected suitable assignments. (Credits for this subject may not be used toward Master's or Engineer's degrees.)

B. **Subject with Major Revisions**

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

4.7 **Undergraduate Program**

The introduction of an undergraduate curriculum in the 1975-76 school year reflected MIT's response to the growing demand for such a program from students prompted by the increasing needs of a maturing nuclear industry. Most of the major nuclear engineering departments in the country now offer such a program. In preparing the undergraduate program we reviewed the programs at a number of other schools. As described below the program incorporates many subjects from other MIT Departments which enables the program to be given in an efficient way by using already existing resources.

4.7.1 Description of Undergraduate Program

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

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

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

4.7.2 Subjects of Instruction

The following subjects of instruction are offered:

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

22.002: Management in Engineering, is an introduction to the concept of management of the engineering function, as found in a variety of industrial and non-industrial settings. The subject's aim is to help students acquire: 1) recognition of the role of engineering and its relationship to other functions in getting a job done, 2) familiarity with some of the managerial

tools and concepts employed in engineering organizations, 3) practice in dealing with both short- and long-term managerial problems in a range of real life circumstances, and 4) incentive to develop a career strategy relevant to engineering training. This subject is a School-Wide Elective.

22.003J: <u>In Pursuit of Arms Control: Analysis of the Past and Choices for the Future</u>, reviews and analyzes nuclear and non-nuclear arms and efforts at arms control since World War II. Focus is on the interaction of technological factors, changing strategic concepts, intelligence estimates, and political judgements in the decision-making process. Topics include nuclear proliferation, Strategic Arms Limitation Talks, Mutual and Balanced Force Reductions, new military technology, and current trends in U.S. and Soviet weapons programs.

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

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

22.021: <u>Nuclear Reactor Physics</u>, is an introductory to fission reactor physics covering reactions induced by neutrons, nuclear fission, slowing down of neutrons in infinite media, diffusion theory, the few-group approximation, and point kinetics. Emphasis placed on the nuclear physics bases of reactor design and their relation to reactor engineering problems. Three lecture hours per week meeting concurrently with 22.211, plus a separate recitation; assignments and quizzes are different from those in 22.211.

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

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22.031: **Engineering Analysis of Nuclear Reactors**, Engineering analysis of nuclear reactors, with emphasis on power reactors. Power plant thermodynamics, reactor heat generation and removal (single-phase as well as two-phase coolant flow and heat transfer) and structural mechanics. Engineering considerations in reactor design. Three lecture hours per week concurrently with 22.312, plus a separate recitation.

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

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

22.069: **Undergraduate Plasma Laboratory**, covers basic engineering and scientific principles associated with experimental plasma physics. Investigation of vacumm pumping phenomena and gauge operation, normal and superconducting magnetic field coils, microwave interactions with plasmas, laboratory plasma production including electrical breakdown phenomena, Langmuir probe characteristics and spectroscopy are also covered.

22.07: **Basic Plasma Physics**, is an introduction to fusion processes and potential for energy production. Fundamental concepts of plasma physics and introduction to the elementary electromagnetic theory needed to describe plasma behavior. Topics studied include physical processes in ionized gases, discussion of fusion reactor concepts and designs and elementary theory of plasma single-particle motions and MHD equations.

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

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

physical interpretation and quantification. The subject meets concurrently with 22.71J, but assignments differ.

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

22.084: _Inventions and Patents_, deals with the history of private and public rights in scientific discoveries and applied engineering leading to the development of worldwide patent systems. The classes of invention protectable under the patent laws of the United States, including the procedures in protecting inventions in the Patent Office and in the courts. Reviews of the past cases involving inventions and patents in (a) the chemical process industry and medical field, (b) devices in the mechanical, ocean exploration, civil, and/or aeronautical fields, (c) the electrical and electronic areas including key radio, solid-state, and computer inventions. (This subject is an Engineering School-wide elective.)

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

22.09: _Introductory Nuclear Measurements Laboratory_, deals with the basic principles of interaction of nuclear radiation with matter, statistical methods of data analysis, introduction to electronics in nuclear instrumentation, counting experiments using Geiger-Muller counter, gas filled proportional counter, scintillation counter, and semiconductor detectors.

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

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

4.8 Engineering Internship Program

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

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

A total of ten students -- one graduate, three juniors and six seniors - are now in the program. Companies which have placed students from the Nuclear Engineering Department are Brookhaven National Laboratory, Commonwealth Edison, EG&G Idaho, Stone and Webster Engineering Corporation, and Yankee Atomic Electric Company.

4.9 Undergraduate Seminar Program

The Undergraduate Seminar Program is an Institute-wide program which offers an opportunity for students to interact with faculty members in small, informal class settings. Seminars vary tremendously both in style and topic. Some are oriented around small, informal class discussions while others may bring in speakers, go out on field trips or involve extensive laboratory projects. The following Undergraduate Seminars have been offered by the Nuclear Engineering Department since Spring 1980: Controlled Fusion (L. Lidsky and J. Freidberg), The Future Prospects for Nuclear Power (M.J. Driscoll), Nuclear Power: Focus of Controversy (revised) (M.J. Driscoll), Three Mile Island: Causes and Effects (staff), Engineering Economics and Energy Options (M.J. Driscoll), Methods in Nuclear Medicine and Radiation Biophysics (A.C. Nelson).

5. RESEARCH FACILITIES

5.1 M.I.T. Reactor

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

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

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

5.2 Inelastic Neutron Spectrometer

A powerful neutron spectrometer has been built in the MITR II at the exit of beam port 6SH4. The construction was funded by the National Science Foundation. This spectrometer can be used for molecular spectroscopy work by measuring the coherent and incoherent double differential cross sections of thermal neutrons. The incident neutron beam can be energy-selected in the range 3 MeV - 100 MeV by a double crystal monochrometer. The scattered neutrons can be energy-analysed at a fixed scattering angle by a multi-crystal small angle analyser spectrometer or by a constant Q variable angle spectrometer. The spectrometer system has an energy resolution as high as 0.2 MeV at a moderate energy transfer.

This spectrometer is being operated by a group headed by Professor Chen and Dr. C.V. Berney. It is used to study molecular vibrational spectra in solid hydrocarbons and hydrogen-bonded solids.

5.3 Texas Nuclear Corporation Neutron Generator

This 150-keV Cockcroft-Walton type accelerator with a versatile pulsing system is located in the accelerator vault of Building NW13. Beam current is

1 ma and either the D(d,n) or T(d,n) reactions may be used. The accelerator has been used for slowing-down investigations, heavy water diffusion parameter measurements, activation analysis experiments, accelerator studies and fusion blanket studies.

5.4 Computing Facilities

The Department makes extensive use of the facilities of the MIT Information Processing Center. These facilities include an IBM 370/168 for batch processing and an IBM 360/67 for time-sharing purposes. Access to the time-sharing system is via consoles located around the Institute.

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.

5.5 Nuclear Engineering Laboratories

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

The rooms in NW12 are equipped with laboratory-type benches and hoods, service air, water and electricity connections. These rooms are presently used for projects in medical applications and chemical engineering. In addition, there are two laser systems being used to study fluid dynamics and cooling tower drift.

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

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

6. DEPARTMENT PERSONNEL

6.1 Faculty

Neil E. Todreas

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

Manson Benedict

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

Gordon L. Brownell

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

I-Wei Chen

Assistant Professor of Nuclear Engineering S.B.'72 National Tsinghus
Univ.; M.S. '75 Univ. of Pennsylvania; Ph.D. '79 (metallurgy) MIT
    Nuclear materials; radiation effects

Sow-Hsin Chen

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

Michael J. Driscoll

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

Thomas H. Dupree

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

Jeffery P. Freidberg

Professor of Nuclear Engineering B.E.E. '61, M.S. '62, Ph.D. '64
(elec. - phys.) Poly. Inst. of Brooklyn
Plasma theory, MHD theory

Michael W. Golay

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

Elias P. Gyftopoulos

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

Kent F. Hansen

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

Otto K. Harling

Professor of Nuclear Engineering; Director, Nuclear Reactor Laboratory;
B.S. '53 Illinois Inst. of Tech.; M.S. '55 University of Heidelberg;
Ph.D. '62 Penn. State Univ.
Neutron scattering; experimental nuclear physics; nuclear materials;
plasma surface interaction

Carolyn D. Heising-Goodman

Assistant Professor of Nuclear Engineering B.S. '74 Univ. of California;
M.S. '75 Stanford Univ.; Ph.D. '78 (mechanical engineering - nuclear)
Stanford Univ.
Reliability; risk assessment

Allan F. Henry

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

Irving Kaplan

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

Mujid S. Kazimi

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

David D. Lanning

Professor of Nuclear Engineering
B.S. '51 U. of Ore.; Ph.D. '63 (nuclear engineering) MIT
Reactor operations; reactor engineering; reactor
safety; reactor physics measurements.

Richard K. Lester

Assistant Professor of Nuclear Engineering B.Sc. '74 London;
Ph.D. '79 (nuclear engineering) MIT
Nuclear chemical engineering; radioactive waste
disposal; energy policy; nuclear proliferation.

Lawrence M. Lidsky

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

John E. Meyer

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

Kim Molvig

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

Norman C. Rasmussen

Professor of Nuclear Engineering; A.B. '50 Gettysburg; Ph.D. '56
(physics) MIT
Reactor safety; environmental effects of nuclear power;
reliability analysis; risk analysis.

David J. Rose

Professor of Nuclear Engineering B.A.Sc. '47 British Columbia; Ph.D.
'50 (physics) MIT
Energy and environmental policy; energy technology;
controlled nuclear fusion.

Kenneth C. Russell

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

Dieter J. Sigmar

Adjunct Professor of Nuclear Engineering M.S. '60, Ph.D. '65,
Tech. Univ. of Vienna
Theory of fully ionized plasmas; controlled thermonuclear
fusion research; statistical mechanics of plasmas
and fluids.

Sidney Yip

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

6.2   Complete Listing of Personnel (as of April 1981)

Professor

M. Benedict (Institute
    Professor Emeritus)
G.L. Brownell
S.-H. Chen
M.J. Driscoll
T.H. Dupree
J.P. Freidberg
E.P. Gyftopoulos
O.K. Harling
A.F. Henry
I. Kaplan (Professor Emeritus
    and Senior Lecturer)
D.D Lanning
L.M. Lidsky
J.E. Meyer
N.C. Rasmussen
D.J. Rose
K.C. Russell
N.E. Todreas
S. Yip

Associate Professor

M.W. Golay
M.S. Kazimi
K. Molvig
G. Brown (Visiting)

Assistant Professor

I-W. Chen
C.D. Heising-Goodman
R.K. Lester
A.C. Nelson
T. Boutros-Ghali (Visiting)

Adjunct Professor

D.J. Sigmar

Senior Research Engineer

B.D. Montgomery

Postdoctoral Associate

F.R. Best

Postdoctoral Fellow

M. Pagitsas
E. Leutheusser

DSR Staff

R. Morton

Lecturer

M.M. Miller

Administrative Officer

J.B. deVries Gwinn

Senior Research Associate

C.V. Berney

Research Affiliate

D.C. Aldrich
R.W. Atcher
J.W. Hopps, Jr.
S. Shortkroff
W.E. Vesely
L. Wolf

Visiting Scientists

Y-S Chao
P. Nicholson
M.L. Xue

Clerical Staff

L.S. Barrett
S. Caloggero
C.M. Egan
G. Jacobson
E.D. Kehoe
M. King
M.B. Levine
C.A. Lydon
J. Phillips
D. Radcliffe
R.E. Scott
D.J. Welsh

Spring 1981 Teaching Assistants

Allen, Stephen
Baker, Douglas (1/2)
Bendedouch, Dalila (1/2)
Chang, Soon
Combs, Andrew (1/4)
Ebeling-Koning, Derek (1/2)
Erickson, Randy
Farish, Thomas
Free, Scott
Gordon, Ethel Sherry
Gulko, Les (1/2)
Ismail, Nassar (1/2)
Kotlarchyk, Michael
Kwok, Thomas
LeClaire, Rene (1/2)
Najafabadi, Reza
Nolley, Jean (P.T.)
Schor, Andrei (1/2)
Sharafi, Mohammad
Tillack, Mark
Tsai, Chon-Kwo (1/2)
Wong, Kean (supplement) (1/4)
Yarman, Faruk (1/2)

Spring 1981 Research Assistants

Adegbulugbe, Tony (1/2)
Ahmad, Saghir (1/2)
Araj, Kamal
Ashtari, Manzar
Aspinall, John (P.T.)
Bazerghi, Hani
Best, Susan
Burke, Richard
Cavoulacos, Panos (P.T.)
Cheng, Alex
Cheng, Shih-Kuei
Cogswell, Kurt
DeWitt, Gregory
Doyle, James
Ebeling-Koning, Derek
Efthimiadis, Apostolos
Fisher, William
Foord, Mark
Gierszewski, Paul
Gilberti, Victor
Giovanetti, Rosanne
Glantschnig, Werner
Griggs, Dan

Hanchar, Deborah
Hizanidis, Kyriakos
Hoxie, Chris
Jackson, Joseph
Kamal, Altamash
Kao, Shih Ping
Khalil, Hussein
Kirsch, John
Kohse, Gordon
LaBombard, Brian
Lingamneni, Jaya
Loh, WeeTee
MacCabe, Stephen P.
Malbrain, Carl
Manahan, Michael
Mohammed, Samir
Moshier, William
Nitta, Cynthia
Ornedo, Renato S.
Pachtman, Arnold
Parsons, Kent
Plys, Martin
Roemer, Peter
Schissel, David
Schor, Andrei (1/2)
Shanfield, Stanley
Stiefel, Michael
Symolon, Paul
Texter, Scott
Tsai, Chon-Kwo (1/2)
Vilim, Richard
Wan, Alan
Wang, Ching Hsiao
Wang, Paul
Wong, Channy (P.T.)
Yu, Ge-Ping
Zielinski, Robert

Spring 1981 Instructor G

Ballinger, Ron

Statistical Summary

Sept. Registration   **Degrees Granted**

Academic Year Sept – June	Under-grad	Regular	Special	Total	B.S.	S.M.	Nuc. E.	ScD., PhD	Total	No. of Professors	No. of Subjects
51 – 52	------------none-----------				-----------none----------					1	none
52 – 53	none in nuclear				-----------none----------					2	4
53 – 54	–	8	–	8	–	4	–	–	4	2	5
54 – 55	–	20	–	20	–	13	–	–	13	2	5
55 – 56	–	46	–	46	–	10	–	–	10	3	6
56 – 57	–	74	–	74	–	32	–	–	32	5	7
57 – 58	–	93	1	94	–	31	–	2	33	6	8
58 – 59	–	95	6	101	–	44	–	7	51	8	12
59 – 60	–	102	6	108	–	32	–	5	37	10	14
60 – 61	–	112	10	122	–	25	1	7	33	10	16
61 – 62	–	118	8	126	–	34	–	11	45	13	17
62 – 63	–	109	8	117	–	27	1	12	40	15	20
63 – 64	–	103	10	113	–	20	2	13	35	15	21
64 – 65	–	124	6	130	–	24	3	14	41	16	24
65 – 66	–	125	6	131	–	30	3	15	48	16	25
66 – 67	–	122	6	128	–	28	11	22	61	18	26
67 – 68	–	132	4	136	–	27	2	13	42	17	27
68 – 69	–	127	3	130	–	35	6	14	55	18	28
69 – 70	–	128	–	128	–	31	8	22	61	20	28
70 – 71	–	111	3	114	–	27	4	14	45	19	37
71 – 72	–	117	1	118	–	20	2	19	41	20	35
72 – 73	–	113	1	114	–	29	5	14	48	20	37
73 – 74	–	127	2	129	–	32	12	8	52	22	44
74 – 75	–	139	7	146	–	38	4	7	49	22	46
75 – 76	22	178	2	202	–	39	8	24	71	26	61
76 – 77	35	187	2	224	2	37	10	23	72	22	66
77 – 78	48	167	3	218	11	57	18	20	106	22	70
78 – 79	44	174	1	219	11	40	10	15	76	23	75
79 – 80	42	174	1	217	11	40	8	19	72	22	77
80 – 81	35	151	2	188	10	34	7	20	65	25	77
TOTALS					45	840	125	340	1328		

8. STUDENTS

Some background information about the 146 full-time students registered in the Department in February, 1981, is presented in Tables 8.1 and 8.2. In past years a plurality of our students have come from undergraduate programs in Physics, with Mechanical Engineering second. We now find Nuclear Engineering undergraduates the single largest discipline.

The distribution of schools from which our domestic students are drawn is very widespread. The number coming from MIT remains under 20%, as it has for many years. The foreign student population is relatively high, approximately 45%, and reflects the widespread recognition among foreign countries of their need for nuclear power. More and more we see the trend of foreign governments sending qualified students to MIT for training in Nuclear Engineering.

Support for students has increased in recent years. In 1973 we had 24 research assistants, while in 1980/81 we now have 56. We have also been most fortunate in having the support of the nuclear industry for a limited number of fellowships.

The distribution of activities of our graduates is given in Table 8.3. The breakdown among the categories of United States Government, Teaching, and Foreign has changed very little in the past six years. A larger percentage of our very recent graduates are now going to industrial positions with the electric utilities and vendors. The distribution of types of employment are summarized in Figure 8.1.

TABLE 8.1

Background of Graduate Students Registered in Nuclear Engineering

Department (Spring 1981)

By Profession (146)

Applied Science (1)
Chemical Engineering (5)
Chemistry (1)
Civil Engineering (2)
Electrical Engineering (9)
Electronics (3)
Energy (2)
Engineering (3)
Engineering Physics (5)
Materials (1)
Math (3)
Mechanical Engineering (10)
Meteorology (1)
Naval Science (1)
Nuclear Engineering (83)
Physics (15)
Telecommunications (1)

Kansas State University (1)
MIT (29)
New Jersey Inst. of Tech. (1)
New Mexico State Univ. (1)
Penn State (1)
Polytechnic Inst. of NY (1)
Princeton (2)
RPI (1)
Stanford (1)
Sweet Briar (1)
Texas A&M (2)
Tufts (1)
UCLA (2)
USMA (3)
University of California (4)
Connecticut (1)
Florida (1)
Lowell (4)
Michigan (3)
Missouri (2)
Tennessee (2)
Texas (1)
Wisconsin (2)
Western Illinois (1)

By College (U.S. citizens only) (76)

Worcester Poly. (2)
Yale (1)

Columbia (2)
Cornell (2)
Florida State (1)
Georgia Inst. of Technology (1)

Table 8.1 (continued)

By Country (146)

Algeria (2)
Argentina (3)
Austria (1)
Belgium (1)
Brazil (5)
Canada (7)
Chile (1)
Columbia (1)
Egypt (3)
France (2)
Greece (4)
India (1)
Iran (3)
Iraq (1)
Italy (1)
Jordan (3)
Korea (9)
Malaysia (1)
Mexico (3)
Nigeria (1)
Pakistan (2)
R. of China (10)
Saudi Arabia (1)
Spain (2)
Turkey (1)
USA (76)
Venezuela (1)

Table 8.2

Sources of Financial Support
    (as of February 1981)

Research Assistantships   (53)
Teaching Assistantships   (18)
Instructor G   (1)
GE Foundation Fellowship   (1)
Hertz Fellowship   (1)
Ida Green Fellowship   (1)
Draper Fellowship   (1)
Fusion Technology Fellowship   (1)
Sherman Knapp Fellowship   (1)
NSF Fellowship   (2)
Thompson Fellowship   (1)
HEW Grad./Prof. Opportunities Program   (1)
INPO Grad. Award   (3)
CAES Award   (1)
GSO Endowed   (1)
Medical Radiological Physics Training Program   (3)
Air Force   (1)
Army   (3)
ROTC   (1)
ACF Foundation Fellowship   (1)
Brazilian Ministry of Education   (1)
Govt. of Brazil   (3)
Govt. of Columbia   (1)
Govt. of Canada   (3)
Govt. of Saudia Arabia   (1)
Govt. of France   (2)
Govt. of Mexico   (3)
Govt. of Spain   (2)
Govt. of Korea   (6)
Govt. of the Republic of China   (1)
Institute of Nuclear Energy Research, Taiwan   (1)
Argenitine Navy   (3)
Venzuelan Navy   (1)
Chilean Navy   (1)
Self-supported   (11)
Did not list support   (10)

Table 8.3

Activities of Nuclear Engineering Department Graduates

(Place of first employment -- information current as of June 1981)

U. S. Industry and Research (314) (29.3%)

Areodyne Research Inc.	Georgia Power Co.
Aerojet Nuclear	General Atomic (2)
Air Research Mfg. Co.	General Dynamics, Elec. Boat (7)
Allis Chalmers (2)	General Electric (24)
American Electric Power	Gulf General Atomic (18)
Amer. Science and Eng.	Hercules
APDA (2)	Hewlett-Packard
Assoc. Planning Res.	Hughes (5)
Atomics Int. (10)	Hybrid Systems
Avco (6)	Hanford Eng. Dev. Lab.
Babcock & Wilcox (8)	IBM (2)
Battelle Northwest (8)	Industrial Technology Services Inc
Bechtel (4)	Inst. for Defense Analysis
Bell Telephone Lab.	Internuclear Co.
Bendix	Isotopes, Inc.
Bettis (4)	
Burns & Roe (2)	Jackson & Moreland
	Jet Propulsion Lab
California Oil	
Combustion Eng. (18)	Lane Wells
Commonwealth Edison (13)	A. D. Little (4)
Computer Processing	Lockheed
Conn. Mutual Life Ins.	Long Island Lighting Co.
Consolidated Edison	
Consultant	Management & Tech. Cons.
Consumers Power	Martin-Marietta (2)
Cornell University (research)	Mass. General Hospital (3)
	Maxson Electric
Detroit Power Co.	McKinsey & Co.
Direct Energy Con. Lab.	MIT (research) (15)
Douglas Unite Nucl. (2)	Mobil Oil
Draper Lab	Monsanto
Duke Power & Light (2)	MPR Associates (3)
Dynatech R/D Co.	
	National Academy of Eng.
Ebasco (2)	New England Nuclear Corp.
Edgerton, Germ. & Grier	New England Power Service Co.
EDS Nuclear	New York Law Firm
EG & G (4)	North American Rockwell (2)
	Northeast Util. Service (3)

Table 8.3 (continued)

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

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

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

Sanders Corp.
Science Applications (6)
Scientific Data Systems
Sloan Kettering Memorial Hospital
Smithsonian Astrophys. Obs.
Southern Calif. Edison (4)
Spire Corp.
Stanford Research Institute
S.M. Stoller Assoc.
Stone & Webster (11)
Systems Sci. & Eng.
Systems Control

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

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

Vacumm Industries

Westinghouse (25)

Yale (research) (2)
Yankee Atomic (14)

National Laboratories (87) (7.3%)
Argonne (16)
Brookhaven (7)
Knolls Atomic Power (17)
Lawrence Livermore (4)
Lawrence Radiation (5)
Los Alamos (11)
Oak Ridge (16)
Sandia (7)
Savannah River (4)

Further Study (183) (15.3%)
MIT (153)
Other (30)

U.S. Government (193) (16.1%)
Atomic Energy Commission (22)
Air Force (15)
Army (78)
Army Nuc. Def. Lab.
Army Research Lab (2)
Ballistic Research Lab
Coast Guard
Dept. of Commerce
Energy Res. & Dev. Admin. (4)
Environmental Prot. Agency (2)
NASA
National Bureau of Standards (1)
Naval Research Lab
Navy (56)
Nuclear Regulatory Comm. (4)
Peace Corps
Picatinny Arsenal
Dept. of Public Health

Teaching (57) (4.8%)
American University (Wash., D.C.)
Brooklyn College (CCNY)
Cal. State (Long Beach)
Carnegie Mellon Univ.
Case Institute
Catholic Univ. of America
Cornell
El Rancho High School
Georgia Inst. of Tech.
Howard University
Iowa State

Table 8.3 (continued)

Teaching (continued)

Kansas State	Brazil (19)
Lowell Tech (4)	Canada (12)
Loyola University	Chile (4)
Mass. Maritime Academy	Columbia, S.A.
Michigan State University	England (2)
MIT (11)	France (19)
Northeastern University	Germany (2)
Northwest Nazarene	Greece (6)
Pennsylvania State	India (13)
Princeton	Indonesia
Radford College	Iran (26)
Rensselaer Polytech.	Israel (3)
Swarthmore	Italy (5)
Texas A & M	Japan (14)
U.S. Military Academy	Libya (1)
Univ. of Brit. Columbia	Malaysia
Univ. of California (6)	Mexico
Univ. of Florida	Nigeria
Univ. of So. Florida	Norway
Univ. of Illinois	Pakistan (3)
Univ. of Kentucky	Philippines
Univ. of Missouri (2)	Poland
Univ. of New Hampshire	Republic of China (9)
Univ. of Texas	Spain (13)
Univ. of Washington	Switzerland (7)
Univ. of Wisconsin	Turkey (4)
	Venezuela (5)

Foreign (190) (16.0%)
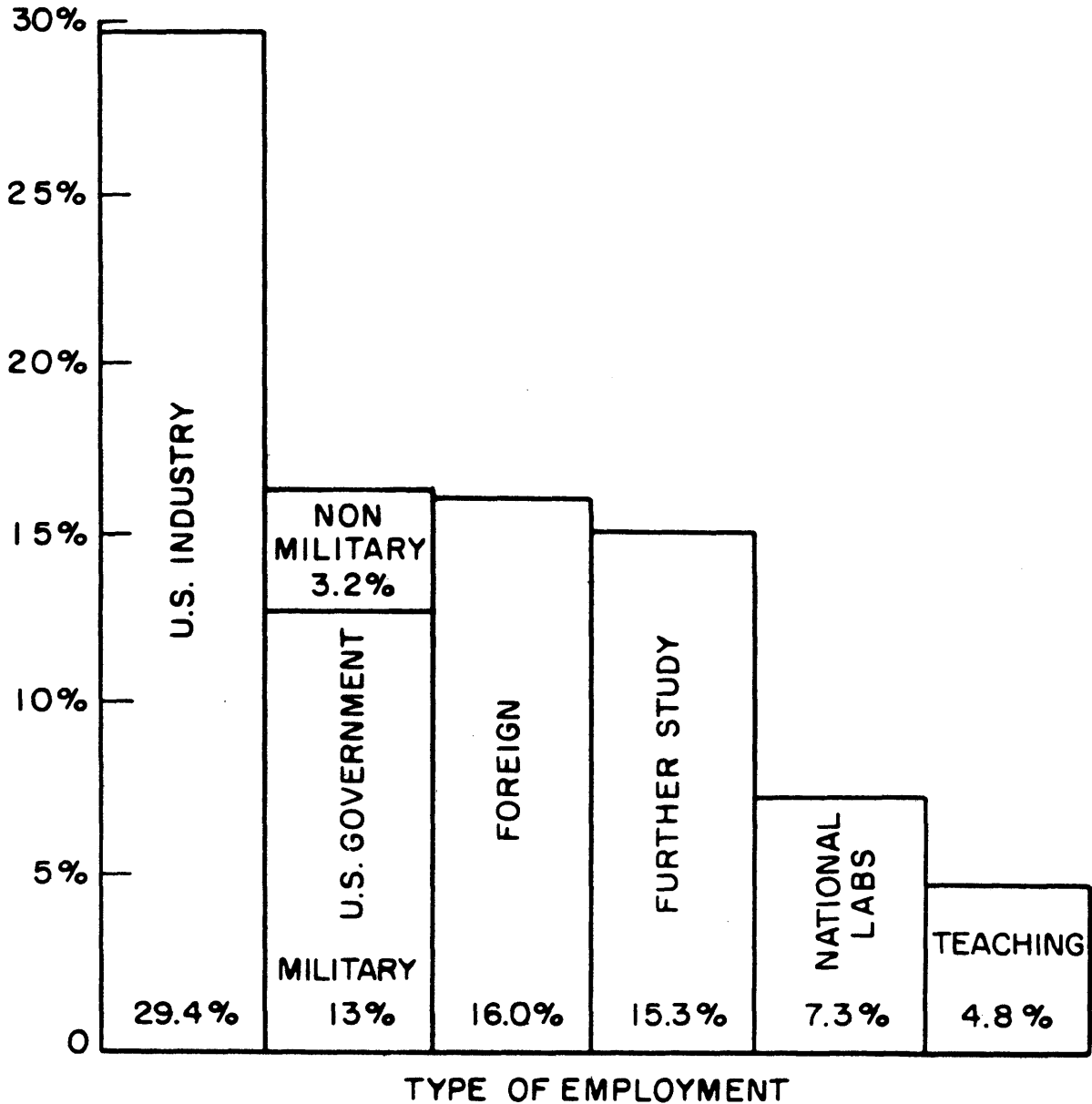
NOT REPORTED (133) (11.1%)

Algeria (3)
Argentina (2)   TOTAL 1194*
Belgium (10)

*Records from early years are
   incomplete

FIGURE 8.1

DISTRIBUTION OF FIRST PLACE OF EMPLOYMENT
OF GRADUATES (REPORTED*)

*EXCLUDES 133 (11.1%) STUDENTS NOT REPORTED

9. List of Theses

The following theses were submitted to the Nuclear Engineering Department in September 1979:

N.A. Al-Mohawes, "Analytical Nodal Technique for Solving the Multigroup, Two-Dimensional Static Diffusion Equation", SM Thesis.

E.C. Chua, "The Effect of Radiation Cooling on the Ablation Rate of a Pellet in a Thermonuclear Plasma", BS/SM Thesis.

F. Correa, "An Evaluation of Tight-Pitch PWR Cores", PhD Thesis.

H. Hsieh, "Long Range Fuel Management for LWR Studies: FLACM Computer Code", NE/SM Thesis.

I. Lira Canguilhem, "A Modified Approach to the Modular Analysis of Complex Fault Trees", SM Thesis.

J.T. Maki, "Thermal Effects of Fuel Pellet Cracking and Relocation", SM Thesis.

W.J. Parkinson, "Sensitivity Analysis of the Reactor Safety Study", SM Thesis.

K. Rubenstein, "Time Evolution of Bulk Fluid Motion in a Low Collisionality Toroidal Plasma", PhD Thesis.

The following theses were submitted to the Nuclear Engineering Department in February 1980:

B. Atefi, "An Evaluation of the Breed/Burn Fast Reactor Concept", ScD Thesis.

F.R. Best, "The Recovery of Uranium from Seawater", PhD Thesis.

D.R. Boyle, "Transient Effects in Turbulence Modeling", PhD Thesis.

M.E. Byers, "An Evaluation of U.S. Export Controls and Their Impact on an Emerging Weapons Development Program", SM Thesis.

S.H. Chang, "Buoyancy Effects in Mathematical and Numerical Turbulence Modeling", SM Thesis.

K.W.T. Chiu, "Fluid Mixing Studies on a Hexagonal, 37-Pin, Wire Wrap Rod Bundle", SM Thesis.

J.H. Cho, "An Analysis of Balanced Bimodal Nuclear Fuel Strategies", NE/SM Thesis.

G.W. Dansfield, "The Influence of Boron on Fusion Reactor Materials During Helium Embrittlement Simulation", SM Thesis.

Z.B. Djordjevic, "A Study of Graphite-Intercalated Compounds", SM Thesis.

A.J.G. Faya, "Development of a Method for BWR Subchannel Analysis", PhD Thesis.

W.A. Fisher, "Numerical Modeling of a Fast Neutron Collimator for the 'Alcator A' Fusion Device", SM Thesis.

E.S. Gordon, "Improved Fuel Pin Conductance Model for Use in the MEKIN Code", SM Thesis.

D.P. Griggs, "Steady-State and Transient Thermal-Hydraulic Design of an Ultra-Tight Pitch Pressurized Water Reactor Core", NE/SM Thesis.

A. Kamal, "The Effect of Axial Power Shaping on Ore Utilization in Pressurized Water Reactors", SM Thesis.

R.K. Lester, "Laser Isotope Separation for Uranium Enrichment: A Technology Assessment", PhD Thesis.

D. Litai, "A Risk Comparison Methodology - For the Assessment of Acceptable Risk", PhD Thesis.

W.T. Loh, "An Evaluation of the Fast-Mixed Spectrum Reactor", SM Thesis.

J. Medina Aguiar, "Desalination Alternatives for the Canary Islands", SM Thesis.

M. Modarres, "Reliability Analysis of Complex Technical Systems Using the Fault Tree Modularization Technique", PhD Thesis.

R. Racana, "Stress Analysis Techniques in Fusion Reactors", PhD Thesis.

M. Raeisinia, "Qualitative Common Cause Failure Analysis of Complex Systems", SM Thesis.

M. Sharafi, "CIVEX: Assessment of the Process and Institutional Problems", NE/SM Thesis.

L.B. Tan, "MEKIN numerical Modeling and Simulation of the SPERT-III E-Core Transient Tests", SM Thesis.

M.L. VanHaltern, "A Sensitivity Study of Thermal Hydraulic Correlations in the Computer Code MEKIN", SM Thesis.

The following theses were submitted to the Nuclear Engineering Department in June 1980:

D. Bendedouch, "^{68}Ga Labeled Protein", SM Thesis.

P.E. Cavoulacos, "Probabilistic Analysis of Nuclear Fuel Cycle Economics", SB/SM Thesis.

D.P. Chou, "Molecular Dynamics Simulation of Self-Diffusion in Hard-Disk Fluids", NE/SM Thesis.

D.E. Coate, "Uncertainties in Energy Technology Assessments", SM Thesis without specification.

B. De Celis, "Molecular Dynamics Simulation Studies of Fracture in Two Dimensions", NE/SM without specification.

W.C. Doskocil, "Tokamak Plasma Modeling: Burn Stability and Radial Dynamics", SM Thesis.

M.R. Granziera, "A Two Dimensional, Two Fluid Model for Sodium Boiling in LMFBR Fuel Assemblies", PhD Thesis.

G.M. Greenman, "A Quasi-Static Flux Synthesis Temporal Integration Scheme for an Analytic Nodal Method", PhD Thesis.

J. Hangst, "Ion Optics of an Electrostatic Lens", SM Thesis.

J.T. Hawley, "Hydraulic Studies of Liquid Metal Fast Breeder Reactor Sub-assemblies", SM Thesis.

D.Y. Hsia, "Steam Generator Flow Instability Modeling", PhD Thesis.

M. Kadri, "An Analysis of the Effect of Ultratight Pitch in PWR Cores", SM Thesis.

R. Karimi, "Qualitative and Quantitative Reliability Analysis of Safety Systems", ScD Thesis.

J.E. Kirsch, "Determination of Spatial Distributions of Boron-10 in Soft Tissue by Use of Alpha-Autoradiographic Techniques", SB/SM Thesis.

H.J. Lee, Jr., "An Application of the Liquid Drop Model to the Prediction of Multiplicity Distributions in Fission Product Gamma Decay", SM Thesis.

J.G. Lepervanche-Valencia, "Safety Analysis of Containment Inerting in Boiling Water Reactors", NE/SM Thesis.

A.E. Levin, "Development of a Model to Predict Flow Oscillations in Low-Flow Sodium Boiling", ScD Thesis.

W.P. Marable, "Fusion Neutron Spectroscopy", BS/SM Thesis.

R.F. Najafabadi, "Design of a Computerized Control System and its Performance Test of a Double Crystal Neutron Monochromator at MITR-II", NE/SM Thesis.

R.E. Potok, "Particle Orbits and Diffusion in Torsatrons", ScD Thesis.

R.C. Smith, "Modeling of Fuel-to-Steel Heat Transfer in Core Disruptive Accidents", PhD Thesis.

M.S. Tillack, "Development and Verification of the LITFIRE Model for Predicting the Effects of Lithium Spills in Fusion Reactor Containments", SM Thesis.

T. Uchikawa, "Design Study of TORSATRON Power Reactors on the Basis of Maintenance Requirements", SM Thesis.

G.S. Was, "Synergistic Effects of Thermal Treatment and Cathodic Polarization on the Fatigue Crack Growth Behavior of Inconel 600", ScD Thesis.

G.J. Wilson, "Development of Models for the Sodium Version of the Two-Phase Three-Dimensional Thermal-Hydraulics Code THERMIT", SB/SM Thesis.

H.R. Wyle, "Quantitative Study of Patient Motion Using Fluoroscopy", SM Thesis.

The following theses were submitted to the Nuclear Engineering Department in September 1980:

S. Akbar, "Design Considerations for a Toroidal Detector for Positron Emission Computerized Tomography", SM Thesis.

R. Baradaran Hossein, "Risk Analysis of High-Level Waste Management at West Valley, N.Y.", SM Thesis.

W.C. Booth, "The Approach to Nuclear Safety Used in the Navy Nuclear Program and its Applicability to the U.S. Commercial Nuclear Industry", SM (Technology and Policy) Thesis.

K.J. Burns, "Thermal Hydraulic Studies of a 37-Pin LMFBR Wire Wrapped Rod Bundle", SB/SM Thesis.

W.C. Booth, "The Approach to Nuclear Safety Used in the Navy Nuclear Program and its Applicability to the U.S. Commercial Nuclear Industry", SM (Technology and Policy) Thesis.

K.J. Burns, "Thermal Hydraulic Studies of a 37-Pin LMFBR Wire Wrapped Rod Bundle", SB/SM Thesis.

A. Chenini, "Set-Theoretic Control of a Pressurized Water Nuclear Power Plant", NE/SM Thesis.

R.W. Davis, "The Modified Mako Zero-Dimensional Plasma Simulation Code", NE/SM Thesis.

D.A. Dube, "Development of a Fully Implicit Two-Fluid, Thermal-Hydraulic Model for Boiling Water Reactor Transient Analysis", PhD Thesis.

C.P. Geffray, "Nuclear Reactor (PWR) Pressurizer Real Time Modeling for Sensor Validation", SM Thesis.

T.E. Greene, "Development and Evaluation of Techniques for Thermal-Hydraulic Analysis of LMFBR Fuel Assemblies", SM Thesis.

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K.J. Kearfott, "Measurement of Glucose Metabolism Using Positron Imaging and ^{18}F-Labeled Analogs", ScD Thesis.

J.E. Kelly, "Development of a Two-Fluid, Two-Phase Model for Light Water Reactor Subchannel Analysis", PhD Thesis.

D.B. Laning, "Average Atomic Nuclear And Electron Density Analysis with Computerized Axial Tomography - Experimental and Computational Feasibility Studies", ScD Thesis.

R.A. Loretz, "The Determination of Equivalent Diffusion Theory Parameters by Local Implementation of the Koebke Method, SM Thesis.

J.S. Marks, "Computational Methods for Thermal and Mechanical Analysis of Nuclear Reactor Fuel Rod Transients", SM Thesis.

K.S. Smith, "Spatial Homogenization Methods for Light Water Reactor Analysis", PhD Thesis.

C.E. Thomas, Jr., "An Experimental Investigation of Solid Hydrogen Pellet Ablation in High Temperature Plasmas Using Holgraphic Interfermetry and Other Diagnostics", PhD Thesis.

The following theses were submitted to the Nuclear Engineering Department in February 1981:

T. Boutros-Ghali, "Theory of Two Point Correlation Function in a Vlasov Plasma", PhD Thesis.

M.A. deFraiteur, "Correlating Economic Optimum Burnup for Light Water Reactors", SM Thesis.

J.L. Jones, "Divertor Plasma Modeling Using Random Electrostatic Deceleration of Intense Ion Beams", SM Thesis.

J.D. Koclas, "A Subnoding Technique in the Context of the Analytic Nodal Method", PhD Thesis.

P.J. Krane, "Safety Aspects of Thermonuclear Reactor Designs Employing Use of Lithium-Lead Alloys", SM Thesis.

K.E. Kreischer, "High Frequency Gyrotrons and Their Application to Tokamak Plasma Heating", PhD Thesis.

D.B. Lancaster, "An Assessment of Internal Blankets for Gas-Cooled Fast Reactors", PhD Thesis.

L.G. Lobo, "Coastdown in Light Water Reactors as a Fuel Management Strategy", SM Thesis.

J.N. Loomis, "Reactor Thermal-Hydraulic Analysis -- Improvement and Application of the Code COBRA-IIIC/MIT", NE/SM Thesis.

J.E. Rivera, "Performance of Light Water Reactor Fuel Rods During Plant Power Changes", NE/SM Thesis.

I.I. Saragossi, "Assigning a Value to Plutonium: Methodology and Policy Implications", PhD Thesis (interdepartmental energy program)

J.A. Sefcik, "Analysis of Strategies for Improving Uranium Utilization in Pressurized Water Reactors", PhD Thesis.

E. Si Ahmed, "Crystallite Orientation Analysis for Zircaloy Application of Three Dimensional Representation of Textures", NE/SM Thesis.

E.T. Testart, "Structure and Properties of a Rapidly Solidified Titanium Modified 316 Stainless Steel", SM Thesis.

S.F. Wang, "Natural Convection Effects in Isolated and Interconnecting Subchannels of a Reactor Fuel Assembly", PhD Thesis.

The following theses were submitted to the Nuclear Engineering Department in June 1981:

O.A. Adegbulugbe, "Structural Design Limits for Fusion First Walls", ScD Thesis.

G.W. Allard, "Application of the Analytic Nodal Method to Graphite and D_2O Moderated Systems", SM Thesis.

G. Baltra Aedo, "Design of a Coordinated Plant Control System for a Marine Nuclear Propulsion Plant", NE/SM Naval Architect and Marine Engineering Thesis.

S.H. Chang, "Comparative Analysis of Numerical Methods for the Solution of Navie-Stokes Equations", PhD Thesis.

A.Y.C. Cheng, "Homogenization of BWR Assemblies by Response Matrix Methods", PhD Thesis.

A.C. Ferreira, "Stability Limits With Waves in Toroidal Configurations with Finite Plasma Pressure", PhD Thesis.

F.R. Field III, "An Assessment of the Expected Value of a Pre-Transportation Testing Program for High Level Nuclear Waste Forms", SM Thesis.

R. Hamza, "Behavior of Buoyant Moist Plumes in Turbulent Atmospheres", PhD Thesis.

D.R. Hanchar, "Tritium Permeation Modeling of a Conceptual Fusion Reactor Design", SM/BS Thesis.

J.W. Jackson, "Thermal Hydraulic Analysis of the Bypass Flow in Boiling Water Reactors", SM/BS Thesis.

J.W. Johnson, "The Effect of Non-Local Alpha Energy Deposition on Torsatron Reactors, SM Thesis.

S.P. Kao, "Disperses Flow Heat Transfer and Prediction of Critical Heat Flux in Light Water Reactorss", SM Thesis.

C.M. Malbrain, "Analytical Characterization of Spent Fuels and High Level Wastes and Application to the Thermal Design of a Geological Repository in Salt", SM Thesis.

J.M. McMurray, "Investigation of Tokamak Solid Divertor Target Options", SM Thesis (Nuclear and Mechanical).

T.J. Miller, Jr., "Measurement of Blood Flow Through Proton Activation of Positron Emitting Tracers", SM Thesis.

J.J. Molina, "Analysis of the Feedwater System for a Pressurized Water Reactor", SM Thesis (Nuclear and Mechanical).

G.Y. Nakayama, "Linearized Model Real Time Reactor Simulation", SM/BS Thesis.

R.S. Ornedo, "Development and Assessment of a Pressurized Water Reactor Core Model for Real-Time Diagnostics", SM Thesis.

M.G. Plys, "The Neutronics of Internally Heterogeneous Fast Reactor Assemblies", SM/BS Thesis.

B.W. Rhee, "Thermal Hydraulic Modeling of Pressurized Water Reactor Steam Generator", SM Thesis.

S.R. Shanfield, "Transient Cooling in Internally Cooled, Cabled Superconductors", PhD Thesis.

Y.H. Yang, "Reliability Analysis of the Control Rod Drive Scram System of the Vermont Yankee Nuclear Power Plant", NE/SM Thesis.

G.P. Yu, "Relationship of Material Properties to the Design of a Fusion Reactor First Wall", ScD Thesis.