MITNE-230

ACTIVITIES IN NUCLEAR ENGINEERING AT MIT

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

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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.

During the year and a half since the last report was prepared much has happened that effects the nuclear industry. The serious nuclear accident at Three Mile Island has caused considerable concern about nuclear power. At the same time the problems in the Middle East have continued to demonstrate the vulnerability of the industrialized world to events in that area. This has intensified the determination to develop substitutes for oil. Following his review of the Report of the President's Commission on the Accident at Three Mile Island the President has stated the necessity of using nuclear power as part of the solution to the energy problem. Nevertheless, the electric industry is apprehensive about ordering new nuclear power plants until the licensing process is more certain.

There are numerous studies and investigations of the Three Mile Island accident, not all of which are yet complete. It seems clear that until all of these reports are finished, and the Nuclear Regulatory Commission has responded to them, a cloud of uncertainty will hang over the licensing process. There are hopeful signs, however. Many of the improvements suggested by the President's Commission on the Accident at Three Mile Island have already been implemented and so progress has been made. To date the various proposed fixes being discussed seem reasonable and are of a type that can be practically implemented. If this situation remains true then it seems possible that the issue can be resolved within 12 to 18 months. Hopefully the whole licensing process will become clearer and better defined as part of this effort. If so then it may produce a climate in which new plants will once again be ordered. In the meantime it seems clear that the 100 or so plants now under construction will almost all be completed. These alone will provide considerable demand for nuclear engineers.

Today about 13% 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.

In June of 1979, 20 freshmen chose to major in Nuclear Engineering. This was encouraging since it happened shortly after Three Mile Island and was an increase over the 15 students who chose Nuclear Engineering the previous year. Nevertheless, the Department has not been able to reach its goal of 80 students in the undergraduate program. This year the total enrollment is 42 -- 19 sophomores, 9 juniors and 14 seniors. The junior class is down to 9 because of transfers of some of the original 15 students. The present sophomore class of 19 is encouraging and if this trend maintains itself an undergraduate enrollment of over 50 could be expected.

The graduate enrollment in 1978-79 was 174 students. During the past year the Department awarded a total of 65 advanced degrees including 15 Doctorates, 10 Nuclear Engineers, and 40 Masters of Science. This represents about 10% of the advanced degrees in Nuclear Engineering awarded nationally.

Despite the fall-off in nuclear orders in recent years, the demand for trained nuclear engineers continues to grow. The best projections available indicate that about 1,500 S.B. graduates and 500 to 800 advanced degree (S.M. and Ph.D.) graduates per year will be needed to support the nuclear industry. These numbers do not include the needs of the growing R&D programs in fusion. Today, the total United States supply of S.B. graduates is about 600 and the number of advanced Nuclear Engineering degrees being awarded is about 650. Currently the short-falls are made up by hiring engineers from other disciplines who have some nuclear courses. Because the demands are not expected to decrease for the next decade it seems likely that there will continue to be a shortage of trained nuclear engineers for some time.

Table 1

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

Academic Year	1972/73	85
	1973/74	102
	1974/75	103
	1975/76	149
	1976/77	129
	1977/78	139
	1978/79	105

Table 2

Enrollment in M.I.T. Nuclear Engineering Department

1971/72	117
1972/73	113
1973/74	127
1974/75	139
1975/76	200
1976/77	222
1977/78	215
1978/79	218

Financial:

The total dollar volume of research supervised by the Nuclear Engineering Faculty during fiscal year 1979 was approximately $2.3M. This represents an increase of $248K, or approximately 12% over the comparable fiscal year 1978 figure of $2.1M.

Fiscal 1979 saw a net reduction in the research volume actually assigned to the Nuclear Engineering Department of $325K - down from $1,382K in fiscal 1978 to $1,057K. Approximately $275K of U.S. Department of Energy and National Science Foundation funding was administratively transferred to the MIT Plasma Fusion Center ($265K) and the MIT Research Laboratory of Electronics ($10K), respectively. Another $110K of research sponsored by DHEW ($80K), DOD ($25K) and NSF ($5K) was brought to conclusion. These reductions in volume were offset, in part, by a $60K increase in the combined support received from the Nuclear Regulatory Commission, national laboratories and private industry.

Approximately 35% of the research conducted within the Department of Nuclear Engineering in fiscal 1979 was sponsored by non-governmental sources, chiefly the Electric Power Research Institute. Investigations in areas other than plasma fusion continued to be funded by the U.S. Department of Energy in an amount approaching 30% of the total NED research volume. Research sponsored by the National Science Foundation in fiscal 1979 was 12% of the Department total and the Nuclear Regulatory Commission funding represented almost 9% of the NED research volume.

The Department continued to receive fellowship support from the General Electric Foundation, Northeast Utilities, and the proceeds from the Theos J. Thompson Memorial Fund. Department spending in this area increased by approximately 45% in fiscal 1979 - up from $24,600 to $35,600.

In Section 2 of this report there is a discussion of developments within the Department since October 1978. 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 OCTOBER 1978

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 the academic program has undergone only modest change. The Department is planning to expand its offerings in more broadly-based energy courses. Professor Lester has proposed a course on nuclear energy policy analysis which we anticipate offering in the spring 1981. This course will analyze interactions between technological developments and institutions in the nuclear fuel cycle and explore the consequences of these interactions for nuclear power policy. Professor Rose contributed to the development of a new course entitled, "The Finite Earth: Agendas for a More Just, Sustainable and Participatory Society", which is offered jointly with the Departments of Political Science, Humanities and Architecture. Depending on the response to these new courses, the Department may continue to expand its curriculum in this area. In the fusion area a new course on MHD theory was developed by Professor Friedberg. This is the first course on MHD theory offered at the Institute and it is designed to meet the growing interest and need in the fusion area.

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 two years ago. A total of 6 students -- 3 juniors and 3 seniors -- are now in the program. We continue to try to increase the number of participatory companies to accommodate the growing interest of students in the program. This program is described in Section 4.8.

The continued high level of research support has enabled the Department to provide research support for about 60 students; in addition another 53 are supported by a variety of teaching assistantships and fellowships.

During the summer of 1979 the Department offered a Special Summer Program on Nuclear Power Reactor Safety directed by Professors N. Todreas and N.C. Rasmussen. This program is an important way of establishing contacts between the Department and the various parts of the nuclear industry, as well as a means of providing added income. The 170 registrants in this program accounted for 10% of the registrants in all MIT Special Summer Programs. The Nuclear Power Reactor Safety Program continues to have one of the largest enrollments in the Institute's Special Summer Programs.

In response to concern regarding the quality of press coverage of nuclear power-related issues a special seminar, Nuclear Power: Challenge for Journalists, was offered in October 1979. The seminar was directed by Professor Golay 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 power issues in a fashion which is as objective as possible, so that reporting of future nuclear power stories could be characterized more by interpretation and independent understanding than has been the case in the past. It was carefully structured to avoid social advocacy presentations. The seminar, which was self-supporting, attracted approximately 40 participants from the United States, Canada, Japan and Denmark.

Professor Rose played a key role in organizing the World Council of Churches Conference on Faith, Science and the Future, held at MIT during the summer of 1979. This successful conference was attended by about 400 people -- engineers, scientist, church delegates, public administrators, and students from all over the world.

The Nuclear Engineering Faculty members continue to be active outside the Department in both MIT non-departmental activities and in a wide variety of activities outside of MIT for professional societies, government, and industry.

Professor Sow-Hsin Chen was invited by Academia Sinica of The Peoples Republic of China to visit the Physics and Nuclear Energy Research Laboratories in Peking and Shanghai. During his one-month stay in May and June, he gave eight lectures on neutron physics. Professor Michael Driscoll completed his term as Chairman of the Reactor Physics Division of the American Nuclear Society, but continues to serve on various division committees. At the Institute he continues as Faculty Chairman of the Undergraduate Seminar Program. He was also recently appointed to the Institute's Committee on Educational Policy as the representative of the School of Engineering, and to the Committee on the Humanities, Arts and Social Sciences. Professor Michael Golay is currently on sabbatical leave at the Laboratoire National D'Hyraulique near Paris. He is also currently Chairman of the Environmental Sciences Division of the American Nuclear Society, and until recently served as Chairman of the Institute's Environmental Engineer Degree Program. Professor Elias Gyftopoulos continues as Chairman of the National Energy Council of Greece. Professor Allan Henry continues to serve on the Institute's Committee on Graduate School Policy. He is a member of the Journal Advisory Board of the American Nuclear Society and serves as an advisor to the Nuclear Regulatory Commission. Professor Mujid Kazimi is a member of the Heat Transfer Committee and is Chairman-designate of the Committee on Nucleonics Heat Transfer of the American Institute of Chemical Engineers. He also serves as Director of the Northeastern Section of the ANS. During the past year, Professor Kazimi has participated in the International study of INTOR Fusion Reactor. Professor Lawrence Lidsky serves as editor of the new Journal of Fusion Energy. Professor Peter Politzer has taken a one-year leave of absence to serve full time on the Plasma Fusion Center's research staff. Professor David Rose has for the past four years been a member of the National Academy of Sciences Committee on Nuclear And Alternative Energy Systems. Professor Kenneth Russell serves as Chairman of the Institute's Student Activities Development Board and as Chairman of the Heat Treatment Committee of Metallurgy for the AICHE. Professor Neil Todreas serves as Vice Chairman of the Technical Working Group on Thermal Hydraulics for the American Nuclear Society and Chairman of the Heat Transfer Division, Honors and Awards Committe of the ASME. He also is on the Editorial Board of the thermal design area of the Journal of Nuclear Engineering and Design. Professor Sidney Yip was on a sabbatical leave in West Germany during the 1979 Spring semester. He spent approximately three and a half months each at the Physics Department, Technical University of Munich and the Institute for Solid State Research, KFA-Julich. Professor Rasmussen was appointed to the Utility Scientific Advisory Committee organized by EPRI to review the Three Mile Island accident and make recommendations to the utiltiy industry. He was appointed a senior consultant to the Defense Science Board. He continues to serve as Chairman of the MIT Reactor Safeguards Committee on which Professors Driscoll, Lanning and Harling also serve. He serves as Chairman of the EG&G INEL Scientific Review Committee and also as Chairman of the Fusion Safety Review Committee at that Laboratory. He is a member of the Board of Directors of the ANS.

Several of the Department faculty were recognized with honors during the past year. Professor David Rose received the J.R. Killian Faculty Achievement award for the academic year 1979-80. This award, made annually by the Institute on the the advice to a faculty selection committee, is given to the faculty member who, in the opinion of the selection committee, has made the greatest contribution toward the Institute's overall excellence. Professor Sidney Yip was a recipient of a U.S. Senior Scientist Award given by the Alexander von Humboldt Foundation. Professor John Meyer received the Outstanding Teacher Award of the MIT Student Chapter of the American Nuclear Society. Professor Manson Benedict was presented the Henry DeWolf Smyth Nuclear Statesman Award by the American Nuclear Society and the Atomic Industrial Forum. This award recognizes outstanding service in developing and guiding the uses of atomic energy in constructive channels. Professor Norman Rasmussen was elected to the National Academy of Sciences. He also received an honorary doctorate from the Catholic University of Leuven.

During the last year and a half there have been a number of changes in the faculty. All the members of the Department were greatly saddened by the sudden passing of Professor Louis Scaturro. He was an intellectually stimulating colleague and a warm friend who will be greatly missed. In the area of plasma theory we have greatly strengthened our staff through the addition of Dr. Jeffery Freidberg formerly of Los Almos as a new professor and Dr. Kim Molvig as a new Assistant Professor. Professor Ralph Bennett was appointed as Assistant Professor in the area of numerical methods to help fill the void created where Professor Kent Hansen took the new position of Associated Dean of Engineering. Professor Richard Lester was appointed Assistant Professor in the areas of energy policy and nuclear chemical engineering. Professor Mujid Kazimi was promoted to the rank of Associate Professor.

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. Conseqently 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 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.

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 analysing 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 transients. Studies related specifically to this area are discussed in Section 3.1.6.

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 may 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 program QUANDRY continues to be one of the most efficient nodal codes for the analysis of light water power reactors. Continued testing demonstrates that for reactors composed of large homogenized nodes it provides nodal powers of a given accuracy about 1000 times faster than does a comparable finite difference code.

QUANDRY has been extended to treat transient problems (see Section 3.1.6). But for both the static and the dynamic case certain problems remain which we are first examining for static conditions. These problems are discussed in the following paragraphs.

2) The Representation of Transverse Leakage

If one considers little elements of length dx at various locations, x, in the X-direction of a node in XYZ space, there is, in general, a different neutron leakage out of the node in the Y and Z directions for every dx. Such neutron leakage is called "transverse leakage". (There are, of course, also neutron leakages transverse to the Y and Z-directions.)

The only assumption made in deriving the QUANDRY equations from the two-group diffusion equations is that the transverse leakage in directions perpendicular to, say, the X-direction is a certain quadratic function of x. However, for nodes next to a light water reflector the particular quadratic function used in the current derivation is a poor representation of the actual shape, and although the errors in nodal power that result are not serious, there is room for improvement.

During the past year we have worked out the algebra of an alternative representation of the transverse leakage. However, since there is some danger that its use might significantly increase running time, and since, subsequently a more attractive alternative came to light (See #5 below) we have deferred implementing this scheme in QUANDRY.

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 is now being debugged.

4) Extension to More Than Two Groups

Both energy groups are treated simultaneously in QUANDRY. This accounts partly for the efficiency of the code. However, the algebra becomes extremely complicated if a direct extension of the present algebra to more than two groups is attempted. We have worked out an alternate method for treating the basic equations and successfully tested it in one dimension. The extra cost in computing time which would result if a full three-dimensional implementation were carried out does not look to be excessive. However, because of lack of sponsor support and since there may be other cheaper ways to extend QUANDRY to more than two groups, we have deferred a three-dimensional implementation.

5) 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.

In one dimension we had earlier established that homogenized parameters could be found that will exactly reproduce reaction and leakage rates. However, numerical tests have indicated that the resultant parameters are quite unphysical. For example, although the total fission rate in a node is given correctly by the homogenized parameters, the fission rate in the fast group can be negative. Because of this artificiality and since the method of generating the homogenized parameters can not be extended to more than one dimension we have not pursued this approach further.

Instead we are implementing an extension of an idea suggested by Klaus Koebke, a reactor physicist working at KWU. Koebke pointed out that exact equivalent homogenized group diffusion parameters can be found provided one permits the (artifical) flux that results when these constants are used to be discontinuous across nodal surfaces. Introducing such discontinuities into QUANDRY is particularly simple, and the code has been altered to accept them.

At first Koebke's scheme seems circular since in order to find the exact homogenized parameters and discontinuity factors it is necessary to know the ratios of nodal-averaged reaction rates and leakage rates for each node in the heterogeneous core. In fact, however, all homogenization methods are really schemes for obtaining this information in an approximate way (i.e. without solving the full heterogeneous core problem). Previously knowing the exact reaction rates would not have helped since no set of nodally constant diffusion theory parameters could have reproduced them. However, Koebke's idea removed this limitation. Hence, now the more exact the estimation of the ratios of nodal-averaged leakage and reaction rates, the more exact will be the final global answer.

Another intriguing possibility arises in this connection. If an exact estimate of the heterogeneous nodal behavior were available, nodal models much simpler than QUANDRY could be made to yield the correct global eigenvalue and nodal power distribution. Thus a model very similar to a one-group finite difference approximation could be used for the global problem and results (eigenvalue and nodal power) would match exactly the same quantities edited from a few group finite difference solution for the full heterogeneous core. This suggests that the most efficient way to analyse for the criticality and power distribution throughout a reactor will be to match the work required to estimate the relative nodal reaction and leakage rates for the heterogeneous core with that required to solve the global problem. The expectation is that more exact nodal methods such as QUANDRY will permit the use of less exact homogenized parameters whereas crude nodal schemes will require very exact parameters.

In order to pin down one end of this hypothesis we attempted to use a rather crude nodal model in conjunction with homogenized parameters obtained in an approximate way. These approximate parameters were sufficiently forgiving that, if they were used in QUANDRY, the resultant maximum error in nodal power would be ≃2%. However, with the crude nodal scheme the parameters were much less forgiving, and errors in average nodal power in excess of 10% were found.

Our present plans are to use response matrices to estimate reaction rates and leakage rates for the nodes making up the heterogeneous core. We expect that this procedure will be sufficiently forgiving that we can find homogenized parameters and discontinuity factors for a QUANDRY model involving a constant (rather than a quadratic) transverse leakage and still obtain accurate global results. If so, the difficulties, described in Part 2 above, of finding the correct quadratic transverse leakage shape will disappear.

Investigators: Professor A.F. Henry; Messrs. N. Al-Mohawes, A. Cheng, J. Cho, C. Hoxie, A. Jodidio, C. Mak, A. Morshed, K. Smith, F. Yarman.

Support: Electric Power Research Institute (approximately $100,000/year)

Related Academic Subjects:

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

Recent References:

A.A. Morshed, Equivalent Diffusion Theory Parameters for Slab Geometry, SM Thesis, MIT, Nuclear Engineering Department (September 1978).

A.F. Henry, B.A. Worley and A.A. Morshed, "Spatial Homogenization of Diffusion Theory Parameters", IAEA Technical Committee Meeting on Homogenization Methods in Reactor Physics, Lugano, Switzerland (November 1978).

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

A. Jodidio, Determination of Nodal Coupling Coefficients Using Response Matrices, SM Thesis, MIT, Nuclear Engineering Department (June 1979).

N. Al-Mohawes, Analytical Nodal Technique for Solving the Multigroup, Two-Dimensional Static Diffusion Equation, SM Thesis, MIT, Nuclear Engineering Department (September 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).

3.1.3 Fast Reactor Physics

Work in this area is underway in three areas -- two new and one old. New research projects were initiated during the past two years to investigate the physics design of the Fast Mixed Spectrum Reactor (FMSR) under subcontract to Brookhaven National Laboratory, and to evaluate the utility of heterogeneous core designs for gas cooled fast breeder reactors, under subcontract to General Atomic. The DOE-sponsored research program on fast reactor blanket research is now entering its eleventh year, and while the emphasis has moved away from experimental research using the Blanket Test Facility at the MIT Research Reactor, useful and interesting topics are still in prospect.

The FMSR is a new concept in fast reactor core design developed at BNL in response to the incentive to reduce the weapons-proliferation potential attributed to conventional breeder designs. In the FMSR natural uranium blanket assemblies are loaded into the core, and bred up to ≈7% plutonium enrichment, at which point they function as fuel assemblies to sustain core criticality and generate useful energy. Spent fuel need not be reprocessed, hence no commerce in separated weapons grade material is required. To realize this remarkable achievement, however, a very hard spectrum (requiring the use of metal fuel) and a very long in-core residence time (≈17 yrs) are necessary -- which leads to a high fluence. MIT was enlisted in early 1979 to carry out an independent evaluation of the neutronic performance of this concept, and to perform additional calculations to assess gamma and neutron heating in the core, blankets and moderator zones of the FMSR. This phase of the work has been successfully completed. FMSR neutronic feasibility has been validated, and useful contributions were made in several areas. Close collaboration with BNL researchers was mutually benefical. During CY 1980 the work will move into new areas, involving core optimization and the interface between thermal and physics design objectives.

While heterogeneous core designs have been studied for some time now with regard to LMFBR applications, almost nothing has been done to evaluate potential benefits for their use in GCFRs. Work was initiated in the summer of 1978 on a project to assess the beneficial and detrimental effects of using heterogeneous core configurations in a reference design GCFR. This work illuminated the need for simultaneous optimization, under the same envelope of constraints, of the standard homogeneous core design, and a considerable part of the overall effort was expended in this area. Although heterogeneous designs are not as attractive for the GCFR as for the LMFBR, since the need for a reduction in coolant positive void coefficient is not present, these cores nevertheless can provide interesting opportunities for alternative realization of design goals.

Although the Blanket Research Project is nearing the end of its productive lifespan, interesting work has been carried out in several areas over the past year and a half. Perhaps of greatest interest has been the development and evaluation of the "breed/burn" concept, in which thorium fueled blanket assemblies, after several in-core cycles, are moderated by insertion of zirconium hydride pins and shuffled into radial or internal blankets zones, where they then help sustain core power and criticality. Advanced versions of this concept can reduce the number of plutonium-bearing assemblies fabricated, transported and reprocessed by a factor of two.

Investigators: Professors M.J. Driscoll, D.D. Lanning; Computer Operations Assistant, R. Morton; Messrs. M. Saidi, D. Lancaster, B. Atefi, W.T. Loh, R. Rogus, F. Field, D. Medeiros; Senior Staff Assistant, A. Holman.

Support: U.S. Department of Energy (approximately $60,000 in FY 1980), Brookhaven National Laboratory (approximately $40,000 in FY 1980), General Atomic Company (approximately $30,000 in CY 1979).

Related Academic Subjects:

22.212 Nuclear Reactor Physics II

22.213 Nuclear Reactor Physics III
22.35 Nuclear Fuel Management

Recent References (since 1/1/78):

F.R. Field, Design of a Thorium Metal Fueled Blanket Assembly, S.B. Thesis, MIT, Nuclear Engineering Department (May 1978).

D.W. Medeiros, Experimental Comparison of Thorium and Uranium Breeding Potential in a Fast Reactor Blanket, S.B. Thesis, MIT, Nuclear Engineering Department, (June 1978)

M.J. Driscoll, et al., "A Comparison of the Breeding Potential of Th-232 and U-238 in LMFBR Blankets," Trans. Am. Nucl. Soc. 30 (November 1978).

M.S. Saidi and M.J. Driscoll, Interfacial Effects in Fast Reactors, COO-2250-37, MITNE-226 (May 1979).

B. Atefi, M.J. Driscoll and D.D. Lanning, An Evaluation of the Breed/Burn Fast Reactor Concept, COO-2250-40, MITNE-229 (December 1979).

D.B. Lancaster and M.J. Driscoll, "An Assessment of Internal Blankets for Gas Cooled Fast Reactors" (to be published).

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

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 project was initiated in May 1976 with an emphasis on thorium utilization and consideration of both recycle and non-recyle modes of operation. As the Nonproliferation Alternative Systems Assessment Program (NASAP) got underway in the U.S., and the International Fuel Cycle Evaluation (INFCE) was undertaken on an international level, the emphasis of the MIT project shifted to the once-through fuel cycle.

Work has been completed on optimization of cores in the recycle mode. It was confirmed that, if very tight pitch cores are practicable from an engineering standpoint, plutonium-uranium fueled lattices having a near-breeder capability could be designed for PWR service. Apart from their high fissile inventory, their performance even exceeds uniform lattices employing the U-233/thorium fuel cycle. Thermal hydraulic analyses show that steady state DNBR limits can be met, however, plant redesign would probably be required to accommodate the higher core pressure drop. The need for additional analyses of transient and accident require performance was also indicated.

The major thrust of the work over the past year, and of the work program for next year is on improvement of PWR performance in the once-through mode. We have moved beyond the obvious strategems, such as increasing burnup, and turned toward more sophisticated options such as the use of axial and radial blankets and power shaping. An important part of the effort has gone into developing criteria and methods for making self-consistent comparisons, since many of the suggested improvements involve accretion of a number of small improvements.

Investigators: Professors M.J. Driscoll, D.D. Lanning, and L. Wolf; Messrs. J. Sefcik, F. Correa, D. Griggs, A. Kamal, L. Lobo, M. Kadri, P. Cavoulacos, A. Abbaspour, E. Fujita; Computer Operations Assistant, R. Morton; Senior Staff Assistant, A. Holman.

Support: U.S. Department of Energy via MIT Energy Laboratory ($48,000 FY 1980)

Related Academic Subjects:

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

Recent References (since 1/1/78):

F. Correa, M.J. Driscoll, and D.D. Lanning, An Evaluation of Tight-Pitch PWR Cores, COO-4570-10, MITNE-227, MIT-EL-7922 (August 1979).

A.T. Abbaspour and M.J. Driscoll, The Fuel Cycle Economics of Improved Uranium Utilization in Light Water Reactors, COO-4570-9, MITNE-224, MIT-EL-79-001 (January 1979).

E.K. Fujita, M.J. Driscoll, and D.D. Lanning, Design and Fuel Management of PWR Cores to Optimize the Once-Through Fuel Cycle, COO-4570-4, MITNE-214, MIT-EL-78-017 (August 1978).

M.J. Driscoll, E.E. Pilat, F. Correa, "Routine Coastdown in LWRs as an Ore Conservation Measure", Trans. Am. Nucl. Soc., 33 (November 1979).

M.J. Driscoll and F. Correa, "The Reactor Physics of Tight-Pitch PWR Cores", Trans. Am. Nucl. Soc., 33 (November 1979).

M.J. Driscoll, E.K. Fujita, and D.D. Lanning, (invited paper), "Improvement of PWRs on the Once-Through Fuel Cycle", Trans. Am. Nucl. Soc., 30 (November 1978).

K. Ghahramani, M.J. Driscoll, "Ore Price Escalation in Fuel Cycle Economic Analysis, Trans. Am. Nucl. Soc., 28 (June 1978).

K. Ghahramani, An Analysis of Prospective Nuclear Fuel Cycle Economics, N.E. Thesis, MIT, Nuclear Engineering Department (September 1978).

H. Aminfar, M.J. Driscoll and A.A. Salehi, "Use of Fast Reactor Methods to Generate Few Group Cross Sections for Thermal Reactors", Proceedings, ANS Topical Meeting, Advances in Reactor Physics, Gatlinburg, TN (April 1978).

D.R. Sigg, Analysis of ATWS in a Tight-Pitched Thorium Fueled PWR, S.M. Thesis, MIT, Nuclear Engineering Department (September 1978).

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

D. Griggs, Steady State and Transient Thermal-Hydraulic Design of an Ultra-Tight Pitch Pressurized Water Reactor, N.E. Thesis, MIT, Nuclear Engineering Department (January 1980).

3.1.5 Advanced Control Systems

Present day light water reactors already have two or three types of computer systems. One system gathers data and presents evaluated information to the operator regarding steady state core conditions. The operator uses this information to determine the control and power changes in order to stay within specified limits. Without the computer, the operator must do hand calculations that are slower and less reliable; hence, in general, full utilization of the reactor is not feasible without the availability of the process computer.

Second, in the control system there are often many simple-function computer systems such as the calculation of average outlet temperatures and power to flow relationships. These "computers" continuously (and automatically) are used to keep the reactor trip system at the correct limit for safe operation. Finally, in the event of a major reactor problem such as a loss-of-coolant accident, there are detectors and instrumentation (effectively a computer system) to automatically initiate the proper safety systems without any required responses from the reactor operator for several minutes. Clearly dependence on the computer for control already exists. This research area is designed to recognize the growing need and to approach the overall automatic control in an organized manner directed toward realization of the true safety significance and the optimized utilization of the operator.

The objectives of the research in progress is outlined as follows:

1) Develop digital instrument validation, information and power reactors and evaluate economic and operational benefits in terms of efficiency, ability, maintainability, improved operation and safety.

2) Investigate and demonstrate NRC licensing on an initial simplified basis by using the MIT Research Reactor.

3) Develop digital information and control designs for nuclear power reactors under transient conditions by utilization of reactor plant simulators; to develop and demonstrate optimization of operator-machine response and information requirements, as well as safety and reliability of computer control.

The research is proposed as a coordinated effort involving MIT and Draper Lab. The experience and ability in computer control is now used in the space program and is being studied by other industries in the nation for uses such as automatic train control, and electrical utility companies system-supply control. It is proposed to combine this type of experience with the growing needs of nuclear power plant operation.

After the review of the Three Mile Island Unit 2 accident, an increased interest has arisen in the area of improved control facing. Many new contracts have been developed and proposals for funding have been made. The group has been expanded and includes the assistance of Professor Sheridan in the Mechanical Engineering Department who is Head of their Man-Machine Systems Laboratory. A one-week Summer Session Program is jointly being planned for the summer of 1980 entitled "Man-Machine Interfacing in Nuclear Power and Industrial Process Control."

Investigators: Professors D.D. Lanning, P. Nicholson, T. Sheridan; Messrs. J. Bernard, K. Dimorier, Several Special Problems Studies by Graduate Students.

Support: Internal Draper Funds and self-supported students.

Related Academic Subjects:

22.32 Nuclear Power Reactors

Recent References:

K.L. Dimorier, Advanced Monitoring and Diagnostic Systems for Nuclear Power Reactors, S.B. Thesis, MIT, Nuclear Engineering Department (May 1979).

B.A. Guillermo, The "State-of-Art" in Fault Diagnosis by Computers on-line. Special Problem, MIT, Nuclear Engineering Department (August 1979).

3.1.6 Reactor Kinetics

During the past year, with support primarily from EPRI, we have continued to develop nodal methods for solving the time dependent group diffusion equations. The nodal code QUANDRY has been extended to solve the two-group, three-dimensional diffusion equations. A simple (constant pressure, axial flow only) heat transfer model has been incorporated into the code so that computing time can be assessed realistically when changes in fuel temperature, moderator temperature and moderator density require that nuclear cross sections for every node be updated at each time step. Control rod motion can also be simulated by the code.

The accuracy and running time of the transient version of QUANDRY compare very well with those of other nodal codes when standard benchmark problems are executed. However, the present experimental version of the code is programmed to be run entirely in the internal memory of a computer. Thus only moderate sized problems can be run on IBM equipment and only very small problems on CDC equipment. This deficiency is being remedied by the code development group at Yankee Electric who have a CDC version running, have created a code manual and are planning a version able to utilize disc memory and hence to analyse large three dimensional transients.

The code has also been exported to the ENEL group in Italy and to Los Almos where it is being considered as the nuclear component of TRAC, the overall plant code capable of analysing transients associated with pipe breaks.

In the present version of QUANDRY the time derivatives in the diffusion equations are treated by the "theta" time integration method which permits any approximation in the range fully implicit to fully explicit to be used. In all situations, however, a new flux shape is found at every time step. With considerable difficulty we have succeeded in developing a quasi-static synthesis method of dealing with the time behavior. With this procedure new fluxes need be computed only when there is a significant change in flux shape. Running time is thereby reduced. The method is currently being debugged and tested.

Investigators: Professor A.F. Henry; Messrs. G. Greenman, K. Smith.

Support: Electric Power Research Institute (approximately $40,000/year)

Related Academic Subjects:

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

Recent References:

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

Additional reactor kinetic studies, involving the coupled reactor physics and thermal hydraulics, are described in Section 3.2.11.

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

22.033: Nuclear Systems Design Project, 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.

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

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

22.314J: Structural Mechanics in Nuclear Power Technology, deals with techniques for structural analysis of nuclear plant components. It is a joint subject with five other engineering departments (Civil, Mechanical, Materials, Ocean, and Aero/Astro) since nuclear plant components illustrate applications of these disciplines. The structural aspects of plant components are discussed in terms of functional purposes and operating conditions (mechanical, thermal, and radiation). A 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: Nuclear Power Reactors, is a descriptive survey of engineering and physics aspects of current nuclear power reactors. Design details are discussed including requirements for safety of light and heavy water reactors, high temperature gas-cooled reactors, fast reactors both liquid-metal and gas-cooled, and fast breeder reactors. Reactor characteristics are compared both in class and by individual student projects. Development problems are discussed and potentials for future improvements are assessed.

22.33: Nuclear Reactor Design, is a project-oriented subject for second-year graduate students in which they carry out a fairly complete system design and analysis of a specific nuclear power plant. By this means the students are given the opportunity to assemble what they have learned elsewhere about reactor physics, engineering principles, properties of materials and economics to accomplish desired objectives. The necessity for making trade-off decisions among conflicting requirements is stressed.

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

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

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

22.37: Environmental Impact of Electric Power Production, 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: Reliability Analysis Methods, principles of the methods of reliability analyses including fault trees, decision trees, and reliability block diagrams. Discussion of the techniques for developing the logic diagrams for reliability assessment, the mathematical techniques for analyzing them, and statistical analysis of required experience data. Practical examples of their application to nuclear power reactors 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.

22.43: 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 consider 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 theroetical and experimental study of flow structure and energy transfer in rod arrays. Recent effort in this program has been on analysis and experimental water testing in wire-wrapped sixty-one pin hexagonal bundles to determine gross mixing between subchannels by salt tracer methods, accompanied by related experiments on pressure drop and flow distribution characteristics.

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

A new code (TRANSENERGY-M) has been written which performs the transient analysis of multi-assembly geometries. This code permits the important effects of transient heat transfer between assemblies to be investigated.

Major effort has also been devoted to analysis of mixed convection conditions. In sodium-cooled reactors, the effect of the power distributions on velocity and temperature fields is enhanced by the buoyancy effects and becomes a controlling factor under low flow situations. The velocity and temperature fields interact and, as a result, local flow recirculation within subchannels and rod assemblies may occur. Under extreme conditions, flow reversal may occur. Conditions of significant buoyant effects and possibly flow reversal can occur:

a) within subchannels with buoyant effects influencing the relative flows between subchannel regions

b) within a bundle with buoyant effects influencing the relative flows between subchannels or regions in the bundle

c) within a core with buoyant effects influencing the relative flows of assemblies

Our model development has been started on a subchannel basis (i.e., stage a) above). Emphasis was on developing a realistic pressure drop model, from phenomenological considerations, for use in the more sophisticated computer programs. It was assumed that the subchannel problem could be divided into three essentially independent parts:

1) pressure drop behavior within a bare rod subchannel due to buoyant effects

2) pressure drop behavior within a wire-wrapped rod subchannel under isothermal conditions

3) transient effects on pressure drop behavior

The resultant effect is simply a superposition of these effects.

In Part 1), a symmetric section of a subchannel, called a cell, was analyzed using a multi-region analytical method. The onset of flow recirculation within this subchannel was predicted from the local velocity distribution. The criteria for the onset of flow recirculation determines the limit on using a lumped parameter approach to model the subchannel. Any analysis beyond that limit should be done in a distributed parameter way, i.e., distributed parameter analysis. The reason is because in lumped parameter analysis, only one velocity and one temperature value is assigned in each subchannel, which makes it unable to handle flow recirculations.

Presently conditions of upflow and downflow in central and edge type subchannels have been analyzed. An experiment is being built to confirm these calculations and investigate the effects of flow development.

B) Experiments: Experiments have been performed on both fuel and blanket sixty-one pin bundles with water to gather the necessary data for these required input data. Based on these data and other data in the literature physical models were proposed for: (a) subchannel and bundle friction factors, (b) the subchannel flows within the assembly, and (c) the sweeping flow constants for turbulent flow. The friction factor and subchannel flow models are particularly significant since they cover for the first time the full range of flow conditions i.e., laminar, transition, turbulent for wire-wrapped bundles of arbitary geometry.

Investigators: Professors N.E. Todreas, W. Rohsenow;*
Messrs. T. Green, P. Symolon, S. Wang, K. Burns, J. Hawley, T. Chiu.
(*Department of Mechanical Engineering)

Support: U.S. Energy Research and Development Administration, ($80,000/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. Glazer, T. Greene, N. Todreas, and L. Wolf, "Transient Thermal-Hydraulic Analysis in the Forced-Convection Regime (TRANSENERGY)," TANSOA, 32, Atlanta (1979).

C. Chiu, W.M. Rohsenow, and N.E. Todreas, "Turbulent Mixing Model and Supporting Experiments for LMFBR Wire-Wrapped Assemblies," Accepted for Symposium on Fluid Flow and Heat Transfer Over Rod or Tube Bundles, New York, NY, (December 1979).

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).

S.F. Wang, W.M. Rohsenow, and N.E. Todreas, "Buoyancy Effects on Subchannel Friction Factors in Bare Rod Bundles", accepted for the Specialists' Meeting on Decay Heat Removal and Natural Convection in FBRs", Upton, New York (February 28-29, 1980).

C. Chiu, R. Morris, and N.E. Todreas, "Experimental Techniques for Liquid Metal Cooled Fast Breeder Reactor Fuel Assembly Thermal/Hydraulic Test", Invited Paper for Special Issue of Nuclear Engineering and Design.

A. Bishop and N.E. Todreas, "Hydraulic Characteristics of Wire-Wrapped Rod Bundles," invited paper for special issue of Nuclear Engineering and Design.

3.2.3 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 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 circumstance. 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.

Originally, the intention was to analyze this problem in the steady state situation. To solve this steady state three-dimensional nonlinear flow problem, Newton-Rafhson's iteration method is used and a very fine computational fluid cell is required. This is time consuming and costly. Hence, it was decided to use the transient approach to solve the steady state problem. Using the transient approach, the nonlinear convection term can be linearized with the value at the old time level. As a result the time step will be restricted by the Courant condition. The latest Implicit Continuous Eulerian (ICE) technique is being adopted here to solve this problem. With both the convection term and the diffusion term expressed explicitly but the pressure gradient term expressed implicitly, a discrete pressure equation can be formulated. In matrix form, it can be written as: $[A]\ \{P\} = \{B\}$

where:

$[A]$ is the coefficient matrix, which has only spatial dependence
$\{P\}$ is the unknown discrete pressure at the advance time level
and
$\{B\}$ is the vector values in terms of old velocities.

Because the matrix has only spatial dependent elements which are constant with time, only one inversion is needed. For the second or the higher time step, back substitution which is much easier and faster is required to obtain the solution vector, {P}. A direct method, known as LU-decomposition will be used. Once the discrete pressures are known, the new velocities can easily be evaluated from the momentum equations.

A computer code using this methodology has been written. In order to verify this computer code, some sample problems such as a three-dimensional circular pipe flow with uniform inlet condition or with a small vortex at the entrance and a three-dimensional circular duct with a twisted tape will be analyzed. Once these analyses are satisfied, this computer code will be applied to solve the wire-wrapped rod bundle heat transfer analysis.

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

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

Related Academic Subjects:

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

Recent References: None

3.2.4 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 the time-dependence of turbulent flows has been investigated experimentally and analytically. It has been found that the major errors which appear in transient turbulent flow predictions arise more from faulty models regarding the basic turbulence transport phenomena than from transient effects in turbulence.

In work concerning coupled turbulent heat and momentum transport it has been found in strongly recirculating flows--such as those in the LMFBR outlet plenum--that the turbulence is strongly anisotropic, and that the tensor diffusivities of heat and momentum do not scale linearly throughout the flow as is often assumed. Recent work has also indicated that the effects of buoyancy can change the turbulent flow field substantially -- resulting in re-laminarized flow in cases of strongly stable stratification. This has important thermal shock implications in the design of thick LMFBR components.

Current work is concerned with buoyant effects in turbulence, and with turbulence in three-dimensional highly anisotropic flows.

Investigators: Professors M.W. Golay, R.G. Bennett; Messers. D. Boyle, S.H. Chang, and R. Sawdye.

Support: Energy Research and Development Administration ($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:

R.G. Bennett and M.W. Golay, "Interferometric Investigation of Turbulently Fluctuating Temperature in an LMFBR Outlet Plenum Geometry", COO-2245-29TR, MIT-ERDA (1977).

R.G. Bennett and M.W. Golay, "Interferometric Investigation of Turbulently Fluctuating Temperature in an LMFBR Outlet Plenum Geometry", J. Heat Transfer, 100, No.2, 334-339 (1978).

V.P. Manno and M.W. Golay, "Measurement of Heat and Momentum Eddy Diffusivities in Recirculating LMFBR Outlet Plenum Flows", MIT, Department of Nuclear Engineering, COO-2245-61TR (1978).

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

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

3.2.5 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 and an experimental study in water of flow oscillations 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. 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. Also, assistance has been provided to DOE, GE and HEDL with other related activities concerned with sodium voiding behavior.

Activities on the mixture model code have recently been initiated. 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 over a year. 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: 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. Autruffe, M. Manahan, M. Granziera, R. Vilim, G. Wilson, A. Schor, A. Levin

Support: DOE/GE/HEDL (approximately $110,000/year).

Related Academic Subjects:

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

Recent References:

M.I. Autruffe, Analysis of Some Thermal Phenomena in LMFBR Safety, M.S. Thesis, MIT, Department of Mechanical Engineering (August 1978).

M.I. Autruffe, G.J. Wilson, B. Steward and M.S. Kazimi, "A Proposed Momentum Exchange Coefficient for Two-Phase Modeling of Sodium Boiling", Proc. Int. Mtg. Inst. Reactor Safety Technology, IV, 2512-2521, Seattle, Washington (August 1979).

M.R. Granziera and M.S. Kazimi, "NATOF-2D- A Two Dimensional Two-Fluid Model for Sodium Flow Transient Analysis" Trans. ANS, 33, 515 (November 1979).

3.2.6 Assessment and Comparison of the Range of Applicability of the Codes COBRA-IIIC/MIT and COBRA-IV-I

The objective of this project was to provide an assessment and comparison of the range of applicability of two LWR thermal hydraulic codes: COBRA-IIIC/MIT and COBRA-IV-I. The code COBRA-IV-I was considered to be the benchmark.

Initially, several deficiencies in COBRA-IIIC/MIT were found and corrected. Specifically, errors were noted when the code was used for transients with small time step sizes. Also, the code did not converge at all for the transient BWR option. These failures were overcome by changing the numerical iteration schemes.

The corrected code was used to analyze a variety of LWR steady-state and transient conditions of interest, and the results were compared to those generated by COBRA-IV-I. These included a BWR bundle-wide steady-state analysis, a simulated PWR rod ejection and PWR loss of flow transients. In carrying out these analyses, the system parameters were changed so as to reach extreme coolant conditions, thereby establishing upper limits.

In addition, both codes were compared to experimental data. This included measured coolant exit temperatures in a PWR core, interbundle mixing for inlet flow upset cases and two-subchannel flow blockage measurements.

The comparisons showed that, overall, COBRA-IIIC/MIT predicted most thermal-hydraulic parameters quite satisfactorily. However, the clad temperature predictions differed from those calculated by COBRA-IV-I and appeared to be in error. These incorrect predictions were attributed to a discontinuity in the heat transfer coefficient at the start of boiling.

As a result of this research, several recommendations were made for improving the code COBRA-IIIC/MIT: (a) replacement of the fuel pin conduction model by an improved version incorporating temperature-dependent properties and variable gap heat transfer coefficients, (b) extension of the heat transfer package, and (c) implementation of a two-phase flow mixing model.

Investigators: Prof. L. Wolf; Messrs. J. Kelly and J. Loomis.

Support: $34,000 for one year. Sponsored by Northeast Utilities Service Company, Long Island Lighting Company, Public Service Electric and Gas Company and Yankee Atomic Electric Company under the MIT Energy Laboratory Electric Utility Program.

Recent References:

J. Kelly, Assessment of the Range of Applicability of Various Codes for Thermal-Hydraulic Design of Light Water Reactors, M.S. Thesis, MIT, Nuclear Engineering Department, (August 1979).

J. Kelly, J. Loomis, and L. Wolf, "LWR Core Thermal Hydraulic Analysis-Assessment and Comparison of the Range of Applicability of the Codes COBRA-IIIC/MIT and COBRA-IV-I", MIT Energy Laboratory Report No. MIT-EL 78-026, (September 1978).

3.2.7 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. Implementation of a fuel pin conduction model which includes temperature dependent properties and burnup dependent gap heat transfer coefficient.
2. Implementation of a heat transfer package which covers a broad range of flow regimes and contains a more consistent logic.
3. Implementation of a quality dependent mixing model for two-phase flow.

4. Assessment of the GEXL methodology and selection of an alternate scheme for use within the framework of the BWR solution option in the code.
5. Assessment of the new code features for a broad class of test cases and comparison to the old version.

The first four of the above tasks have been completed. The remaining task and writing of a final report and updated user's manual for the code are presently underway.

Investigators: Dr. W. Hinkle and Mr. J. Loomis

Support: $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.

Publications: None to date.

3.2.8 Development of a Drift-Flux Code for BWR Core Analysis

The purpose of this research was the development of a subchannel computer code specifically suited for the steady-state and transient thermal-hydraulic analysis of BWR fuel rod bundles. The code is also applicable to PWR bundle analysis as long as these bundles are enclosed by bundle walls. This situation frequently arises in experimental setups for mixing and void fraction experiments. This development has spanned over several years and recently was concluded by the completion of the code CANAL. Work was begun in the fall of 1976 by Louis Guillebaud who performed the first consistent check on the models and method of solution employed by the computer program WOSUB which is an extension of the MATTEO code. Alan Levin provided the additional subroutines for calculating the heat transfer coefficients and critical heat flux thus enabling WOSUB to analyze data beyond the scope of the MATTEO code.

In the spring of 1977 William Boyd concentrated his work on a parametric sensitivity study of the empirical parameters of the WOSUB code and their effects upon the overall results. He was succeeded by Artur Faya who added to the code a fuel pin model based on the collocation method.

In the fall of 1977 Arthur Faya started the development of the CANAL code which represents the latest step. New physical models were necessary because WOSUB results for some important experiments were not satisfactory. Besides WOBUS physical models tend to overestimate the transport of vapor for bulk boiling conditions. This in turn leads to numerical instabilities in some cases.

The similarities between WOBUS and CANAL reside only on the numerical scheme, heat transfer coefficient package and fuel pin model. CANNAL and WOBUS differ in the following main points:

- mixing model

- vapor generation rate
- liquid and vapor are treated as compressible in CANAL and incompressible in WOSUB
- correlations for fluid physical properties
- correlations for friction pressure losses

The following experiments were used for the purpose of the assessment of the code CANAL under steady-state conditions:

1) GE Nine-rod tests with radially uniform and non-uniform heating

2) Studsvik Nine-rod tests with strong radial power tilt.

3) Ispra Sixteen-rod tests with radially uniform heating.

Comparison of calculated results wiht these data show that the program is capable of predicting the correct trends in exit mass velocity and quality distributions.

Investigators: Professors L. Wolf and N. Todreas; Messrs. L. Guillebaud, A. A. Boyd and A. Faya.

Support: Initially under Nuclear Power Reactor Safety Program sponsored by New England Utilities under MIT Energy Laboratory Program ($26,000/year). None in 1979.

Related Academic Subjects:

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

Recent References:

L. Wolf, *et al*, "WOSUB - - A Subchannel Code for Steady State and Transient Thermal-Hydraulic Analysis of BWR Fuel Pin Bundles;
Vol I: The Model, MIT-EL-78-023, September 1978,
Vol II: User's Manual, MIT-EL-78-024, July 1977,
Vol III: Comparison with Experiments and Other Codes, MITEL-025, August 1977.

A. Faya, L. Wolf, "A BWR Subchannel Code with Drift Flux and Vapor Diffusion Transport, *Trans*. *ANS*, *28* pp 553-555, (1978).

A. Faya, L. Wolf and N. Todreas, "Development of a Method for BWR Subchannel Analysis"' MIT-EL-79-027, (November 1979).

A. Faya, L. Wolf and N. Todreas, "CANAL User's Manual", MIT-EL-79-028, (November 1979).

3.2.9 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 measurement have been used when available and, otherwise, comparisons have been make with COBRA-IV.

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 CHF criteria and post CHF heat transfer models need to be improved.

A third conclusion is that in order to accurately predict the flow and enthalpy distribution in subchannel geometry, a turbulent mixing model must be added to THERMIT. Both single-phase and two-phase measurements illustrate this point. Without such a model, the mass flux and quality predictions are poorly predicted.

Finally, for multi-dimensional transients it can be concluded that the predictions of THERMIT appear to be qualitatively correct and, additionally, THERMIT is at least as computationally efficient as COBRA-IV (explicit). Differences between the predictions of the two codes may be anticipated in light of their respective two-phase flow models.

Investigators: Professors M.S. Kazimi, L. Wolf, Messrs. J. Kelly and M. Massoud.

Support: Energy Laboratory Electric Utility Program ($55,000/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:

M. Massoud, " A Condensed Review of Nuclear Reactor Thermal-Hydraulic Computer Codes for Two-Phase Flow Analysis", MIT-EL-29-018, (April 1979.)

J. Kelly and M.S. Kazimi, "Development and Testing of the Three-Dimensional, Two-Fluid Code THERMIT for LWR Core and Subchannel Applications", MIT-EL-74-046, (December 1979.)

3.2.10 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 transfered 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.

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) An analysis was performed of the effect of pressure wave reflections within a fuel drop on the volume of gas nuclei within the droplet. It was determined that even for small magnitudes of pressure, for a range of frequencies the nuclei may experience rapid growth and hence may contribute to the process of fuel fragmentation.

b) Fuel-to-Steel Heat Transfer: 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 to and constructed to test the model. The apparatus is now being checked out.

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

Support: NRC (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:

M.S. Kazimi, M.I. Autruffe, "On the Mechanism for Hydrodynamic Fragmentation", Trans. Am. Nucl. Soc. 30, 366, (November 1978).

R.A. Rothrock and M.S. Kazimi, Experimental Investigation of the Thermal-Hydraulics of Gas Jet Expansion in a Two-Dimensional Liquid Pool, MITNE-223, (October 1978).

3.2.11 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.

Studies are now underway on the thermal-hydraulics section of the code and the related feedback effects for the neutronic calculations. Specifically, the following sections are under investigation:

- Heat transfer across the pellet-clad gap
- Thermal-hydraulic correlations for the prediction of critical heat flux, mixing, nucleate boiling, and others
- Flow variation transient sensitivity
- Comparison of MEKIN to experimental results (SPERT tests)
- Formulation improved thermal-hydraulic methods utilizing the two-fluid two-phase models

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

Support: Electric Power Research Institute ($342,000 over 3 years)

Related Subjects:

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

Recent References:

T. Rodack, Sensitivity to the Assembly Averaged Thermal Hydraulic Models of the MEKIN Computer Code in Power Transients, N.E., S.M. Thesis, MIT, Nuclear Engineering Department (September 1977).

C. Barbehenn, Neutronic Sensitivity on MEKIN, An Accident Analysis Computer Code for Nuclear Reactors, N.E., S.M. Thesis, MIT, Nuclear Engineering Department, (September 1977).

A. Cook, Light Water Reactor Kinetics Analysis with Feedback: An Investigation of the Computer Code MEKIN, Ph.D. Thesis, MIT, Department of Nuclear Engineering (1978).

D.A. Dube, Two-Fluid, Two-Phase Transient Thermal-Hydraulic Calculations for One Dimensional Flow Through Parallel Channels, MIT, Nuclear Engineering Department, Status Report (June 1979).

3.2.12 Fusion Reactor Blanket and First Wall Thermal Design

This effort consists of several studies involving: 1) forced convection cooling of blankets, 2) natural convection cooling of blankets and 3) thermal and design of the first wall. These areas of research are discussed in Section 3.10.

3.2.13 Fault Tree Analysis by Modular Decomposition

Fault tree analysis is one of the principle methods for analyzing safety systems. It is a valuable tool for identifying system failure modes, and for predicting the most likely causes of system failure in the event of system breakdown.

A review of available methods and codes showed that all of them are based upon the methodology of minimal cut sets. At this point it was thought that a modular representation of fault trees should result in substantial savings of computation time and should offer additional flexibility in analyzing more complex trees.

Defined in terms of reliability network diagram, a module is a group of components which behaves as a super-component. This means that it is completely sufficient to know the state of the super-component, and not the state of each component in the module, to determine the overall state of the system.

A number of computational advantages result by using this modular representation:

(1) Probabilities of the occurrence for the TOP and intermediate gate events may be efficiently computed by evaluating these modular events in the same order that they have been generated;

(2) modular and component importance measures are easily computed by stating at the TOP and successfully using a modular importance chain-rule which has been specifically designed for this purpose;

(3) for complex fault trees necessitating the use of minimal cut-set upper bounds for their quantification. Sharper bounds will result by using the minimal cut upper bound at the level of modular gates.

The original work at M.I.T. by J. Olmos and L. Wolf and the PLMOD code employing this technique has been further improved with the development of a code, PLMODT, which permits the analysis of fault trees containing components with time-dependent failure rates. A second modification of this code permits Vesely-Fussell importance to be calculated in a rapid efficient way for both the modules and components of the fault tree.

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

Support: U.S. Nuclear Regulatory Commission ($15,000/yr)

Related Academic Subjects:

22.38 Reliability Analysis Methods

Recent Publications:

J. Olmos and L. Wolf, A Modular Representation and Analysis of Fault Trees, Nuclear Engineering and Design, 48, 531-561 (1978).

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

3.2.14 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 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:

J. Olmos, M. Modarres, L. Wolf, "User's Manual for PL-MOD and PL-MODT: A Steady-state and Transient Computer Program for the Analysis of Fault Trees Using the Modular Concept", MIT, Department of Nuclear Engineering, Revised Edition, March 1978.

M. Modarres, L. Wolf, "PL-MODT: A Modular Fault Tree Analysis and Transient by PMODT," accepted for presentation at the American Nuclear Society Winter Meeting, Washington, D.C. November 1978.

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

3.2.15 Sensitivity Analysis of the Reactor Safety Study

The Reactor Safety Study (RSS), or WASH-1400, developed a methodology for estimating the public risk from light water nuclear reactors. In order to give further insights into this study, a sensitivity analysis has been performed to determine the significant contributors to risk for both PWR and BWR. The sensitivity to variation of the point values of the failure probabilities reported in the RSS was determined for the safety systems identified therein, as well as for many of the generic classes from which individual failures contributed to system failures. Increasing as well as decreasing point values were considered. An analysis of the sensitivity to increasing uncertainty in system failure probabilities were also performed. The sensitivity parameters chosen were release category probabilities, core melt probability, and the risk parameters of early fatalities, latent cancers and total property damage. The latter three are adequate for describing all public risks identified in the RSS. The results indicate reductions of public risk by less than a factor of two for factor reductions in system or generic failure probabilities as high as one hundred. There also appears to be more benefit in monitoring the most sensitive systems to verify adherence to RSS failure rates than do backfitting present reactors. The sensitivity analysis results do indicate, however, possible benefits in reducing human error rates.

Investigators: Professor N.C. Rasmussen, Dr. William Hinkle; Mr. W. Parkinson.

Support: Northeast Utilities and Yankee Atomic Electric Co. under the Energy Laboratory Electric Utility Program ($39,000).

Related Academic Subjects:

22.38 Reliability Analysis Methods

Recent References:

W.J. Parkinson, Sensitivity Analysis of the Reactor Safety Study, S.M. Thesis, MIT, Nuclear Engineering Department (February 1979).

3.2.16 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.

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, L. Wolf, "BIT-FRANTIC: A Convenient and Simple Code Package for Fault Tree Analysis and Unavailability Calculations," Trans. Amer. Nuc. Soc., Washington, D.C. (November 1978.)

R. Karimi, J. Schwartz, L. Wolf, N.C. Rasmussen, "Test Interval Optimization of Nuclear Power Plant Safety Systems" MIT Energy Laboratory Report Number MIT-EL-78-027.

3.2.17 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: Professors J.E. Meyer and M.N. Fardis; Messrs. M.H. Kargarnovin and R.O. Racana.

Support: Some funds for computer from other research topics (e.g., Sec. 3.10.2 (Part C) Fusion Reactor Blanket and First Wall Thermal Design and Sec. 3.10.2, Fusion Reactor Technology).

Related Academic Subjects:

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

Recent References:

M.H. Kargarnovin, Analysis of Structrual Supports for a TORSATRON Fusion Reactor Magnetic Coil, S.M. Thesis, MIT, Nuclear Engineering Department and Mechanical Engineering Department (October 1978).

M.N. Fardis, C.A. Cornell, and J.E. Meyer, "Accident and Seismic Containment Reliability", J. Structural Div. ASCE 105, No. ST1, Proc. Paper 14305, 67-83 (1979).

3.2.18 Analysis of Forces on Core Structures During a Loss-of-Coolant Accident

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.

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

Support: Several electric utilities under the MIT Energy Laboratory Electric Utility Program.

Related Academic Subjects:

22.38	Reliability Analysis Methods

3.2.19 Fuel Management Code Development

Nuclear fuel management is one of the major responsibilities of a utility with nuclear power plants. The objective is to obtain the maximum utilization of the fuel while meeting scheduling and safety constraints. There are currently a number of computational tools that are used in this area, ranging from the simple estimates to complicated analyses. However, the simple estimates require significant normalization and the complicated are very costly and time consuming. Therefore, a computer program has been developed embodying the benefits of both the simple and the complicated tools.

The model as developed makes use of equations on a regionwise basis. Thus it keeps the regionwise data of the simple codes but solves for the k_{eff} and power distribution as do the complicated codes.

A computer code, FLAC, has been written which incorporates many options and automated input preparation to enable it to be easily used. It has been tested, verified and qualified for PWR facilities. Its usefulness has been demonstrated with numerous studies which can be done quickly and easily.

Work on the code has continued and now includes extension to BWR facilities and incorporation of simple estimates of peaking and reactivity limits. Also, a simple economic analysis is incorporated into this version called the FLACM code.

Investigators: Professor D.D. Lanning, M.J. Driscoll; Dr. E.E. Pilat, Mr. C.L. Beard, and H. Hsieh.

Support: Yankee Atomic Electric Company ($1,000/one year), Northeast Utilities Co. ($2,500)/one year).

Related Academic Subject

22.35 Nuclear Fuel Management

Recent References:

C.L. Beard, An Improved Long Range Fuel Management Program, S.M. Thesis MIT, Nuclear Engineering Department (May 1978). Also, MIT report MITNE-216.

H. Hsieh, Long Range Fuel Management for LWR Studies FLACM Computer Code. Nuclear Engineering Thesis, MIT, Nuclear Engineering Department (August 1979).

3.3 Nuclear Materials and Radiation Effects

The nuclear materials program has four major objectives: (1) to provide students in the Department with sufficient background in the principles of physical metallurgy and physical ceramics to incorporate a fuller consideration of reactor structural and fuel materials in their thesis programs; (2) to advance reactor materials technology in the areas of materials selection, component design, irradiation behavior modeling, safeguards analysis, quality assurance, and reliability assessment; (3) to conduct instructional and research programs into both the fundamental nature of radiation effects to crystalline solids and the interrelationships between radiation-induced structural problems on an interdepartmental and interdisciplinary manner in the general fields of energy conversion, energy transmission, and environmental technology as related to power production.

3.3.1 Subjects of Instruction

22.71J: Physical Metallurgy Principles for Engineers, is the introductory course in this sequence of study and is intended for students who did their undergraduate work in engineering and science fields which did not provide formal instruction in metallurgy or materials science. This course emphasizes the following topics: crystallography and microstructure; deformation mechanisms and the relationship of mechanical properties to metallurgical structure; thermodynamics and rate processes to include phase equilibria, recovery and transformation mechanism, diffusion, corrosion, and oxidation; mechanical property testing methods, strengthening mechanisms, fracture mechanics, fatigue and creep. 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 theory of atomic displacement, spike phenomena, correlated collisions, inelastic scattering and range laws for both ordered and disordered lattices. Experimental and analytical methods for characterizing defect structures, determining the effects of various defects on physical properties, and describing the kinetics and rate laws for defect annealing are described.

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

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:

G.E. Lucas, "Effects of Anisotropy and Irradiation on the Creep Behavior of Zircaloy-2," Sc.D. Thesis, MIT, Department of Nuclear Engineering (August 1978).

R. Ballinger, R.M.N. Pelloux, "The Anisotripic Mechanical Behavior of Zircaloy-2", The Third International Conference on Mechanical Behavior of Materials, Cambridge, U.K., (August 1979).

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, 690, and Incoloy 800 at room themperature 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. G. Was, R. Ballinger.

Support: Electric Power Research Institute

Related Academic Subjects:

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

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 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 germanium precipitates in irradiated undersaturated Al-Ge solid solutions.

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

Support: National Science Foundation ($50,000/year).

Related Academic Subjects:

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

Recent References:

K. Bertram, F.J. Minter, J.A. Hudson and K.C. Russell, "Irradiation-Enhanced Precipitation in Al-Ge Alloys", J. Nuclear Mats. 75, 42-51 (1978).

M. Mruzik and K.C. Russell, "The Effect of Irradiation on the Nucleation of Incoherent Precipitates" J. Nuclear Mats. 78, 343-353 (1978).

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

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

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

3.3.6 Surface Effects in Fusion Reactors

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

Previously this work has been concentrated in the areas of neutron sputtering, fast neutron induced radioactive recoil particle emission yield measurements and 14 MeV neutron cross section measurements. During this report period the effort was directed toward understanding the importance of the charge state of plasma particles which reach the first wall. This work has shown that, for reasonable assumptions of operating conditions, the high energy helium particles arrive at the first wall in an ionized state and at small angles of incidence. An analysis of the resulting wall effects indicates a greatly increased severity in wall erosion and consequent plasma contamination than what has previously been expected.

Investigators: Professor O.K. Harling; Mr. H. Andresen, Drs. M.T. Thomas, D.L. Styrus.

Support: U.S. Department of Energy

Recent References:

H. Andresen, O.K. Harling, "The Importance of the Charged Neutral Particle Fraction on Plasma Wall Interaction in Toroidal Devices", Presented at the 3rd International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Culham Laboratory, U.K.,(April 1978).

D.L. Lessor, M.T. Thomas, and O.K. Harling, "Projected Range Calculations of Radionuclide Produced Ejection from Metal Surfaces by 14.8 MeV Neutrons", Journal of Applied Physics, Vol. 48, pp 4337-4343 (1977).

O.K. Harling, M.T. Thomas, R.L. Brodzinski, and L.A. Rancitelli, "Fast Neutron Sputtering of Niobium", Journal of Applied Physics, Vol. 48, pp 4315-4327(1977).

O.K. Harling, M.T. Thomas, R.L. Brodzinski, and L.A. Rancitelli, "Fusion Neutron Induced Nuclear Recoil Emission Probabilities", Journal of Applied Physics, Vol. 48 pp 4328-4336 (1977).

R. Behrisch, O. Harling, R. Brodzinski, R. Meisenheimer, M. Thomas, L.G. Smith, J. Wendelken, M. Saltmarsh, M. Kaminski, S. Das, G. Logan, J. Robonson, M. Shimotomai, D. Thompson, J. Biersack, "Sputtering of Niobium by Energetic Neutrons and Protons, A Round Robin Experiment," Journal of Applied Physics, Vol 48, pp 3914-3918 (1977).

R. L. Brodzinski, M.T. Thomas and O.K. Harling, "Some (n,γ), (n,p), and $(n,2n)$, Cross Sections for 14.8 MeV Neutrons in MFFR Candidate Materials", in the Physical Review, (December 1977).

3.3.7. 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, K.C. Russell, A.S. Argon; Dr. H. Frost, Messrs. H. Andresen, G. Dansfield, G. Tong, M. Manahan, M.V. Tsakonas.

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 Structrual Materials

Recent References:

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

G.W. Dansfield, The Influence of Boron on Fusion Reactor Materials During Helium Embrittlement Simulation, S.M. Thesis, MIT, Departments of Nuclear Engineering and Materials Science (December 1979).

S.E. Best, A. Fadaai 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 Harbor, Fla. (June 29-31, 1979).

G.W. Dansfield, The Influence of Boron on Fusion Reactor Materials During Helium Embrittlement Stimulation, S.M. Thesis, MIT, Nuclear Engineering Department (1980).

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

S.E. Best, A. Fadaai and O.K. Harling, "Initial Results Using Splat Cooling in the Development of Boron Doping for the Simulation of Fusion Reactor Helium Embrittlement", Trans. Nuc. Mater. (in press)

H. Andresen and O.K. Harling, "A New Approach to Simulation of Helium and Simutaneous Damage Production in Fusion Reactors - in Reactor Tritium Trick", Trans. Nuc. Mater. (in press).

M.S. Saidfar and K.C. Russell, "Simulation of Oxide Dispersoid Stability in Irradiated Type 316 Stainless Steel", J. Nucl. Mats. (in press)

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

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

Investigators: Professors O.K. Harling, D.D. Lanning, R. Latanision, G. Yurek, 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

3.3.9 Characterization of MITR-II for Neutron Activation Analysis

Various irradiation facilities of the rebuilt MIT Reactor have been characterized for activation analysis use. This work includes absolute determination of slow neutron and epithermal neutron fluxes for the pneumatic transfer tubes in the reflector, the new high flux facility next to the core, the vertical graphite facilities, the hohlraum and various other locations in the thermal column. Measurements for spacial variations of flux have been carried out for most of these facilities.

Investigators: Professor O.K. Harling, Dr. M. Janghorbani, and Mr. A.M.S. Almasoumi.

Support: Government of Saudi Arabia and the Nuclear Reactor Laboratory, MIT.

Related Academic Subjects:

22.04 Radiation Effects and Uses
22.29 Nuclear Measurement Laboratory

Recent References:

A.M.S. Almasoumi, "Charaterization of MITR-II Facility for Neutron Activation Analysis", M.S. Thesis, MIT, Department of Nuclear Engineering (August 1978).

3.3.10 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, R. Lantanision, K.C. Russell, J.E. Meyer, R. Pelloux, and J. VanderSande; Dr. J. Megusar, Messrs, U. Tsach, A. Adegbelugbe, (several other students and post doctorals will be added as project is fully staffed).

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:

K. Genssler, Properties of Rapidly Solidified 316 Stainless Steel, S.M. Thesis, MIT, Nuclear Engineering Department (1980).

3.3.11 Light Water Reactor Fuel Performance Analysis

The fuel rods in light water reactors must perform to permit reasonable lengths of 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) Study of the thermal effects of fuel pellet cracking and movement (relocation) of the cracked pieces within the fuel rod.

(b) Examination of methods for including Zircaloy creep-recovery effects in computer code calculations. Performance of out-of-pile variable stress Zircaloy creep experiments to evaluate the calculational methods.

(c) Establish design/operating criteria for light water reactor fuel rods with stainless steel clad.

Investigators: Professor J.E. Meyer; Messrs. G. R. Alberthal, J.T. Maki, and J.E. Rivera.

Support: Several electric utilities under the MIT Energy Laboratory Electric Utility Program.

Related Academic Subjects:

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

Recent References:

Y.Y. Liu, J.E. Meyer, and A.S. Argon, "Theoretical Analysis of Pellet-Cladding Mechanical Interaction," Trans. Am. Nucl. Soc. 30, 184-185 (1978).

J.T. Maki and J.E. Meyer, LWR Fuel Performance Analysis, Fuel Cracking and Relocation, MIT Energy Laboratory Report MIT-EL78-038, (October 1978).

J.T. Maki, Thermal Effects of Fuel Pellet Cracking and Relocation, SM Thesis, MIT, Nuclear Engineering Department (July 1979).

Y.Y. Liu, J.E. Meyer, and A.S. Argon, "A Formulation for the Analysis of Pellet-Cladding Mechanical Interaction," Trans 5th Intl. Conf., Str. Mech. in Reactor Tech. D Paper D3/5 (1979).

3.4 Nuclear Chemical Technology

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

3.4.1 Subject of Instruction

22.76J: Nuclear Chemical Engineering, 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 Recovery of Uranium from Seawater

Funded by seed money from the MIT Energy Laboratory, a small project has been carried out to evaluate the economic prospects for the extraction of uranium from seawater. Since the ocean contains roughly 5000 million tons of U_3O_8--enough to fuel thousands of LWR's for thousands of years--its recovery for less than about $150/lb U_3O_8 (the breakeven price vs breeder reactors or coal fired units) could have a profound effect on energy planning. The resource is extremely dilute, however, and only carefully designed and optimized process can have a chance at success. The MIT work has focussed on defining target adsorber properties (such as capacity) and adsorber bed configuration (particle size, bed thickness, etc.) which a successful system must have. We have identified an optimum envelope in the area of small particle sizes, thin beds, and low seawater velocity, where either actively pumped or current-driven system might eventually prove competitive if adsorber capacities can be increased over currently-available values. Recent evidence suggests that it may be possible to develop special purpose ion exchange resins which are attractive sorber materials.

Investigators: Professor M.J. Driscoll; Dr. F.R. Best.

Support: MIT Energy Laboratory ($20,000 total funding 1978-1979)

Related Academic Subjects:

22.76J Introduction to Nuclear Chemical Engineering

Recent Reference:

F.R. Best The Recovery of Uranium from Seawater, Ph.D. Thesis, MIT, Nuclear Engineering Department (January 1980).

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, startup and checkout operation of the modified reactor. Recent studies are in the area of experimental-facility design, fuel management, and advanced control systems.

Investigators: Professors M.J. Driscoll, S.H. Chen. O,K. Harling, D.D. Lanning, N.E. Todreas, G. Brownell, A. Argon, Drs. M. Janghorbani, W. Ting; Messrs, L. Clark, Jr., H. Andresen, M. Manahan, J. Bernard, W. Fecych and Ms. S. Best.

Support: MIT Reactor Depreciation Account and Reactor Operating Research Account

Related Academic Subjects:

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

Recent References:

R.J. Chin, DEPLESYN: A Three-Dimensional Discontinuous Synthesis, Diffusion-Depletion Code, Ph.D. Thesis, MIT, Nuclear Engineering Department (1977).

F. Bamdad-Haghighi, Natural Convection Cooling After Loss-of-Flow Accident in the MITR-II, N.E. Thesis, MIT, Nuclear Engineering Department (August 1977).

K.D. Collins, L. Clark, Jr., D.D. Lanning, "Renovation of the MIT Research Reactor", Trans. Am. Nucl. Soc. (August 1977).

MIT Reactor Staff, Report of Educational and Research Activities for Academic Years 1975-76, 1976-77 and 1977-78, MITNRL-001, COO-3340-2 (December 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, (See Section 3.7).

3.6.1 Subjects of Instruction

The following subjects of instruction are offered:

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

22.04: 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 measurements at the MIT Reactor.

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, 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 line width, 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.

22.111: Nuclear Physics for Engineers I, deals with basic nuclear physics for advanced students majoring in engineering. Basic properties of nucleus and nuclear radiations, introductory quantum mechanics including calculations of transition probabilities, and nuclear cross sections, two-body collision, ionization of matter by charged particles, passage of electromagnetic radiation through matter, alpha, and beta decays, and radiative transmissions.

22.112: Nuclear Physics for Engineers II, is a continuation of 22.111 with emphasis on detailed studies of nuclear reactions. Optical model calculations of total and differential cross sections. Hauser-Feshback theory of inelastic neutron scattering. Resonance absorption of neutrons in the resolved and unresolved regions. Scattering kernels for neutron thermalization. Availability of cross section data and selected applications.

3.6.2 Neutron Spectrometry and Molecular Dynamics in Solids and Fluids

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

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

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: Professors S.-H. Chen and S. Yip; Dr. C.V. Berney, Mr. Z. Djorgevic.

Support: National Science Foundation (cumulative support since 1973, $593,000)

Related Academic Subject:

22.51 Radiation Interactions and Applications

Recent References:

C.V. Berney and J.W. White, "Selective Deuteration in Neutron-Scattering Spectroscopy: Formic Acid and Deuterated Derivatives", J. Am. Chem. Soc. 99, 6878-80 (1977).

C.V. Berney and A.D. Comier, "Spectroscopy of CF_3COZ Compounds -- VI. Vibrational Spectrum of Trifluoroacetyl Bromide", Spectrochimica Acta 22A, 929-35 (1977).

S.-H. Chen, J.D. Jorgensen and C.V. Berney, "Neutron Molecular Spectroscopy Using a White Beam Time-of-Flight Spectrometer", J. of Chem. Phys. 68, 209-15 (1978).

C.V. Berney, S.-H. Chen, D.H. Johnson and S. Yip, "Analysis of Neutron Inelastic Scattering Spectra of Normal and Deuterated Formic Acid", *Neutron Inelastic Scattering I*, 345-61, International Atomic Energy Agency, Vienna (1978).

C.V. Berney and D. Spickerman, "Enthalpy of Sublimation of Trifluoroacetamide", *J. of Chem. Thermodynamics* 10, 637-40 (1978).

D.H. Johnson, C.V. Berney, S. Yip and S.-H. Chen, "Analysis of Neutron Incoherent Inelastic Scattering Spectra of Normal and Deuterated Formic Acid." I. Planar Chain Model, *J. of Chem. Phys.* 71, 292-97 (1979).

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).

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.

Support: National Science Foundation (two years, January 1978 - December 1980; $92,000)

Related Academic Subjects:

22.51 Radiation Interactions and Applications

Recent References:

S.-H. Chen and A. Rahman, "Molecular Dynamic Simulation of Dense Gases, I. Test Particle Motion", Molecular Physics 34, 1247 (1977).

S.-H. Chen, H.C. Teh and S. Yip, "Molecular Interactions and Neutron Scattering from Moderately Dense Gases", in Neutron Inelastic Scattering, 1977 (International Atomic Energy Agency, Vienna, 1978), Vol. II, 81.

S.-H. Chen and A. Rahman, "A Scaled Boltzmann Theory for k-dependent Test Particle Correlation Functions in Moderately Dense Gases", J. of Chem. Phys. 70, 3730 (1979).

S. Yip, "Renormalized Kinetic Theory of Dense Fluids", Annual Reviews of Physical Chemistry 30, 547 (1979).

S. Ranganathan and S. Yip, "Density Fluctuations in Dilute Gas of Lennard-Jones Molecules", J. of Chemical Physics 71, 1978 (1979).

S. Ranganathan, M. Rao and S. Yip, "Binary Collision Approximations to Space-Time Correlation Functions", Physics Letters 74A, 180, (1979).

S. Ranganathan and S. Yip, "Space-Time Memory Functions of Simple Kinetic Models", Physica, in press.

J.-P. Boon and S. Yip, Molecular Hydrodynamics, McGraw-Hill, in press.

3.6.4 Computer Molecular Dynamics Studies

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

A problem to which we have devoted considerable efforts is the dynamics of grain-boundaries. Our computer simulation results for two- and three-dimensional crystals show that coupled boundary sliding and migration is a general phenomenon in grain-boundary motions. This is the first time that such observations have been reported and the significance is that theories of grain-boundary migration which heretofore consider only single-particle dynamics such as diffusion or hopping must now be re-examined to take into account highly cooperative processes.

Current activities have been mainly concerned with the development of computer molecular dynamics techniques and associated simulation programs for the study of grain-boundary dynamics, crack progagation, chemical reactions, and nonlinear lattices. Each problem is an area of thesis research for a graduate student in the Department.

1) Grain-Boundary Dynamics

We have begun to study grain-boundary diffusion by observing the diffusion of vacancies. Initial results showed that strong driving forces are needed in order to have such processes occur frequently on the time scale of simulation. A pseudopotential function deduced by P. Ho (IBM) for aluminum is being used, and collaboration with the IBM group currently measuring grain-boundary diffusion is planned.

2) Crack Propagation

A flexible boundary condition following the general approach described by Sinclair, Gehlen, Hoagland, and Hirth (J. Appl. Phys. 49, 3890 (1978)) for use in studying crack propagation has been implemented. In this method the atomic region to be simulated is coupled to a second region (II) which is treated as an elastic continuum, and the atoms in region II also interact with the atoms in a third, outer, region. This condition is expected to give much more realistic results compared to periodic or fixed boundary conditions. We are applying the method to verify the Griffith criterion for brittle materials and have started to investigate the plastic relaxation in the region around the crack tip.

3) Chemical Reactions

We have previously developed a simulation program for reacting hard spheres in two and three dimensions. More recently programs for computing the static and dynamic properties of the fluid have been completed and will be used to study chemical instabilities in systems far from equilibrium. A basic objective is to simulate a fluid undergoing exothermic reaction while contained in an enclosure with heat conducting walls. By making the reactions release more energy than can be conducted away, we hope to be able to investigate the mechanisms underlying the phenomenon of thermal explosion.

4) Nonlinear Lattices

The dynamics of atoms moving in double-well single-particle potentials while also experiencing normal dispersive forces in harmonic lattices is being studies to elucidate the different types of wave propagation which nonlinear lattices can sustain.

Investigators: Professor S. Yip; Messrs. D. Chou, A. Combs, B. DeCelis, and T. Kwok.

Support: Army Research Office - Durham (continuing support since July 1974, current contract period extends to December 1980 at an annual level of about $70,000)

Related Academic Subjects:

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

Recent References:

P. Ortoleva and S. Yip, "Computer Molecular Dynamics Studies of a Chemical Instability," *J. of Chem. Phys.* *65*, 2045 (1976).

G.H. Bishop, R.J. Harrison, T. Kwok and S. Yip, "Computer Molecular Dynamical Observations of Coupled Grain Boundary Sliding and Migration", *Trans. Am. Nucl. Soc.* *27*, 323 (1977).

T. Kwok, *Computer Molecular Dynamics Studies of Two-Dimensional Grain-Boundary Crystals*, S.M. Thesis, MIT, Department of Nuclear Engineering, June 1978.

R.J. Harrison, G.H. Bishop, S. Yip and T. Kwok, "Grain Boundaries as Solitary Waves", in *Solitons and Condensed Matter Physics*, ed. A.R. Bishop and T. Schneider, Springer-Verlag (1978), 183.

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 $<I(t)\ I(t+\tau)>$ 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: NSF (Biophysics Section): Current Contract period February 1, 1979-January 31, 1981 ($90,000).

Related Academic Subjects:

22.51	Radiation Interactions and Applications
8.442	Statistical Optics and Spectroscopy

Recent References:

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

S.-H. Chen, M. Holz and P. Tartaglia, "Quasi-elastic Light Scattering from Structural Particles", Appl. Opt. 16, 187 (1977).

M. Holz and S.-H. Chen, "Structural Effects in Quasi-elastic Light Scattering from Motile Bacteria of E. coli", Appl. Opt. 17, 1930 (1978).

M. Holz and S.-H. Chen, "Tracking Bacterial Movements Using a One-Dimensional Fringe System", Opt. Lett. 2, 109 (1978).

M. Holz and S.-H. Chen, "Quasi-elastic Light Scattering from Migrating Chemotactic Bands of E. coli", Biophys. J. 23, 15 (1978).

M. Holz and S.-H. Chen, "Rotational-Translational Models for Interprelation of Quasielastic Light Scattering Spectra of Motile Bacteria", Appl. Opt. 17, 3197 (1978).

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).

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. We are synthesizing a series of partially deuterated diblock copolymers to be run on available SAXS and SANS instruments. The principal aim of the experiments is to determine interphase thickness as a function of molecular weight. Theoretical predictions for this dependence will be checked.

Investigator: Dr. C.V. Berney

Support: National Science Foundation-DMR ($8,000)

Related Academic Subject:

22.51 Radiation Interactions and Applications

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 In Vivo Neutron Activation Analysis

Studies are being carried out on the possible use of neutron activation analysis to measure calcium, nitrogen and other elements in vivo. Studies include theoretical calculations and experiments.

Investigator: Professor Gordon L. Brownell

Related Subjects:

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

Recent References:

R.G. Zamenhof, The Measurement of Body Elemental Composition by Radiative Capture Gamma Ray in vivo Neutron Activation Analysis, Ph.D. Thesis, MIT, Nuclear Engineering Department (1977).

3.7.3 Boron Neutron Capture Therapy

An extensive new program of preclinical studies of BNCT is currently underway. 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 Drs. Murphy, M. Shalev 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:

G.L. Brownell, R.G. Zamenhof, B.W. Murray, and G.R. Wellum, "Boron Neutron Capture Therapy," in Therapy in Nuclear Medicine, edited by R. P. Spencer, Grune & Stratton, New York (1977).

3.7.4 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 purposes.

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, Ms. K. Kearfott, D. Benadouch

Support: National Institutes of Health, 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, J.A. Correia, R.G. Zamenhof, "Positron Instrumentation", Recent Advances in Nuclear Medicine (1978).

3.8 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. They also continued their studies of energy productivity in industrial processes.

3.8.1 Subjects of Instruction

22.571J: General Thermodynamics I, presents the foundations of thermodynamics in a general way, followed by the application of thermodynamic principles to energy conversion systems and industrial processes. First part: the first and second laws are introduced together with the definitions of work, energy, stable equilibrium, available work, entropy, thermodynamic potentials, and interactions (work, 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: General Thermodynamics II, is a continuation of the application of thermodynamic principles to practical problems, followed by a presentation 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 phenomenological 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.

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

3.9 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.

3.9.1 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: Reliability Analysis Methods, 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 National Socio-Technological Problems and Responses, 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: Energy Assessment, is an introduction to the broad field of energy, including technological, social, environmental, economic, and political aspects. Energy provision, transformation, and utilization. Development of energy options for the future, and analyses of present regional, national, and international energy programs. Intended for graduate students entering energy fields in which energy is important, and who desire a holistic overview.

22.83J: The Finite Earth: Agendas for a More Just Sustainable and Participatory Society, 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: Graduate Seminar in Energy Assessment, is primarily designed as a communication medium among students conducting research in energy related areas, and as a means for obtaining critical evaluation of their ongoing research work. Covers topics ranging from technological comparisons to environmental, social, resource, and political impacts, depending on current student and faculty interest.

3.9.2 Light Water Reactor Study

A general study has been completed covering the U.S. Light water reactor industry, including electric utilities, major vendors, regulatory bodies, attitudes of governmental and public interest groups, and our own analysis of present difficulties and possible improvements. This work, which is a major part of a study carried out with MIT's Energy Laboratory for the Department of Energy, concludes that, while some worthwhile technical improvements in LWRs can be made (such as reduced refueling time, better fuel, and standardization) the LWR sector in the U.S. Faces grave difficulties and may collapse if a number of serious institutional difficulties are not repaired promptly. Chief among these is uncertainty in the minds of electric utilities, vendors and regulatory groups, not only about each other's intentions but also about the Federal Government's long-term goals and policy with respect to nuclear power. In addition, regulatory changes can be proposed to permit advanced siting studies, and to reduce time between application to build a power plant and license to operate, without jeapordizing opportunity for groups to be heard in an orderly manner (the present delays are becoming very long, and tend to drive utilities away from nuclear power). These lack: even-handed comparative assessments between energy options; the study of new cooperative arrangements between utilities, vendors, the government, and other groups in order to develop new technical options better matched to needs and better timed; and real attempts to explain the nuclear problem to the public, on a long-term basis. All these and more have been indentified in detail.

Investigators: Professors M.J. Driscoll, M.W. Golay, D.J. Rose, D.D. Lanning, N.C. Rasmussen; Messrs. I. Saragossi, S. El-Magboub, R. Marley, T. Montgomery, D. Bley.

Support: Part of DOE contract for $325,000.

Related Academic Subjects:

22.311	Engineering Principles for Nuclear Engineers
22.312	Engineering of Nuclear Reactors
22.37	Environmental Impact of Power Production
22.80	National Socio-Technological Problems and Responses
22.085	Introduction to Technology and Law
22.81	Energy Assessment

Recent References:

N.C. Rasmussen and D.J. Rose, "Nuclear Power: Safety and Environmental Issues," in Option for US Energy Policy, Institute for Contemporary Studies, San Francisco, CA (1977).

The MIT LWR Study Group, The Future Development and Acceptance of Light Water Reactors in the U.S., MIT-EL 78-035 (September 1978).

M.W. Golay, I. Saragossi, and J.M. Willefert, Comparative Analysis of United States and French Nuclear Power Plant Siting and Construction Regulatory Policies and Their Economic Consequences, Energy Laboratory Report No. MIT-EL-77-044WP (December 1977).

M.W. Golay and I. Saragossi, Effects of Environmental Protection and Public Safety Regulatory Practices Upon Light Water Reactor Economics, Energy Laboratory Report No. MIT-EL-78-009 (June 1978).

S.A. El-Magboub and D.D. Lanning, Assessment of Light Water Reactor Power Plant Cost and Ultra-Acceleration Depreciation Financing, MIT-EL-78-041 (September 1978).

D.C. Bley, Light Water Reactor Productivity Improvement, Ph.D. Thesis, MIT, Nuclear Engineering Department (July 1978).

A.T. Abbaspour, Fuel Cycle Economics of Thorium and Uranium Fueled Light Water Reactors, Nuclear Engineers Thesis, MIT, Nuclear Engineering Department (August 1978).

K. Ghahramani, An Analysis of Prospective Nuclear Fuel Cycle Economics, Nuclear Engineers Thesis, MIT, Nuclear Engineering Department (July 1978).

D.E. White, Extensions and Revisions of the MIT Regional Electricity Model, Energy Laboratory Working Paper No. MIT-EL-78-018WP (July 1978).

3.9.3 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) to be published.

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) to be published

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).

3.9.4 Nonproliferation Alternative Systems Assessment Program (NASAP)

The research consists of analyzing the nonproliferation potential of nuclear power systems in support of the Department of Energy (DOE) Non-Proliferation Alternative Systems Assessment Program (NASAP) and the United States contribution to the International Nuclear Fuel Cycle Evaluation (INFCE). During the past year, work has been performed in the following areas:

1. A study of the proliferation implications of the utilization of heavy water-moderated power and research reactors.
2. A case study of the development of heavy water production capability in India.
3. A study of the proliferation implications of the education of foreign nationals at U.S. universities.
4. A study of the prospects for small nuclear power reactors in developing countries.

Investigators: Professors M. Benedict, N.C. Rasmussen, D. Rose; Drs. C. Heising-Goodman, M. Miller (Energy Laboratory), and O. Marwah (Center for Science and International Affairs, Harvard University); Support Staff, Marie Southwick.

Support: U.S. Department of Energy contract through MIT Energy Laboratory ($260,000).

Related Academic Subjects:

22.003J	In Pursuit of Arms Control and industrial sectors via increased
22.76	Introduction to Nuclear Chemical Engineering

Recent References:

M.M. Miller, "The Nuclear Dilemma: Power, Proliferation, and Development", Technology Review (May 1979).

J. Lamarsh and M.M. Miller, "University Training of Foreign Nationals: A Route to Weapons Proliferation?" Bull. Atomic Scientist, (January 1980).

C. Heising-Goodman, "The Supply of Appropriate Nuclear Technology for the Developing World: Small Power Reactors for Electricity Generation", (July 1979).

3.9.5 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, and has benefited from interactions with the NASAP support program (See Section 3.9.4). 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.

Also in the past year, 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; Drs. M.M. Miller, C. Heising-Goodman.

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, Ph.D. Thesis, MIT, Nuclear Engineering Department (September 1979).

3.9.6 Community Total Energy System Analysis

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

1) Total Energy Analysis for Large Military Bases

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

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

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

Additional analysis has shown that interconnection of multiple district heating systems has relatively little benefit.

An additional important contribution of this work has been development of the computer programs TDIST2--for demand and performance simulation of single-power-plant community total energy systems, and TDIST3--for multi-heat source systems. These programs have been requested by several energy conservation analysts, and are coming into relatively widespread use.

This work is continuing currently in its fifth year of funding, with the focus of effort being upon extension and further improvement of the TDISR codes and upon analyzing community subsystems at Ft. Knox.

Investigators: Professor M. Golay; Messrs. F. Best, S. Goldman, D. Ebeling-Koning.

Support: U.S. Army, Facilities Engineering Support Agency ($42,000/year for the HTGR total energy system design).

Related Academic Subjects:

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

Recent References:

S.B. Goldman, F.R. Best, and M.W. Golay, TDIST2, A Computer Program for Community Energy Consumption Analysis and Total Energy System Design, FESA-RT-2047 (1977).

F.R. Best, S. B. Goldman, and M.W. Golay, Final Report: Analysis of Nuclear and Coal Fueled Total Energy System Options for Ft. Knox, Kentucky, FESA-RT-2039 (1977).

S.B. Goldman and M.W. Golay, "Strategies for Scheduling Power Producing Both Heat and Electric Energy", Energy (December 1978).

3.9.7 Bouyant Atmospheric Plume Modeling

Over the past three 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 positions 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: Professors M.W. Golay, R.G. Bennett; 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
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
2.283	Fluid Physics of Pollution

Recent References

R.G. Bennett, and M.W. Golay, *Numerical Modeling of Buoyant Plumes in a Turbulent, Stratified Atmosphere*, MIT-EL-79-002 (1979).

R.G. Bennett, and M.W. Golay, *User's Guide for Numerical Modeling of Buoyant Plumes in a Turbulent, Stratified Atmosphere*, MIT-EL-79-004 (1979).

R.G. Bennett, and M.W. Golay, "Airborne Plume Dispersion from Two-Dimensional Computational Hydrodynamic Simulations," invited paper, *Trans. Amer. Nuclear Soc.*, *33*: 179-180 (1979).

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

3.10 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.

3.10.1 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.

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

22.615: 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 feasibility on basis of economic and technical considerations, detailed critical review of U.S. NRC's prototype references reactor designs, non-maxwellian reactors, laser induced fusion, blanket neutronics, fission-fusion symbiosis, radiation damage, environmental hazards.

22.622: Special Topics in Thermonuclear Reactor Design, Engineering physics of CTR subsystem: large superconducting magnetic materials and design, neutral beam generation and control, divertors and gas blankets, energy storage and recovery, structural material behavior. There 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, technological and economic reality in a large scale research device such as a mirror reactor neutron source or break-even two component Tokamak.

22.63: Engineering Principles for Fusion 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 generation by normal, cryogenic and superconduction coils: electrical, heat transfer and structural requirements, high voltage engineering and practices, methods of plasma heating: ion, electron and neutral beam production, microwave and laser systems, applications to fusion systems.

22.64J: Plasma Kinetic Theory, content varies from year to year. Typical subjects: the linearized Vlasov equation, Fokker-Planck and diffusion approximations for the average distribution function, autocorrelation functions, resonant and nonresonant diffusion, free energy, energy and momentum conservation, 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 collective phenomena such as linear instability and non-linear saturation mechanisms in plasma, particularly in regimes described by the Vlasov Maxwell equations. Effects of wave-particle resonance; trapping and scattering of particles by waves. Linear theory in instabilities in inhomogeneous plasma. Reflection and eigenmode problems in bounded systems. Diffusion phenomena and anomalous resistivity associated with wave-particle interaction. Discussion of experiments.

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

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

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

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.

3.10.2 Fusion Reactor Technology

The demonstration of the scientific feasibility of controlled fusion power--a milestone that might possibly be reached within ten years -- is not sufficient to ensure that fusion will become ultimately a significant contributor to our energy requirements. The development of controlled thermonuclear reactors for commerical power generation will require also the solution of many extraordinarily difficult technological problems. Many of these problems are similar to, but more difficult than, those associated with fission reactor technology. Thus, the Nuclear Engineering Department with its unique combination of skills and fission reactor expertise, is the ideal locus for a balanced attack for these problems. The Fusion Technology Program is supported by the Development and Technology Branch of the Office of Fusion Energy. The Program's goal is the investigation of various engineering problems of controlled fusion reactors with particular emphasis on reactor fueling, reactor blanket and shielding analysis, reactor safety and environmental studies, and new concept development. Because of its multidisciplinary nature (structural design, thermal-hydraulic analysis, materials selection, environmental effects, safety analysis, plasma physics, etc,) this project has involved a substantial fraction of the Nuclear Engineering Department's Faculty. In addition, faculty members from the Departments of Metallurgy, Materials Science and Engineering and Mechanical Engineering have participated as well as members of the National Magnet Laboratory staff. There is usually a complement of fifteen to twenty students associated with this program.

A) Pellet Fueling of Fusion Reactors

One of the outstanding problems in the operation of a steady state or long pulse fusion reactor plasma is the question of how cold deuterium-tritium fuel is to be added to the reacting plasma. The most promising method is the injection, at high velocity, of solid D-T pellets. It is anticipated that such pellets will be partially shielded from the intense bombardment in the reactor plasma by the cold, dense cloud of ablating material, and thus will be able to penetrate to the center of the reactor. It is, therefore, important to evaluate the effectiveness of this shielding, and the ablation rate to be expected under reactor-like plasma conditions. Once the ablation rate is known as a function of plasma parameters such a density, temperature, and magnetic field, it becomes possible to specify the velocity requirements for the pellet accelerator.

We have been working on three aspects of the pellet ablation problem. First of all, we have developed a theoretical model which includes magnetic shielding effects. We expect that, under reactor-like conditions, the ablated material will become ionized and will form a high pressure cloud which excludes the ambient magnetic field from the region around the pellet. Since the reactor plasma is tied to this magnetic field the energy deposition at the pellet surface will be reduced. Second, we are engaged in an experimental investigation of the ablation process under reactor-like plasma conditions. We have constructed a Z-pinch system which generates a plasma with energy density and flux larger than might be found in a reactor, but only for a short time. This experiment will determine the extent to which magnetic shielding occurs, and will provide measurements of the ablation rate as a function of plasma parameters. Finally, in a cooperative effort with the Oak Ridge National Laboratory, we are designing, constructing, and will operate an experiment on the ISX-TOKAMAK at Oak Ridge which will measure the details of the ablation process for hydrogen pellets injected at high velocity into ISX-B.

B) Fusion Reactor Environmental and Safety Studies

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

This effort has so far accomplished the following:

1. A methodology has been proposed to provide system reliability criteria based on an assessment of the potential radiological hazards associated with a fusion reactor design and on hazard constraints which prevent fusion reactors from being more hazardous than light water reactors. The probabilistic consequence analyses, to determine the results of radioactivity releases, employed the consequence model developed to assess the risks associated with light water reactors for the Reactor Safety Study.

The calculational model was modified to handle the isotopes induced in the structural materials of two conceptual TOKAMAK reactor designs, UWMAK-I and UWMAK-III. Volatile oxidation of the first wall during a lithium fire appears to be a primary means of disrupting induced activity, and the molybdenum alloy. TZ (UWMAK-III) tends to be more susceptible than 316 stainless steel (MAK-I) to mobilization by this mechanism. It was determined that the radiological hazards associated with induced activity in these reactor designs imply reliability requirements comparable to those estimated for light water reactors. The consequences of estimated maximum possible releases of induced activity, however, are substantially less than the maximum light water reactor accident consequences.

2. A lithium pool combustion model was developed to describe the physical and chemical processes which occur during a hypothetical lithium spill and fire. The model (LITFIRE) was used to study the consequences of lithium fire within a typical containment. Calculations show that without any special fire protection measures, the reference containment may reach pressures of up to thirty-two psig when one coolant loop is spoiled inside the reactor building. Temperatures as high as 2000° F would also be experienced by some of the containment structures. These consequences were

found to diminish greatly by the incorporation of a number of design strategies including initially sub-atomospheric containment pressures, enhanced structural surface heat removal capability, initially low oxygen concentrations, and active post-accident cooling of the containment gas. A modular design was found to limit the consequences of a lithium spill, and hence offers a potential safety advantage. Calculations of the code are now being compared to experimental measurements at Hanford Engineering Development Laboratory.

3. The effects of various approaches to modeling of consequences of tritium releases from fusion plants have been assessed. Both local dispersion and global dispersion models have been reviewed. The implications of the uncertainties involved in the models have been determined. The allowable release rates on routine basis from fusion plants have been determined.

Investigators: Professors M.S. Kazimi, L.M. Lidsky, N.C. Rasmussen; Messrs. R.W. Sawdye R. Green, S. Piet, and M. Tillack.

Support: Department of Energy and EG&G, Idaho (approximately $70,000/year).

Related Academic Subjects:

22.38 Reliability Analysis Methods
22.621 Thermonuclear Reactor Design

Recent Publications:

R. Green and M.S. Kazimi, "Aspects of Tokamak Toroidal Magnet Protection", PFC/TR-79-6, Plasma Fusion Center, MIT (July 1979).

S.J. Piet and M.S. Kazimi, "Uncertainties in Modeling of Consequences of Tritium Release from Fusion Reactors", Plasma Fusion No. PFC/TR-79-5, Nuclear Engineering Department (July 1979).

R.W. Sawdye and M.S. Kazimi, "Fusion Reactor Reliability Acquirements Determined by Considerations of Radiological Hazards," Trans. Am. Nuc. Soc. 32, 66 (June 1979).

R. Green and M.S. Kazimi, "Safety Considerations in the Design of Tokamak Toroidal Magnet Systems," Trans. Am. Nuc. Soc., 32, 69 (June 1979).

C) Fusion Reactor Blanket and First Wall Thermal Design

This effort consists of several studies involving:
1) forced convection cooling of blankets, 2) natural convection cooling of blankets and 3) thermal and design of the first wall. Theses areas are discussed below.

1) Previous work initiated on comparing the performance of various coolants with regard to forced convection heat removal from a stagnant lithium blanket was completed. The previously established methodology, of

first establishing a desired set of parameters and constraints and then finding the allowable range or design window for the remaining free variables, was utilized.

For the tubular stainless steel systems considered, it was concluded that helium and lithium are nearly equally effective as coolants in terms of their thermo-hydraulic characteristics. Both appear capable of acceptable steady state performance for the range of wall loadings currently considered. The helium systems require fewer tubes but a higher pumping power and have a slightly lower breeding ratio. These conclusions are based on the assumption that it will be possible to fabricate a sandwich insulation for the lithium coolant pipes. If the sandwich construction proves to be impractical, a different configuration would have to be found for the lithium coolant.

In this study, only configurations employing tubes and headers for lithium-cooled systems are considered. The results and comparison methods may not be applicable to other types of designs such as U-cell type blanket adopted by UWMAK-I and III.

If TZM structures can be fabricated and material testing shows acceptable properties after irradiation, then the TZM - Flibe system has the best thermo-hydraulic characteristics of the systems studied. The pumping power required is extremely small and low system pressures are required. Long tubes can be used without excessive pressure drops so the number of tubes and welds is small.

The TZM - Helium system has similar parameters compared to the 316 SS System. The principal difference is the increase in thermal efficiency possible at the higher temperatures. For this system the limiting constraint was the maximum pool temperature instead of the wall temperature or wall temperature drop as in the 316 SS design.

2) The relative importance of natural circulation and heat conduction as heat transfer mechanisms in lithium, sodium and flibe was investigated for a range of magnetic field strengths of interest in fusion reactor blankets. The calculations were based on an order-of-magnitude simplification of the fluid equations, and a modified version of the 3-D fission reactor thermal-hydraulic code THERMIT.

The results showed that conduction is dominant for lithium (and sodium) under typical conditions, but that natural circulation is most important in flibe. In fact, preliminary culculations suggest the possibility of a simple flibe blanket module with coolant tubes only along the module boundaries.

3) The thermal/mechanical assessment of the first wall was initiated by classifying the existing concepts into common approaches and identifying the design objectives and contraints. For each approach the allowable design window will then be identified. Work to date has identified the following objectives and constraints. Construction of the design window has not yet been completed for the first approach investigated, that of front (plasma side) cooling of the first wall by a flow channel.

The most important design questions for economic first wall system designs are:

1) radiation damage resistance

2) compatibility of structural materials with the coolant and with tritium

3) mechanical and thermal properties.

For near-term experimental power reactors, a long operating life is secondary to questions of industrial capability and fabricability of structural materials, since these may well be fairly exotic alloys or ceramics. Keeping these priorities in mind, the first wall must be designed:

- to be resistant to fast neutron damage (dpa, the production, transmutation, segregation leading to embrittlement, swelling, blistering and loss of ductility);

- to be compatible between materials (especially the first wall itself and the coolant);

- to have sufficient hydrogen permeability (or lack of permeability) that there is no serious buildup causing embrittlement (or that tritium leakage from a breeding blanket seriously affects safety and tritium inventory questions);

- to withstand the pressure stress from the coolant;

- to withstand the thermal stress and thermal strain cycling (the burning plasma is at a few hundred million degrees while the first wall system is strictly limited to less than a few thousand degrees, the burn cycle can range from 0.1 seconds for inertial confinement reactors, to 1000 seconds for tokamaks, to continuous for mirrors);

- to be weldable with good ductility in the weld zone because of the inevitable thermal stresses;

- to be able to handle accidents (plasma dumps, magnet quenches);

- to be maintainable (the replacement time strongly affects the plant economics);

- to have a reasonably long lifetime (most recent designs have first wall lifetimes varying from 6 to 20 MW-y/m^2);

- to operate at a high average temperature for good efficiency (better than a 30% overall plant efficiency is necessary to be competitive);

- to have sufficient cooling, not necessarily dictated by breeding and high efficiency considerations;

- to allow for some elongation;

- to have a low vapor pressure at the operating temperature to avoid contaminating the plasma or interfering with the energy transport to the fuel pellet in inertial confinement reactors;

- to be resistant to sputtering;

- to be reliably manufacturable at low cost;

- to be redundant, to withstand a partial failure of part of the first wall system and still keep on running;

- to withstand differential thermal expansion and thermal distortion;

- to be resistant to creep buckling (for example, use membranes which are curved intention);

- to use resources which are readily available to the U.S.;

- to use materials which have low residual activity and afterheat.

Investigators: Professor N.E. Todreas, B. Mikic; Messrs. J. Chao, T. McManamy, and P. Gierszewski

Support: U.S. Department of Energy, $30,000/year for thermal design of fusion reactor blankets.

Recent References:
J.Chao, B.Mikic, and N.Todreas, Hydraulic and Neutronic Considerations for Designing Lithium-Cooled Tokamak Blanket, PFC/RR-79-11, MIT (December 1978).

T. McManamy, B. Mikic, and N. Todreas, Fusion Reactor Blanket Heat Removal Using Helium and Flibe, PFC/RR-79-10; MIT (February 1979). Paul

P. Gierszewski, B. Mikic, and N. Todreas: Natural Circulation in Fusion Reactor Blankets, to be issued as Plasma Fusion Center Report in January 1980.

D) Torsatron Reactor Reference Design

Heretofore, Fusion Reactor Design studies have attempted to extrapolate particular plasma confinement geometries to reactor scale. These designs without exception encountered severe technological and economic penalties at reactor scale. This result is not surprising; the boundaries of acceptable engineering are more sharply drawn than those of potential plasma confinement schemes and there is no *a priori* reason to expect them to overlap. We concluded that the most efficient search scheme required an inversion of the usual process; we developed a list of desirable reactor properties (steady state, ignited, diverted, modular, moderate size, etc.) and searched the literature for a confinement scheme compatiable with these requirements. Recent stellarator/torsatron experimental results were very encouraging (comparable, or superior to equivalent TOKAMAKS) and there are strong indications that extrapolation to the zero current steady state operation would yield further improvement. An essential step was our recognition that the magnetic forces on the helical winding could be appreciably reduced (factors of ten to possibly thirty) by proper disposition of the current carrying coils. The T-1 design evolved from simultaneous satisfaction of the engineering and plasma physics constraints.

The reference design reactor (T-1) is steady-state, large aspect ratio, modular, beam ignited, possesses natural divertors, and is in a nearly "force free" configuration. With rather conservative engineering and plasma physics assumptions (e.g., $\bar{\beta} = 3.45\%$) this reactor produces 1520 MW_e with $\bar{n}\tau_e = 3 \times 10^{20} \mathrm{sec.m}^{-3}$.

The reactor is constructed of twenty identical modules, each 9.17m long, giving a major radius of 29.2m. The relatively open helical coil structure permits ample assess to the reactor plasma and the blanket. The choices of ℓ, coil radius, and pitch length are constrained by the requirements for generating a plasma of suitable size, allowing space for blanket and shield, minimizing the forces on the windings, for generating a plasma of suitable size, allowing space for blanket and shield, minimizing the forces on the windings, and generating the required magnetic field. The plasma size and the magnetic field requirements are determined by the plasma β assumed attainable in a given configuration, and by the plasma energy confinement scaling law. For a neutron wall loading, W_n , of 1.25MW /m^2 and "Alcator Empirical Scaling" the optimized choices for this reactor are $\ell = 3$, $a_c = 4.0$m, and p = 27.5m. In the force free configuration an $\ell = 4$ torsatron would not allow sufficient room for blanket and shield and an $\ell = 2$ torsatron would provide an adequate plasma volume.

The basic reactor requirements of modularity and ease of remote handling and maintenance are met in this design because of the periodicity of the magnetic field structure and because we have incorporated low resistance normally conducting joints in the superconducting coil. Demountable joints of sufficently low resistance to be used in this reactor have already been achieved in the laboratory.

The reactor configuration allows at least 1.5m at all points between the first wall and the superconducting coils for blankets and shields. We postulate the use of near stagnant lithium pool blankets with circulating molten salt coolant. This design, originally developed for the HFCTR, has sufficiently high breeding (1.2 T/n) in thin systems (0.6m) to allow room for adequate shielding using relatively low cost materials. This blanket has the further advantage that the coolant, breeding material, and some of the shielding can be drained so that entire modules may be more easily lifted for repair and replacement. The plasma scrape-off layers immediately outside the separatrix are directed into special heat transfer and pumping sections at a radius of 4.5m where the neutron wall loading is reduced.

The reactor design described here is based on relatively conservative plasma physics assumptions. The reactor could be made somewhat smaller if better confinement could be achieved or higher betas successfully confined. The limiting parameters would then be blanket thickness and minimal allowable aspect ratio. We estimate that $\ell = 3$ torsatron reactors could be made as small as approximately twenty meters in major radius with a power output of approximately 800 MW_e.

Because we have not yet reached the point of diminishing returns in torsatron reactor studies and because such multi-disciplinary projects furnish an excellent medium for motivation and educating students, we will continue our conceptual design studies. This work will include (a) the design of a minimum size torsatron reactor, (b) the design of a torsatron ignition experiment, (c) structural design of force-reduced systems, and (d) possible advantages of other coil winding laws.

Investigators: Professors L.M. Lidsky, P.A. Politzer, M. Kazimi, N.E. Todreas, B. Mikic; Dr. D.B. Montgomery.

Support: Department of Energy, EPRI.

3.10.3 Theory of Magnetically Confined Toroidal Plasma

One purpose of this activity is to determine the important MHD equilibrium and stability limits (both ideal and resistive) of magnetic confinement systems, in particular tokamaks, torsatrons, EBT and the tandem mirror. Specifically, one needs to calculate β 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., β, q, helical current, etc.) scale with basic geometries and technological constraints (i.e., aspect ratios, ring current, beam energy, etc.) in order to optimize the design of future experiments and possible reactors. The approach to be used consists of solving the ideal and resistive MHD equilibrium and 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. Given microscopic (anomalous 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 mechanism of anomalous heat loss, and (c) development of a self-consistent turbulence theroy for the magnetic fluctuations associated with the universal drift instability in a screw pinch.

The predicted transport coefficients (anomalous electron thermal conductivity) has 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 Ousager matrix of anomalous transport coefficients.

Investigators: Professors J.P. Freidberg, K. Molvig, Dr. A.B. Rechester, and Mr. K. Swartz.

Support: U.S. Department of Energy.

Related Academic Subjects:

22.64J	Plasma Kinetic Theory
22.65J	Advanced Topics in Plasma Kinetic Theory
22.68J	Introduction to Plasma Kinetic Theory
22.615	Magnetohydrodynamic Stability of Magnetic Fusion Systems

3.10.4 Theory of Non-Linear and Turbulent Fluctuations in Plasma

Most plasmas of laboratory or astrophysical interest contain a non-thermal spectrum of fluctuations. These fluctuations are generally non-linear and turbulent and play a major role in determining the important properties of the plasma. For example, in plasmas of thermonuclear interest, such fluctuations can transport heat and particles across the magnetic field lines at a rate greatly in excess of the collisional rate. Also, non-linear fluctuations can enhance the rate of plasma heating for a given current in the plasma. The study of these fluctuations is not only worthwhile from the point of view of practical applications, but is an important problem in many-body physics. For example, our work is closely related to problems in fluid turbulence and the dynamics of self-gravitating systems. Generally speaking, non-linear and turbulent fluctuations are the end result of linear instabilities, which have grown past the linear stage. Unfortunately, the resulting fluctuations frequently bear little resemblance to the linearly unstable waves which drive them. Our research is concerned mainly with discovering and identifying the types of non-linear 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 non-equilibrium situations, and (3) the deduction of exact non-linear 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, Messrs. T. Boutros-Ghali, and P. Diamond

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

3.10.5 Torsatron Design Studies

The Nuclear Engineering Group's work on the T-1 Torsatron Reactor design has led to a significant resergence of interest in this concept on the part of the National Fusion Program. Unfortunately, this interest has not yet resulted in significant new experiments; our proposed TOREX-4 and TOREX-A experiments have not been funded. However, the important technological advantages of the Torsatron concept (steady-state diverted, distruption free, etc.) and the recent experimental results from the English and German programs are most encouraging. We have developed numerical techniques for analyzing particle orbits in the complex magnetic field geometry of Torsatrons and are applying these techniques to studies of both alpha particle slowing down and thermal diffusion. The extensive calculations required for these studies were carried out on the National Fusion Computational Facility at Livermore, California. The results indicate that large aspect ratio of Torsatron devices have unexpectedly favorable alpha-particle confinement properties in that theoretically suggested large-scale enhancements of thermal conductivity will not be troublesome. We have also developed a non-linear multi-parameter optimization program to facilitate understanding of the interaction of detailed winding geometries and coil placements with flux surface geometries and magnetic forces on coils. We have just begun a detailed conceptual design study for an "ignition scale Torsatron experiment". This study is intended to be a framework within which to investigate several outstanding questions about Torsatron reactors, notably questions of minimum reactor size and ideal winding geometry.

Investigators: Professors, L.M. Lidsky, P.A. Politzer, J.G. Aspinall, R.E. Potok, T. Uchikawa

Support: Office of Fusion Energy, DOE

Related Academic Subjects:

22.611J	Introduction to Plasma Physics
22.612	Plasmas and Controlled Fusion
22.621	Thermonuclear Reactor Design

Recent Publications:

J.G. Aspinall, L.M. Lidsky, P.A. Politzer, R.E. Potok, "Physics and Technology of Torsatron Confinement Schemes", to be presented at 8th IAEA Conference on Plasma Physics, Brussels (1980).

P.A. Politzer, L.M. Lidsky and D.B. Montgomery, "Torsatrons and the TOREX Proof of Principle Experiment", PFC/TR-79-1 (1979).

J-M Noterdaeme, "Demountable Resistive Joint Design for High Current Superconductors", PFC/RR-78-11 (1978).

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 searching and difficult general examination and then to complete a major research investigation of sufficient scope and originality to constitute a contribution of permanent value to science and technology. Although no set time is specified for completion of the doctoral program, most students require from three to five years.

Students completing the Doctor's program in Nuclear Engineering are prepared and motivated to work on the frontiers of nuclear technology.

4.2 Fields of Study

Although each student's program of study is arranged to suit her/his individual interests and objectives, most programs fall into one of the 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
22.005	Dynamics of Physical and Social Systems
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 Reactor 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
22.08J	Energy
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 Reactor Design
22.34	Economics of Nuclear Power
22.35	Nuclear Fuel Management
22.36J	Two-phase Flow and Boiling Heat Transfer
22.37	Environmental Impact of Electric Power Production
22.38	Reliability Analysis Methods
22.39	Nuclear Reactor Operations and Safety

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
22.58J	Quantum Foundations of Mechanics and Thermodynamics

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

Plasmas and Controlled Fusion

22.610	Controlled Fusion Power
22.611J	Introduction to Plasma Physics
22.612	Plasmas and Controlled Fusion
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
22.64J	Plasma Kinetic Theory
22.65J	Advanced Topics in Plasma Kinetic Theory
22.66	Transport Phenomena in Toroidal Systems
22.67	Plasma Diagnostics
22.68J	Introduction to Plasma Kinetic Theory
22.69	Plasma Laboratory

Nuclear Materials

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

General

22.80	National Socio-Technological Problems and Responses
22.81	Energy Assessment
22.83J	The Finite Earth: Agendas for a More Just, Sustainable and Participatory Society
22.86	Entrepreneurship
22.89	Basic Electronics

22.901-	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 Siminar in Energy Assessment
22.915	Seminar in Reactor Safety
22.92	Advanced Engineering Intership

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

Civil Engineering

1.143	Mathematical Optimization Techniques
1.146J	Engineering Systems Analysis
1.159	Judgement, Prediction and Risk in Engineering Planning
1.502	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
2.283	Fluid Physics of Pollution
2.30	Mechanical Behavior of Solids
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 Failure of Engineering Alloys in Service
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 and94iscrete Time Optional 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

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

In January 1979, the Nuclear Engineering Department offered 9 activities. Professor K. Hansen organized a seminar entitled "Audiovisual Feedback Seminar" in which audiovisual equipment was available for students to tape practice presentations to audiences and then review them. The "Fusion Reactor Safety Seminar" was conducted by Professor M. Kazimi. This two-hour seminar presented some of the department's research on safety aspects of future fusion power reactors. A seminar on "Fuel Processing for Fusion Power Systems" was offered jointly with the Chemical Engineering Department. In this one-hour seminar, Dr. Robert H. Sherman of LASL described the Tritium Systems Test Assembly under development at Los Alamos to demonstrate the safe, long-term handling of the deuterium-tritium mixtures used as fuel in fusion power systems.

There were five student-sponsored activities. Mr. William Fisher organized tours to energy generating and distribution facilities in New England. Mr. Donald Dube coordinated "Seabrook Week", which included a series of speakers, films, panel discussions, and a tour of the Seabrook plant.

"Films on Energy Development", organized by Messrs. K. Smith and G. Greenman addressed the technical and political considerations of energy development. The films dealt with fission, fusion, solar and geothermal energy sources. Mr. Fred Best arranged another series of films on the topic of fluid dynamics. A course on the theory and practice of cardiopulmonary resuscitation was organized by Mr. James McCormack.

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 1978-1979 academic year, fifteen undergraduates were engaged in projects within the Department.

4.6 Description of New and Revised Subjects

Since the fall of 1978 four new subjects have been added to the curriculum. These subjects are described below.

A. New Subjects

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

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

22.83J: The Finite Earth: Agendas for A More Just, Sustainable and Participatory Society, covers problems such as food supply, energy, material resources, global environment, and rapid changes in third world countries in context. The purpose of the subject is to introduce interested students to these issues, to 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.

22.84: Nuclear Energy Policy Analysis, technology assessment and policy analysis of nuclear fuel cycle topics. Overview of selected cycle technologies. Quantitative and qualitative assessments of the social, political, and environmental consequences of nuclear energy policy decisions. Functions and organization of institutions participating in research and development, management and regulation. Institutional alternatives. Topics covered include: nuclear waste management and regulation; nuclear fuel supply; development of advanced reactor and fuel cycle systems; and the relationships between nuclear power and nuclear weapons proliferation.

B. Subject with Major Revision

22.56J: Principles of Medical Imaging, covers 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 are covered, as well as medical applications, biological hazards and cost-benefit analysis of imaging modalities.

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.

22.003: In Pursuit of Arms Control: Analysis of the Past and Choices for the Future, 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.

22.005: Dynamics of Physical and Social Systems, introduces the conceptual and technical foundations of systems dynamics, a method for analyzing the behavior of systems. By focusing on the common characteristics of systems -- such as the process of integration and the structure of feedback loops -- the subject emphasizes the unity, rather than the uniqueness, of diverse disciplines. Numerous case examples from engineering, medicine, management, economics, urban policy, and population-environment interactions demonstrate the transferability of system insights from one field to another. This subject is an Engineering School-Wide Elective.

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

22.02: Introduction to Applied Nuclear Physics, is an introduction to nuclear physics and neutron physics, with emphasis on those aspects of the subject which are applied in nuclear engineering. Topics include elementary results of quantum theory and special relativity, detection of atomic and nuclear particles, properties of atomic nuclei (isotopes and isotopic masses, nuclear reactions, natural and 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: Nuclear Reactor Physics, 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: Engineering of Nuclear Power Reactor Systems, considers the principles of component and system design, and the operating characteristics of nuclear reactors for central station and marine power generation. A study is made of the application of the various engineering disciplines contributing to reactor design, to examine tradeoffs involved in the realization of system performance objectives. Examples are selected from current and projected U.S. reactor designs.

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.

22.08: 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.

22.085: 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, 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.

Our Department had three students accepted for the program in each of the two program years. Both students and companies have been enthusiastic about the learning opportunities and the job accomplishments.

Companies which have placed students from the Nuclear Engineering Department are Commonwealth Edison, EG&G Idaho 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. Departmental offerings during the past two years include the following seminars: The Fast Breeder Reactor (M. Driscoll), Controlled Fusion (L. Lidsky), The Future Prospects for Nuclear Power (M. Driscoll), Minicomputer Applications in Nuclear Engineering (M. Driscoll), and Three Mile Island: Causes and Effects (M. Driscoll).

5. RESEARCH FACILITIES

5.1 M.I.T. Reactor

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

Since its shutdown in May 1974, the reactor has been redesigned and restarted (see Section 3.5). On July 1, 1976 it was designated an Institute Laboratory under the responsibility of the Vice President of Research. Dr. Otto K. Harling was appointed Director of the 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 with a doctoral student, Zoran Djorgevich. 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

Norman C. Rasmussen

Professor of Nuclear Engineering; Head of the Department A.B. '50 Gettysburg; Ph.D. '56 (physics) MIT

Reactor safety; environmental effects of nuclear power; reliability analysis; risk analysis.

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.

Ralph G. Bennett

Assistant Professor of Nuclear Engineering B.S.E. '73 U. of Michigan; S.M. '76; Ph.D. '79 (nuclear engineering) MIT

Numerical methods; environmental impact of nuclear power; reactor thermohydraulics.

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.

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

Associate 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.

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

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

Peter A. Politzer

Associate Professor of Nuclear Engineering
B.S. '64 MIT; Ph.D. '69 (plasma physics) Princeton
Plasma physics; controlled fusion.
(On leave to: Plasma Fusion Center)

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 methanics of plasmas and fluids.

Neil E. Todreas

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

Sidney Yip

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

6.2 Complete Listing of Personnel (as of January, 1980)

Professor

M. Benedict (Institute Professor Emeritus)
G. L. Brownell
S. H. Chen
T. H. Dupree
J. P. Freidberg
E. P. Gyftopoulos
O. K. Harling
A. F. Henry
I. Kaplan (Professor Emeritus and Senior Lecturer)
L. M. Lidsky
N. C. Rasmussen
D. J. Rose
K. C. Russell
N. E. Todreas
S. Yip

Associate Professor

M. J. Driscoll
M. W. Golay
M. S. Kazimi
P. A. Politzer

Assistant Professor

R. G. Bennett
R. K. Lester
K. Molvig

Adjunct Professor

D. J. Sigmar

Senior Research Engineer

B. D. Montgomery

Postdoctoral Fellow

C.D. Heising-Goodman

DSR Staff

R. Morton

Lecturer

M. M. Miller

Administrative Officer

J. J. Hynes

Assistant to Department Head

D. Dutton

Administrative Assistant

J. B. deVries Gwinn

Senior Research Associate

C. V. Berney

Research Affiliate

W. M. Akutagawa
R. H. Ackermann
J. W. Hopps, Jr.
D. Hnatowich
P. E. McGrath
S. Shortkroff
S. Treves
W.E. Vesely
L. Wolf

Clerical Staff

P. D. Arman
C. M. Egan
R. L. Esformes
M. Halverson
A. Y. Holman
E. D.Kehoe
P. F. Kelly
M. B. Levine
C. A. Lyndon
J. Phillips
D. Radcliffe
D. J. Welsh

Fall 1979 Teaching Assistants

Akbar, Shahzad
Araj, Kamal
Bamdad, Farid
Cavoulacos, Panayotis
Chang, Soon
Cho, Joon
Cogswell, Kurt
Coate, David
Djordjevic, Zoran
Hanchar, Deborah
Ismail, Nassar
Johnson, Joseph
Jones, James
Litai, Dan
Moerschell, Richard
Moshier, William
Parsons, Donald K.
Reilly, John
Roemer, Peter
Touqan, Khaled

Fall 1979 Research Assistants

Adegbulugbe, Anthony (1/2)
Atefi, Bahman
Ballinger, Ron
Best, Fred
Best, Susan
Booth, William
Boutros-Ghali, T.
Bronick, Douglas
Cheng, Alexander
Cho, Joon Ho (1/2)
Combs, J. Andrew
Doskocil, William
Dube, Don
Fisher, Bill
Foord, Mark
Glantschnig, Werner
Greene, Tom
Greenman, Gregory
Griggs, Dan
Hamza, Redouane
Hawley, Jim
Hizanidis, Kyriakos
Hoxie, Chris
Kamal, Altamash
Karimi, Roy
Kelly, John
Kim, Sang Won
Krisch, John
Koclas, Jean (1/2)
Kohse, Gordon
Kreischer, Kenneth
Kwok, Thomas
LaBambard, Brian
Lancaster, Dale
Laning, Dave
Levin, Alan
Loh, Wee Tee
Loomis, Jim
Manahan, Mike
Modarres, Mohammad
Piet, Steven
Potok, Robert
Raeisinia, Mohsen
Rogus, Ron
Saragossi, Isi
Sawdye, Bob
Schissel, David
Sefick, Joe
Shanfield, Stan
Smith, Kord
Smith, Russ
Steufekm, Michael
Tan, Lip-Bu
Tillack, Mark
Van Haltern, Marty
Vilim, Rick
Wang, Paul
Wilson, Greg
Wong, Channy
Yu, Ge-Ping

7. DEPARTMENTAL STATISTICS

Statistical Summary

Academic Year Sept - June	Sept. Registration				Degrees Granted						
	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
				TOTALS	24	766	110	301	1191		

8. STUDENTS

Some background information about the 174 full-time students registered in the Department in September 1979, is presented in Tables 8.1 and 8.2. In past years a plurality of our students have come from undergraduate programs in Physics, with Mechanical Engineering second. We now find Nuclear Engineering undergraduates the single largest discipline.

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

Support for students has increased in recent years. In 1973/ we had 24 research assistants, while in 1979/80 we now have 60. 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 (Fall 1979)

By Profession (174)

Applied Science (1)
Chemical Engineering (8)
Chemistry (1)
Civil Engineering (1)
Electrical Engineering (11)
Electronics (2)
Electro-Mech. Engineering (1)
Electrophysics (1)
Energy (1)
Engineering (5)
Engineering Physics (5)
Industrial Engineering (1)
Materials (1)
Math (2)
Mechanical Engineering (14)
Meteorology (1)
Naval Science (3)
Nuclear Engineering (83)
Nuclear Materials (1)
Physics (31)

By College (U.S. citizens only) (87)

Brown University (1)
Carnegie Mellon (1)
Columbia (2)
Cornell (2)
Florida State (1)
George Washington (1)
Ga. Inst. of Technology (3)
Kansas State University (1)
MIT (26)
New Jersey Inst. of Tech. (1)
New Mexico State Univ. (1)
Notre Dame (1)
Oakland Univ. (1)
Ohio State Univ. (1)
Oregon State (1)
Penn State (1)
Polytechnic Inst. of NY (2)
Princeton (2)
RPI (5)
Rose Hulman Inst. of Tech. (1)
Swarthmore (1)
Sweet Briar (1)
Texas A&M (2)
UCLA (2)
USMA (2)
Univ. of California (3)
Florida (1)
Lowell (5)
Michigan (4)
Missouri (1)
Texas (1)
Virginia (1)
Wisconsin (4)
Villanova (1)
Westminister (1)
Worcester Poly. (2)

Table 8.1 (continued)

By Country (174)

Algeria (5)
Argentina (2)
Austria (1)
Belgium (2)
Brazil (8)
Canada (8)
Chile (2)
Egypt (2)
Great Britain (1)
Greece (3)
India (1)
Iran (1)
Iraq (1)
Israel (1)
Italy (1)
Japan (1)
Jordan (2)
Korea (7)
Malaysia (2)
Mexico (2)
Nigeria (1)
Pakistan (2)
R. of China (13)
Saudi Arabia (2)
Spain (3)
Turkey (1)
USA (87)
Venezuela (3)
Yugoslavia (1)

Table 8.2

Sources of Financial Support
(as of September 1979)

Research Assistantships (60)
Teaching Assistantships (20)
HST Fellowships (2)
MIT Fellowships (1)
NSF Fellowships (2)
Saudi Arabian Govt. (1)
Argentian Navy (1)
Canadian Govt. Scholarships (5)
Chilean Navy (1)
Algerian Govt. (4)
USAF (1)
ARMY (2)
ROTC (1)
Fulbright Fellowship (1)
Brazilian Govt. (6)
Govt. of Spain (2)
Sherman Knapp Fellowship (1)
Governmnet of The Republic of China (3)
Minorities Award (1)
Korean Govt. (3)
Hertz Fellowship (1)
Venezuelan Govt. (3)
Young Memorial Fellowship (1)
Israel Govt. (1)
Westinghouse (1)
Graduate/Professional Opportunities Award (1)
Award (1)
GE Fellowship (1)
Mexican Govt. (2)
Chilean Govt. (1)
Japanese Govt. (1)
Thompson Fellowship (2)
self-supporting (11)
(did-not list support) (35)

Table 8.3

Activities of Nuclear Engineering Department Graduates

(Place of first employment -- information current as of June 1979)

U. S. Industry and Research (314) (29.3%)

Areodyne Research Inc.
Aerojet Nuclear
Air Research Mfg. Co.
Allis Chalmers (2)
American Electric Power

Amer. Science and Eng.
APDA (2)
Assoc. Planning Res.
Atomics Int. (10)
Avco (6)

Babcock & Wilcox (8)
Battelle Northwest (8)
Bechtel (3)
Bell Telephone Lab.
Bendix
Bettis (4)
Burns & Roe (2)

California Oil
Combustion Eng. (16)
Commonwealth Edison (13)
Computer Processing
Conn. Mutual Life Ins.
Consolidated Edison
Consultant
Consumers Power
Cornell University (research)

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

Ebasco (2)
Edgerton, Germ. & Grier
EG & G (2)

Georgia Power Co.
General Atomic (2)
General Dynamics, Elec. Boat (7)
General Electric (22)
Gulf General Atomic (18)

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

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

Jackson & Moreland
Jet Propulsion Lab

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

Management & Tech. Cons.
Martin-Marietta (2)
Mass. General Hospital (3)
Maxson Electric
McKinsey & Co.
MIT (research) (11)
Mobil Oil
Monsanto
MPR Associates

National Academy of Eng.
New England Nuclear Corp.
New England Power Service Co.
New York Law Firm
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)

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 (3)
Scientific Data Systems
Smithsonian Astrophys. Obs.
Southern Calif. Edison (4)
Spire Corp.
Stanford Research Institute
S.M. Stoller Assoc.
Stone & Webster (10)
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 (23)

Yale (research) (2)
Yankee Atomic (12)

National Laboratories (77) (7.2%)
Argonne (14)
Brookhaven (6)
Knolls Atomic Power (17)
Lawrence Livermore (3)
Lawrence Radiation (5)
Los Alamos (10)
Oak Ridge (13)
Sandia (5)
Savannah River (4)

Further Study (157) (14.7%)
MIT (128)
Other (29)

U.S. Government (185) (17.3%)
Atomic Energy Commission (22)
Air Force (13)
Army (75)
Army Nuc. Def. Lab.
Army Research Lab (2)
Ballistic Research Lab
Classified - Wash., D.C.
Coast Guard
Dept. of Commerce
Energy Res. & Dev. Admin. (4)
Environmental Prot. Agency (2)
NASA
National Bureau of Standards (1)
Naval Reseach Lab
Navy (53)
Nuclear Regulatory Comm. (3)
Peace Corps
Picatinny Arsenal
Dept. of Public Health

Teaching (54) (5%)
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
Lowell Tech (4)
Loyola University
Mass. Maritime Academy
Michigan State University
MIT (8)
Northeastern University
Northwest Nazarene
Pennsylvania State
Princeton
Radford College
Renesselaer Polytech.
Swarthmore
Texas A & M
U.S. Military Academy
Univ. of Brit. Columbia
Univ. of California (6)
Univ. of Florida
Univ. of So. Florida
Univ. of Illinois
Univ. of Kentucky
Univ. of Missouri (2)
Univ. of New Hampshire
Univ. of Texas
Univ. of Washington
Univ. of Wisconsin

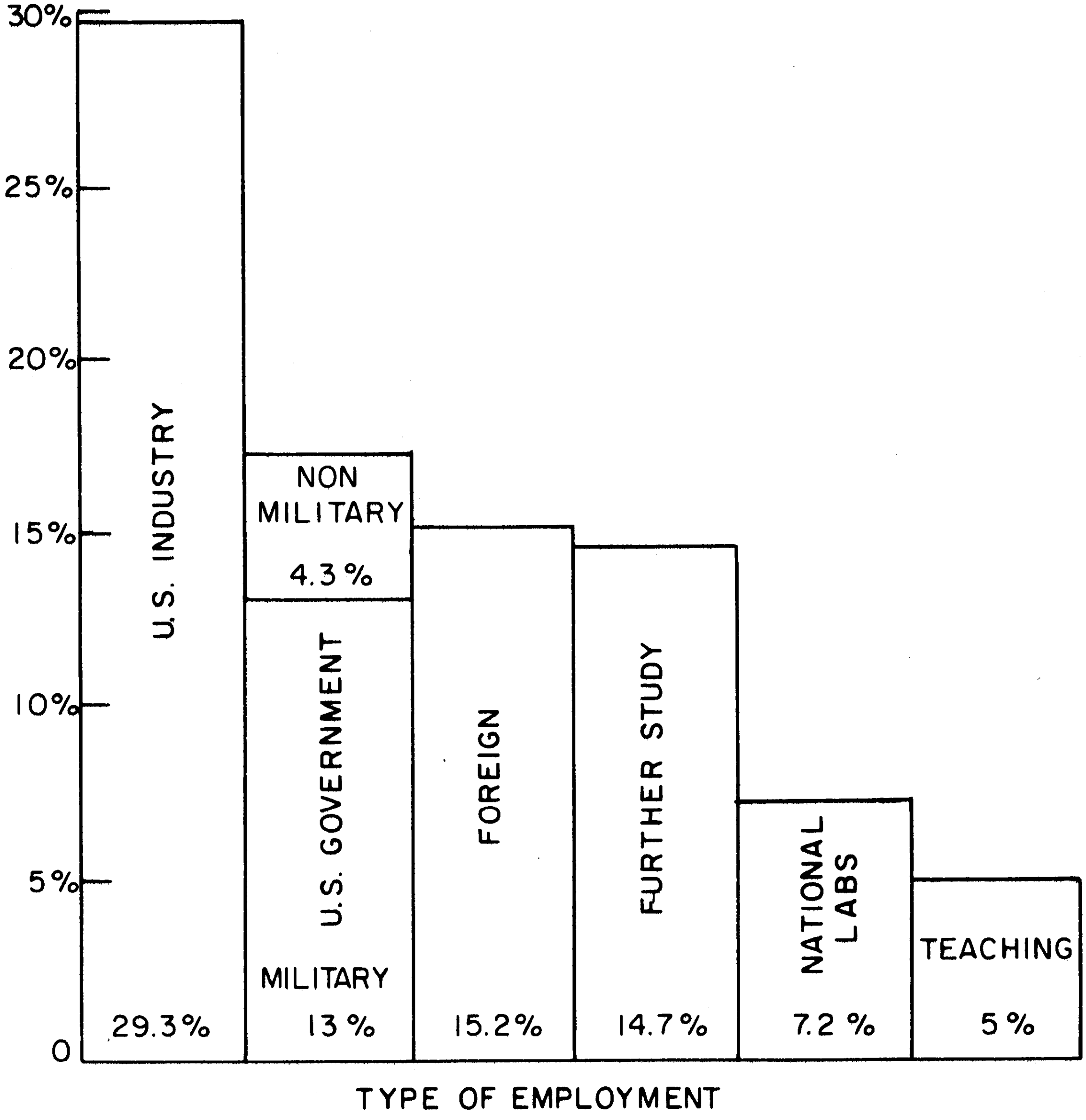
Foreign (163) (15.2%)

Argentina
Belgium (9)
Brazil (15)
Canada (11)
Chile
Columbia, S.A.
England (2)
France (17)
Germany (2)
Greece (6)
India (13)
Indonesia
Iran (26)
Isreal (2)
Italy (5)
Japan (13)
Libya (1)
Malaysia
Mexico
Norway
Pakistan (3)
Philippines
Poland
Spain (12)
Switzerland (7)
Taiwan (4)
Turkey (4)
Venzuela (2)
NOT REPORTED (121) (11,3%)

TOTAL 1071*
*Records from early years are incomplete

FIGURE 8.1

DISTRIBUTION OF EMPLOYMENT OF GRADUATES (REPORTED*)



*EXCLUDES 121 (11.3%) STUDENTS NOT REPORTED

9. List of Theses

The following theses were submitted to the Nuclear Engineering Department in September 1978:

A. Almasoumi, "Characterization of MITR-II Facility for Neutron Activation Analysis", SM Thesis.

L. Alt, "Freshwater in the United States: Constraints on Future Energy Provision", SM Thesis.

M. Badavam, "A Stochastic Computer for Reactor Noise Simulation," SM Thesis.

B. Boghosian, "A Parametric Study of a Torsatron Thermonuclear Power Reactor", SM Thesis.

A. Cook, "Light Water Reactor Kinetics Analysis with Feedback: An Investigation of the Computer Code MEKIN," Ph.D. Thesis.

D.J.L. Del Valle, "A Comparison of Models for Electric Generation Planning As Applied to the System of Spain", NE/SM Thesis.

A. Fadaai, "Determination of 3-D Boron Distribution", SM Thesis

J. Felsted, "Solutions of Two Dimensional Space Dependent Kinetics Equations Using Matric Splitting Methods", SM Thesis.

E. Fujita, "Design and Fuel Management of PWR Cores to Optimize the Once Through Fuel Cycle", ScD Thesis.

G. Garner, "Flow Induced Vibration of Tubular Components of Nuclear Power Plants", SM Thesis.

K. Ghahramani, "An Analysis of Prospective Nuclear Fuel Cycle Economics", NE Thesis.

M. Gottlieb, "Feasibility Study of Cf-252 Based Neutron Irradiators for InHospital Application of Boron Neutron Capture Therapy", SM Thesis.

T. Jenks, "Feasibility of Breed/Burn Fuel Cycles in Pebble Bed HTGR Reactors", SM Thesis.

D. Kaplan, "Start-up and Burn Periods of a High Field Compact Tokamak Reactor", SM w/o specification.

J. Kelly, "Assessment of the Range of Applicability of Various Codes for the Thermal-Hydraulic Design of Light Water Reactors", SM Thesis.

S. Keyvan, "The Application of Albedo Type Boundary Conditions to the Replacement of Reflectors", SM Thesis.

M. Kotlarchyk, "Light Scattering from Cells", SM Thesis.

M. Massoud, "Comparison of Conservative and Best Estimate Heat Transfer Packages with COBRA-IV-I", NE Thesis.

A. Moghaddamjoo, "Measurement of Prompt Neutron Lifetime by Cross-Correlation Technique", SM Thesis.

A. Morshed, "Equivalent Diffusion Theory Parameters for Slab Geometry", SM Thesis.

R. Racana, "Analysis of Structure Operating at High Temperature in a High Radiation Field", SM w/o specification.

T. Remsen, "Development of a Fast Fourier Transform Based Deconvolation Method for Data Analysis in the Regional Blood Flow Measurement by 133-Xenon Inhalation", SM Thesis.

R. Rothrock, "Experimental Investigation of the Thermal Hydraulics of Gas-Jet Expansion in a Two-Dimensional Liquid Pool", SM Thesis.

F. Seifaee, "An Improved Method for Steady State and Transient Thermal-Hydraulic Analysis of Fast Breeder Reactor Fuel Pin Bundles", NE Thesis.

M. Szulc, "Effect of Source X-rays Filtration on Dose and Image Performance of CT Scanners," SM Thesis.

M. Yeung, "A Multicell Slug Flow Heat Transfer Analysis for LMFBR Bundles", ScD Thesis.

The following theses were submitted to the Nuclear Engineering Department in February 1979:

T.F.A. Abbaspour, "The Fuel Cycle Economics of Improved Uranium Utilization in Light Water Reactors", NE/SM Thesis.

R. Bennett, "Numerical Modeling of Buoyant Plumes in a Turbulent Stratified Atmosphere", Ph.D. Thesis.

J. Chao, "Thermal-Hydraulic and Neutronic Considerations for Designing a Lithium-Cooled Tokamak Blanket", Ph.D. Thesis.

M. Corradini, "Heat Transfer and Fluid Flow Aspects of Fuel-Coolant Interactions," Ph.D. Thesis

D. Ebeling-Koning, "Performance Optimization of a Multi-Heat Source Thermal Utility System", SM Thesis.

S. El-Magboub, "Assessment of Light Water Reactor Power Plant Fixed Cost and Ultra-Accelerated Depreciation Financing," ScD Thesis

D. Johnson, "A New Spectometer for Neutron Molecular Spectroscopy and a Study of Formic Acid", ScD Thesis.

M. Kargarnovin, "Analysis of Structural Supports for a Torsatron Fusion Reactor Magnetic Coil", SM Thesis.

J. Lazewatsky, "A Portable Multiwire Proportional Chamber Imaging System for the Diagnosis of Deep Vein Thrombosis in the Legs", Ph.D. Thesis.

V. Manno, "Measurement of Heat and Momentum Eddy Diffusivities in Recirculating Flows, NE Thesis.

D. Sigg, "Analysis of ATWS in a Thorium Fueled Tight-Pitched PWR", SM Thesis.

T. Suzuki, "The Role of Technological Choices in International Nuclear Fuel Assurance Strategies", SM Thesis.

S. Tajik, "Recovery of Neptunium in the Modified Purex Process," SM Thesis.

S. West, "Characterization of the MIT Research Reactor for Fusion Reactor Related Studies", SM Thesis.

W. Zimmermann, "Finding Reactor Refueling Strategies that Minimize Fuel Revenue Requirement in Electric Utilities with Large Nuclear Capacity", ScD Thesis.

The following theses were submitted to the Nuclear Engineering Department in June 1979:

P. Bayless, "A Performance Model for a Helically Coiled Once-Through Steam Generator Tube", SB/SM Thesis.

J. Bernard, "MITR-II Fuel Management, Core Depletion, and Analysis: Codes Developed for the Diffusion Theory Program CITATION", NE/SM Thesis.

D. Bley, "Light Water Reactor Productivity Improvement", Ph.D. Thesis.

G. Dooley, "The Application of Three Dimensional Reactor Physics Calculations Utilizing Synthesis Techniques", SM Thesis.

J. Egan, "Nuclear Power for the LDCs: Changing Implications for U.S. Non-Proliferation Policy", SM Thesis.

J. Egan, "M.I.T. K-E-Y M-O-U-S-E: Animated Technnlogy and the Social Production of Engineers", SM (Technology and Policy) Thesis

J. Guerra, "Competitive Ordering of Energy Sources for Electricity Generation: A Dynamic Analysis", ScD. Thesis.

A. Jodidio, "Determination of Nodal Coupling Coefficients Using Response Matrices", SM Thesis.

H. Kahn, "Design of a Heater to be Installed in the Proposed M.I.T. Reactor Test Loop", NE/SM Thesis.

M. Lussier, "The Separation and Assessment of High and Low LET Radiation by Mixed Field Dosimetry", NE/SM Thesis.

M. McKinstry, "An Experimental Simulation of Fusion Reactor Fuel Pellet Ablation", Ph.D. Thesis.

T. McManamy, "Fusion Removal Using Helium and Flibe", Ph.D. Thesis.

N. Novich, "An Experimental Study of Current Transfer to M.H.D. Electrodes", SM Thesis.

J. Pasztor, "Alpha Autoradiography and Its Uses in Boron Neutron Capture Therapy", SB/SM Thesis.

S. Piet, "Uncertainties in Modeling of Tritium Hazards from Fusion Reactors", SB/SM Thesis.

M. Saidi, "Interfacial Effects in Fast Reactors", Ph.D. Thesis.

K. Smith, "An Analytic Nodal Method for Solving the Two-Group, Multidimensional Static and Transient Neutron Diffusion Equations", NE/SM Thesis.

J. Violette, "An Analysis of the Feasibility of a Thermonuclear Rocket", SM w/o specification.