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ACTIVITIES IN NUCLEAR ENGINEERING AT MIT



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I. INTRODUCTION

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

In the two years since the last Activities Report the enrollment and research of the Department of Nuclear Engineering has maintained a high level. Nationally, the number of orders for nuclear power plants is at a low level, yet most analyses still continue to predict that a substantial increase in nuclear power plants will be needed to meet our national goals. For this reason it seems very likely that as reserve electrical capacity diminishes during the next few years there will be an increase in the rate of ordering for new nuclear and coal plants. Today, there are about 70 operating nuclear power stations; in 1978 they are expected to produce nearly 13% of the nation's electricity. In New England about one third of all electricity is produced by nuclear plants. Thus, although nuclear power growth has slowed in the last two years there seems little doubt that because of the plants now under construction fission reactors will provide an increasing fraction of the electricity of the United States, Western Europe and Japan for the rest of this century.

By 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.

Despite this current lull in orders the demand for well-trained nuclear engineers remains high. Although the student interest remains strong, for the second year we have noted a decrease in applications (see Table 1). Nevertheless, the number of qualified applicants is still more than two times the number of openings of about 50 graduate students per year. Among the 1978 applicants we noted an increased fraction expressing interest in our fusion option.

In June of 1978 the undergraduate program graduated its first full class. The senior class numbered 17 of whom 12 were awarded the B.S. degree. The other 5 opted for the five-year program and will receive both a B.S. and M.S. degree at the end of 5 years. The junior class had 11 students and the sophomore class, 21. Our original goal of about 80 undergraduates has not yet been achieved and it may be difficult to do so in the present controversy surrounding nuclear power. Nevertheless, we do appear to be able to maintain an undergraduate enrollment of about 50.

The graduate enrollment in 1977-78 was 170 students which included 20 in the special Iranian program. Next year we expect to return to a total graduate enrollment of about 150 which is the level that has been maintained for several years (see Table 2), not including the students in the special Iranian program. This size is limited by the available faculty.

During the 1977-1978 school year the Department awarded a total of 95 advanced degrees including 20 Doctorates, 18 Nuclear Engineers, and 57 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 500 and the number of advanced Nuclear Engineering de-

grees being awarded is about 550. Currently the short-falls are made up by hiring engineers from other disciplines who have some nuclear courses. Because the demands are not expected to decrease for the next decade it seems likely that there will continue to be a shortage of trained nuclear engineers for some time.

Table 1

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

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

Table 2

Enrollment in M.I.T. Nuclear Engineering Department

	1971/72	117
	1972/73	113
	1973/74	127
	1974/75	139
	1975/76	200*
	1976/77	230
	1977/78	218

*includes special Iranian program and new Undergraduate program.

In 1977-78 the research support within the Department tapered off slightly from \$1.7 million last year to about \$1.5 million this year. This was due in part to the fact that some of the new research contracts were obtained through interdepartmental laboratories such as the Energy Laboratory and the Research Laboratory for Electronics. This latter type of research increased from about \$750,000 to about \$1.0 million, so overall the level of support remains about constant. As in previous years the majority of this support came from the Department of Energy although in 1977-78 roughly \$250,000 was obtained from non-governmental sources, mainly from the Electric Power Research Institute and private utilities. The Department continues to be fortunate to receive fellowship support from the General Electric Foundation, Northeast Utilities, and the proceeds from the Theos J. Thompson Memorial Fund.

In Section 2 of this report there is a discussion of developments within the Department since September 1976. Section 3 is a detailed discussion of our research and educational activities. Section 4 presents a discussion of our curriculum, including the S.B. program. Section 5 discusses the facilities of the Department as well as those available to the Department. In Section 6 there is a summary of Departmental personnel. Sections 7 and 8 provide statistical information about the Department and its students. The final section, 9, is a listing of theses completed since our last report.

2. SUMMARY OF DEVELOPMENTS SINCE SEPTEMBER 1976

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

The most significant change in the academic program during the last two years has been the development of the Nuclear Engineering Internship program. This new option offers undergraduates the opportunity to have actual on-the-job experience as part of their overall education. In the initial phase of this program 3 students have been placed with EG&G Idaho Laboratory. It is expected that we will be able to expand this program significantly next year. The program has two options, one leading to the B.S. in 4 years, the other to the M.S. in 5 years. An on-the-job problem will be used in lieu of a thesis. We feel this program offers a different dimension to the educational opportunity and will be of interest to a number of students. The development of this new program has been ably lead by Professor Meyer in conjunction with the Office of the Dean of Engineering.

The other parts of the academic program underwent only modest changes. The principal new features were the senior level undergraduate courses that were taught for the first time. The new undergraduate fusion laboratory course developed by Professor Scaturro was quite successful. Professor Rose offered a special seminar on the "Energy for Developing Countries" which attracted more than 20 highly interested students. Professor Hansen participated in the development of a new course entitled "Dynamics of Physical and Social Systems" which has been accepted as a school wide elective. In the area of fusion the courses remain the same in title; significant changes in content have been made to keep them abreast of this rapidly developing field. The major changes in the reactor engineering programs carried out a year ago seem to have achieved their objective of giving the students a better understanding of the systems aspects of large nuclear power stations.

The continued high level of research support has enabled the Department to provide research support for about 58 students; in addition another 38 are supported by a variety of teaching assistantships, fellowships, and traineeships. Only about 18% of the students do not receive financial aid.

During the summer of 1977, the Department offered four Special Summer Programs. These Programs are 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 310 registrants in Nuclear Engineering Programs in 1977 accounted for 18% of the registrants in all MIT Special Summer Programs. This enrollment was the second highest of all Institute summer offerings. The Programs offered in 1977 were, Nuclear Power Reactor Safety, 22.96s/95s/94s, directed by Professors Rasmussen and Todreas; Computerized Axial Tomography, 22.85s, directed by Professor Brownell; Principles of Nuclear Medicine, 22.83, directed by Professor Brownell, Doctors Murray, Hnatowich, and Zimmerman; and Fundamentals of Controlled Fusion, 22.80s, directed by Professors Woo, Lidsky, Politzer, and Rose. The programs offered in 1978 were radiology (TCT) and Nuclear Medicine (ECT), 22.85s, directed by Professor Brownell, and Nuclear Power Reactor Safety, 22.95s/96s, directed by Professors Rasmussen and Todreas. The Nuclear Power Reactor Safety Program continues to have one of the largest enrollments of any course in the Institute's Special Summer Programs.

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.

In June Professor Lidsky was named Acting Director of the MIT Plasma Fusion Center following the resignation of Dr. Albert Hill. Professor Lidsky continues to advise the U.S. Department of Energy on its fusion program. Professor Rose is currently very active as Chairman of the Advisory Committee to the World Council of Churches Division of Church and Society. In this capacity he is organizing an International Conference on Faith, Science, and the Future to be held at MIT next year. He continues as a member of the Steering Committee of the National Academy of Sciences Committee on Nuclear and Alternative Energy Systems. In addition he serves on the Advisory Committee of the Comptroller General, U.S. General Accounting Office and is a member of the Oak Ridge Advisory Committee for the Energy Division. Professor Golay is currently Vice Chairman of the of the American Nuclear Society in the Environmental Sciences Division and is Chairman of the Northeast Section of the American Nuclear Society. He is also a member of the K19S Subcommittee of the American Society of Mechanical Engineers Heat Transfer Division. Professor Chen serves on the Argonne National Laboratory Review Committee for the Solid State Division and the Argonne Intense Neutron Source Project. Professor Kazimi serves as a member of the Board of Directors of the Northeast Section of the American Nuclear Society and a member of the A.I.Ch.E. Nucleonics Heat Transfer Committee. Professor Gyftopoulos continues as Chairman of the National Energy

Council of Greece and is also Chairman of the Institute's Committee on Junior Faculty Career Development Fund. Professor Meyer serves as a member of the Executive Committee of the Mathematics and Computation Division of the American Nuclear Society. Professor Hansen continues to serve as Chairman of The Reactor Physics Division of the American Nuclear Society as well as an advisor to the U.S. Department of Energy and the Office of Science and Technology Policy. Professor Henry is a member of the Journals Advisory Board of the American Nuclear Society. Professor Reed serves as Chairman of the Mathematics and Computation Division of the American Nuclear Society. Professor Rasmussen completed a 4-year term on the Defense Science Board. He was elected to the Board of Directors of the American Nuclear Society. He serves on the Argonne National Laboratory Review Committees of the Components and Technology Division and the Reactor Safety Division. He also continues as Chairman of the Scientific Review Committee of the Idaho National Engineering Laboratory. He remains Chairman of the Institute's MIT Reactor Safeguards Committee on which Professors Lanning, Harling, and Driscoll also serve.

As noted above the research volume of the Department remained at the relatively high level of last year at about \$2.5 million. Although this income is adequate to support a strong research program we have noted some disturbing trends away from support for hard engineering, especially experimental work, and toward paper studied. Many of these paper studies are indeed valuable to sponsors in helping set government policy and so they represent important and valuable work. However, if the trend continues it will be harder and harder for students to obtain top level experimental research experience which we judge to be vital in a well-rounded engineering program.

The research volume in the area of fusion technology is increasing. This includes a recent study grant to Professors Lidsky, Politzer, and Dr. Montgomery for a design study of a new stellarator concept called the Torsatron. This is an exciting concept which we hope may lead to the construction of such a machine here at MIT. Professor Kazimi continues to work with Professor Lidsky on fusion machine safety and risk analysis. Fortunately this increased research activity in the fusion area coincides with the increased student interest in fusion noted above. Professor Dupree continues his work in plasma theory concentrating on non-linear phenomena. Professor Sigmar although on leave of absence at Oak Ridge National Laboratory, has maintained close ties with our program and will become an Adjunct Professor in the fall and continue to teach and do research part time. Professor Scaturro has been working with the Alcator project in the area of plasma diagnostics.

About one third of the Department's research activity involves the various aspects of fusion. In addition to the projects noted above the fusion technology continues to get considerable support from other faculty especially in the areas of materials and heat transfer. Thus although fusion devices are considerably different from fission devices many of the detailed engineering problems are similar and the expertise gained from fission reactor studies is very valuable in solving fusion problems.

In the area of reactor physics Professors Henry, Hansen, and Reed continue their work for the Electric Power Research Institute on the development of major codes for the analysis of reactor transients. In the area of fission reactor engineering the research effort deals with a broad range of problems in both water and sodium-cooled reactors. Major projects in heat transfer, materials behavior, reliability, and structures are being studied by Professor Todreas, Golay, Driscoll, Meyer, Wolf, Rasmussen, and Kazimi. In addition, students from our department have worked closely with Professors Russell and Pelloux of Materials Science and Engineering and Professors Griffith and Rohsenow of Mechanical Engineering. This close cooperation we have maintained with other departments in the School of Engineering has greatly increased the opportunities for our students and our ability to provide valuable research results to the nuclear industry.

This year Professors Gyftopoulos, Rasmussen, and Rose undertook a major research problem for the Department of Energy on aspects of the nuclear proliferation problem. Dr. Marvin Miller of the Energy Laboratory was also a major participant in this project. Professors Lanning, Golay, Rose, and Rasmussen worked with Doctors Hinkle and Wood of the Energy Laboratory on a second contract on light water reactor technology for the U.S. Department of Energy. In addition the Department faculty participated in a number of small Energy Laboratory research contracts with various electric utility companies of the Northeast. In total the Department faculty is heavily involved in Energy Laboratory research contracts totaling about \$750,000. We believe these cooperative projects are very valuable and to the mutual benefit of both the Department and the Energy Laboratory.

Professors Chen and Yip have had another very productive year in their research using neutron scattering as a tool for understanding various aspects of molecular and solid state physics. Professor Brownell continues his research in the applications of radiation to the diagnosis and treatment of disease. Professor Harling continues as Director of the Nuclear Reactor Laboratory in addition to his research work in both fusion and fission materials problems.

Overall the Department has been able to obtain a high level of research support on a variety of challenging research problems. They have provided students with valuable educational experiences as well as financial support. This research has been at a level of about \$137,000 per faculty member and paid approximately one third of the faculty salaries. The slowdown in nuclear power plant orders has not as yet had a significant impact on our ability to raise research support although the nature of the projects is shifting somewhat away from experimental research.

This year Professor Manson Benedict reached the mandatory retirement age for Institute Professors. For the 5 years since his normal retirement date Professor Benedict has continued half time, teaching Economics of Nuclear Power, and Nuclear Chemical Engineering. Professor Benedict started the MIT Nuclear Engineering Program as part of the Chemical Engineering Department in the fall of 1952 and then established an independent Department of Nuclear Engineering in 1958. Certainly no single person has contributed more to the growth and success of the Department. His outstanding leadership has earned both him and the Department world-wide recognition. He will be surely missed. Dr. William Reed joined the Department as a Visiting Professor for the 1977-78 academic year. During this time Dr. Reed carried out research in the general area of reactor physics and taught Numerical Methods of Reactor Physics. Professor Irving Kaplan, who has been with the Department since its inception, retired on July 1, 1978. Over the years Professor Kaplan's outstanding contributions have enriched the scholastic and personal lives of his students and colleagues. The breadth of Professor Kaplan's interests have resulted in his interaction with the Humanities Department where he has taught courses in Greek and the History of Science. We are indeed fortunate that Professor Kaplan will continue on part time as a lecturer in the Department. Professor Arden L. Bement, who was on leave of absence from the Institute as Director of Material Science Defense Advanced Research Projects Agency of the Department of Defense, resigned from the Department to continue in this position at DARPA. Professor Bement had been with the Department since 1971 and during the past 8 years has contributed significantly to the Department's growth and development in the nuclear materials area. Professor Dieter Sigmar has been on leave for the past two years at Oak Ridge National Laboratory, where he has had major responsibility for the ORNL TOKAMAK theory program. He plans to remain at ORNL, but will continue to contribute to the Department as an Adjunct Professor. Professor Owen Deutsch has left the Department to work at the Los Alamos Scientific Laboratory. Professor Michael Golay was appointed an Associate Professor with Tenure in July 1977. Professor James Woo has left the Depart-

ment to accept a faculty position at Rensselaer Polytechnic Institute. Professor Neil Todreas has spent the last year on sabbatical in France working on heat transfer problems with Electricité de France.

Several of the Department faculty were recognized with honors. Professor Kent F. Hansen received the American Nuclear Society Arthur Holly Compton Award in June 1978. Professor Sidney Yip received the Graduate Student Council Award for Outstanding Graduate Teaching. David Aldrich, a graduate student, won the 1978 American Nuclear Society Reactor Safety Division Best Student Paper Award. Professor Norman C. Rasmussen received the Outstanding Teacher Award of the MIT Student Chapter of the American Nuclear Society.

3. RESEARCH AND EDUCATIONAL ACTIVITIES

3.1 Reactor Physics

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

3.1.1 Subjects of Instruction

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

22.021, Nuclear Reactor Physics, which 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 reactor bases of reactor design and their relation to reactor engineering problems. Lectures in common with 22.211, homework, exams, and recitation are separate.

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

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

22.213, Nuclear Reactor Physics III, which considers current methods for predicting neutron behavior in complex geometrical and material configurations, the transport

equation and methods for solving it, systematic derivation of group diffusion theory, and homogenization, synthesis, finite element and response matrix techniques applied to reactor analysis.

Most 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.

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

22.09, Introductory Nuclear Measurements Laboratory, which deals with the basic principles of interaction of nuclear radiation with matter. Statistical methods of data analysis; introduction to electronics in nuclear instrumentation; counting experiments using Geiger-Müller 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, basic principles of interaction 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.

22.35, Nuclear Fuel Management, integrates the disciplines of reactor physics, reactor engineering, engineering economics and numerical methods to analyze the burnup dependent composition of nuclear fuels and its interrelation with key neutronic and safety related core characteristics. Design and operation of reactor cores under pertinent constraints is emphasized using both generalized principles and specific examples.

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

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

3.1.2. Reactor Theory

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. However, before space-dependent transients can be analyzed, more efficient ways for solving static problems must be devised. These are discussed in the present section.

1) Synthesis Methods

If one wishes to describe the detailed flux distribution throughout a reactor accounting for small heterogeneities such as those due to control rods, lumps of burnable poison, multizone enrichment, etc., the flux synthesis scheme becomes a very attractive procedure. The essential idea of this scheme is to combine two-dimensional flux shapes computed for different radial slices of the core into a three-dimensional composite. A synthesis program aimed specifically at analyzing the MIT Reactor throughout a depletion cycle was created. Under certain conditions the method was found to provide accurate flux shape and criticality predictions. However, in anticipation of wanting to account for the effect of thermal hydraulic conditions on flux shape and critical control rod position, a new, non-linear scheme for finding the critical control rod position was introduced. For many cases this led to numerical instabilities and we have had to return to the more conventional method of finding the critical control rod position.

2) Representation of a Reflector By a Boundary Condition

If the criticality and flux shape for a light water reflected core is found by solving the group diffusion equations by the finite difference method, some 30% to 40% of the computing time is spent finding the flux shape in the reflector. We have developed a way of circumventing this difficulty by accounting for reflector effects by a boundary condition imposed at the core-reflector (or core-shroud) interface. The boundary conditions can be found either empirically by solving small auxiliary problems, or analytically through application of an approximate formula. During the past year we have extended this scheme to account for the presence of control rods in the axial reflector and tested its dependence on core characteristics more thoroughly. The method continues to look very attractive. The boundary conditions depend almost entirely on the reflector properties and geometry and very little on whether the adjacent core region is homogeneous or heterogeneous, clean or depleted, control rod bearing or free. Position-dependent, empirical boundary conditions appear most accurate. However, for large cores, the use of spatially averaged values constant for a given fuel assembly appear to be adequate. A more careful study of the use of such boundary conditions for reflector materials other than light water and for fast transient situations remains to be done.

3) Response Matrix Techniques

The response matrix method is another way to account systematically for the heterogeneous nature of the fuel assemblies making up reactors. For each different type of assembly one partitions the assembly axially into large "nodes" and precomputes "response matrix elements" specifying the neutron current emerging from a given face of the node due to a current of unit magnitude entering some other face. The method is very efficient if the spatial shapes of the entering and exiting currents across the nodal faces are simple (for example, spatially flat). However, if matrix elements for several components of these shapes must be computed and used in the overall core calculation, computation costs rise drastically. The situation is particularly difficult for faces perpendicular to the axial direction of the core since often control rods penetrate such faces, and neutron currents across them have a very complicated shape. We have developed a method for overcoming this difficulty by representing currents across nodal surfaces as having a spatial shape which is the product of a linear function and a "fine structure shape" that accounts for spatial heterogeneities such as those caused by control rods penetrating the surface. The scheme has been tested successfully in two

dimensions. However, we do not plan to develop it further at this point since the nodal scheme described in the next section appears to be a more promising approach for obtaining full core flux shapes.

4) Nodal Schemes

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

During the past year we have extended the "analytical nodal method" mentioned in Section 3.1.6 so that, for a standard set of numerical test cases (benchmarks) it appears to be the most efficient of all the nodal methods so far described in the literature. The code (called QUANDRY) embodying this method shows dramatically how much more efficient a nodal method is than a finite difference method for solving the class problems for which it is designed. Thus, for the IAEA 3-dimensional benchmark problem (a rather artificially difficult PWR with a light water reflector and no shroud), QUANDRY provides a solution with accuracy 1×10^{-6} in k_{eff} and 0.7% maximum error in assembly power in 17 seconds on an IBM 370/168; the finite difference code VENTURE takes 6 hours to run the same problem on the IBM 370/195 (a machine about 5 times faster than the 168). Moreover, the (uniform) mesh size for the finite difference solution is still a bit large (1-2/3 cm) in that the maximum assembly power error is still 2.1%.

QUANDRY is presently being extended to run transient problems.

5) Homogenized Group Parameters

The remarkable efficiency of the nodal method makes it increasingly important to obtain sets of spatially constant,

homogenized group parameters that will predict accurately the power level and neutron leakage for each node. During the past year, for two dimensional, two-group, static situations we have completed testing a new method for determining equivalent homogenized parameters. The scheme is based on computing response matrices for the heterogeneous node and then finding homogenized group-diffusion-theory parameters such that response matrices found using these homogenized parameters match the corresponding matrices for the heterogeneous node. For a two-dimensional, two-group test case involving assemblies containing cross shaped rods or water holes the new procedure results in a reduction of the error in predicted assembly power from 5% to 1%.

For two-dimensional geometry, homogenized parameters that will reproduce exactly the nodal power levels and reactor eigenvalue depend on the characteristics of surrounding nodes as well as on those of the nodes themselves. (For the homogenization method we have developed yield parameters that have this property.) For slab geometry the situation is different. Under certain conditions the equivalent homogenized parameters for a given heterogeneous node composed of several different slab materials are independent of the medium in which the node is embedded. Since it may suggest approximations which will be useful in two and three dimensions we have examined further the nature of exact equivalent diffusion theory parameters for heterogeneous nodes composed of slabs. We have been able to prove that, if diffusion theory is valid for a heterogeneous node composed of a slab array symmetric about the center plane of the node, then, for any number of energy groups, exact homogenized parameters exist. The numerical values of these homogenized parameters can differ by as much as 40% from the corresponding quantities found by the standard flux-weighting procedure. We are currently examining further the significance of this difference.

Investigators: Professor A.F. Henry, Ms. S. Keyvan, Messrs. R. Chin, G. Greenman, T. Sbarounis, K. Smith, R. Smith.

Support: USERDA (approximately \$25,000/year); EPRI (approximately \$80,000/year).

Related Academic Subjects:

- 22.211 Nuclear Reactor Physics I
- 22.212 Nuclear Reactor Physics II
- 22.213 Nuclear Reactor Physics III
- 22.41 Numerical Methods of Radiation Transport

- 22.42 Numerical Methods of Reactor Analysis
 22.43 Numerical Methods in Reactor Engineering Analysis

Recent References

- R.J. Chin, "DEPLESYN: A Three Dimensional, Discontinuous Synthesis, Diffusion-Depletion Code", Ph.D. thesis, MIT, Nuclear Engineering Department (September 1977).
- B.A. Worley and A.F. Henry, "Spatial Homogenization of Diffusion Theory Parameters", ERDA Report COO-2262-10, MIT report MITNE-210 (September 1977).
- B.A. Worley and A.F. Henry, "The Computation of Homogenized Group Parameters", Transactions of the American Nuclear Society, 27, 392 (1977).
- T. Sbarounis, "Treatment of the Spatial Shape of the Currents in the Response Matrix Method", Ph.D. thesis, MIT, Nuclear Engineering Department (February 1978).
- R. Smith, "Extending Core-Reflector Albedo-Type Boundary Conditions to include Geometrically Simple Multiregion Reflectors", S.M. thesis, MIT, Nuclear Engineering Department, (February 1978).
- S. Keyvan, "The Application of Albedo Type Boundary Conditions to the Replacement of Reflectors", N.E. thesis, MIT, Nuclear Engineering Department (June 1978).
- A. Morshed, "Equivalent Diffusion Theory Parameters for Slab Geometry", S.M. thesis (in progress), MIT, Nuclear Engineering Department.

3.1.3 Fast Reactor Physics

The research program using the Blanket Test Facility at the MIT Research Reactor is entering its ninth year, and although nearing the end of its productive lifespan, has continued to provide a useful focal point for both experimental and theoretical research. Recent work has involved an inter-comparison of thorium and uranium breeding-related characteristics, self-shielding corrections in bulk media and near interfaces, and further analysis of fast neutron penetration in steel reflectors. We also participate in DoE-sponsored benchmark calculational efforts together with other organizations in the FBR field.

A new research project has been initiated, sponsored by General Atomic Company, to examine the breeding, safety and engineering-related characteristics of GCFR cores having internal blankets.

Investigators: Professors M.J. Driscoll, D.D. Lanning, Engineering Assistant A.T. Supple, Computer Operations Assistant R. Morton, Messrs. J.I. Shin, A.A. Salehi, M. Saidi, D. Lancaster, B. Atefi, M. Macher, F. Field, D. Medeiros, S. Kim, J. Pasztor, L. Paglia, G. Nakayama, T. Reckart, W. Wolfe.

Support: U.S. Department of Energy (approximately \$100,000 in FY 1978; \$48,000 in FY 1979) GA (approximately \$26,000 in FY 1978; \$40,000 in FY 1979, approval pending).

Related Academic Subjects:

22.211 Nuclear Reactor Physics I
 22.212 Nuclear Reactor Physics II
 22.213 Nuclear Reactor Physics III
 22.35 Undergraduate Research Opportunities Program
 22.39 Nuclear Reactor Operations and Safety
 22.29 Undergraduate Research Opportunities Program
 22.UR Nuclear Measurements Laboratory

Recent References:

M.J. Driscoll, et al. "Safety and Breeding-Related Aspects of Fast Reactor Cores Having Internal Blankets", Proceedings Int. Mtg. on Fast Reactor Safety and Related Physics, Chicago, Illinois, October 1976.

LMFBR Blanket Physics Project Progress Report, Number 7. COO-2250-28, MIT Report MITNE-211, September 30, 1976.

A.A. Salehi, M.J. Driscoll and O.L. Deutsch, "Resonance Region Neutronics of Unit Cells in Fast and Thermal Reactors," COO-2250-26, MIT Report MITNE-200, May 1977.

M.S. Macher, "Fast Reactor Blanket Benchmark Calculations," S.M. Thesis, MIT, Department of Nuclear Engineering, Sept. 1977.

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

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

M.J. Driscoll, "The Use of Thorium in LMFBR Blankets," (invited paper) Trans. Am. Nucl. Soc., 27, 2, 1977.

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

3.1.4 Thermal Reactor Physics and Fuel Management

We are currently in the second year of a three-year project sponsored by DoE through the MIT Energy Laboratory to determine whether significant reductions in LWR uranium ore consumption are possible by means of technological improvements such as thorium utilization. This effort has been made an integral part of the DoE effort in support of the NASAP/INFCE programs.

Analysis of the once-through fuel cycle for PWR's has shown the potential for a 25% reduction in ore usage through adoption of a number of improvements, chiefly extending the burnup and increasing the number of fuel batches used in the core. Recent work has focused on tight pitch lattices using thorium in the recycle mode. Here, in addition to the physics problems, extensive thermal-hydraulic analysis is required to determine whether such cores can meet safety limits during steady-state, transient and accident conditions.

Work on fuel cycle economics has shown that ore conservation and energy cost minimization are generally compatible objectives in the LWR fuel cycle; a simple method to account for the scarcity-related escalation of uranium ore in reactor fuel cycle studies has also been developed.

Investigators: Professor M.J. Driscoll, D.D. Lanning, L. Wolf, D.J. Rose; Computer Operations Assistant R. Morton; Messrs. K. Garel, F. Abtahi, E. Fujita, F. Correa, H. Aminfar, D. Griggs, K. Ghahramani, D. Sigg, A. Abbaspour, D. Hsia, H. Hsieh, F. Bamdad-Haghighi, M. Plys.

Support: Department of Energy (via MIT Energy Laboratory)
\$92,000 in FY 1978)

Related Academic Subjects:

- 22.211 Nuclear Reactor Physics I
- 22.212 Nuclear Reactor Physics II
- 22.213 Nuclear Reactor Physics III
- 22.34 Economics of Nuclear Power
- 22.35 Nuclear Fuel Management
- 22.313 Advanced Engineers of Nuclear Reactors

Recent References:

K.C. Garel and M.J. Driscoll, Fuel Cycle Optimization of Thorium and Uranium Fueled PWR Systems, MIT-EL-77-018, MITNE-204, Oct. 1977.

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

K. Ghahramani and M.J. Driscoll, "Ore Price Escalation in Fuel Cycle Economic Analyses," Trans. Am. Nucl. Soc., 28, p. 383, June 1978.

K. Ghahramani, "An Analysis of Prospective Nuclear Fuel Cycle Economics", S.M. Thesis, MIT, Department of Nuclear Engineering August 1978.

F. Abtahi, "Out-of-Reactor Aspects of Thorium Utilization in Light Water Reactors, Ph.D. thesis, MIT, Department of Nuclear Engineering, July 1977.

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, Tennessee, April 1978.

B. Atefi, "Specific Inventory and Ore Usage Correlations for Pressurized Water Reactors" N.E. Thesis, MIT, Department of Nuclear Engineering, May 1977.

W.A. Boyd, "Thermal-Hydraulic Analysis of Tight Lattice Light Water Reactors" S.M. Thesis, MIT, Department of Nuclear Engineering, May 1977.

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 core conditions. The operator uses this information to determine his control and power changes in order to stay within specified limits. Without the computer he 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 limit of the safe

operating range. 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 response 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 control technology for nuclear power reactors and evaluate economic and operational benefits in terms of efficiency, availability, maintainability, improved operation and safety.
- 2) Investigate and demonstrate NRC licensing on an initial simplified basis by using the MIT Reactor.
- 3) Develop digital control designs for nuclear power reactors 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 being studied by other industries in the nation 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.

Investigators: Professor D.D. Lanning, P. Nicholson, Messers. J. Mesner, J. Bernard.

Support: Internal Draper Funds and self-supported student.

3.1.6 Reactor Kinetics

During the past ten years with support primarily from ERDA the Department has carried out a method development program in the general area of reactor kinetics applicable to fast reactor systems. The scope of the effort has been very broad including both the study of mathematical procedures for solving the neutron diffusion equations more efficiently (new finite element, response matrix and synthesis techniques were all developed) and the exploration of sophisticated numerical techniques.

During the past year both the sources of support and the emphasis of the program have changed. Major support now comes from ERDA, and the immediate emphasis is on the analysis of PWR and BWR transients (although, as is always the case, the method developed will generally be extendable to other thermal and to fast reactor systems).

During the past year the nodal method for solving the few group diffusion equations has shown great promise for light water reactors. Two such programs for solving the two-group, space-dependent diffusion equations in XY geometry were created and tested with standard static and transient benchmark problems. Both these codes require that the spatial shape of the neutron leakage over the faces of a node be approximated in some fashion. One code, making use of what we call "the analytical method", assumes that the leakage is spatially flat. It has acceptable running times but (for mesh cubes 20 cm on a side) leads to assembly power errors that we consider unacceptable (as high as 10% for one test problem). The other code, using what we call "the polynomial method", approximates the leakage shapes over the nodal faces by quadratic functions. This scheme is acceptably accurate but is longer running than the analytical method--particularly for transient cases. On the basis of these results we decided to concentrate on the analytical method trying to incorporate into it the quadratic leakage approximation. As discussed in Section 3.1.2 this attempt (the three-dimensional code, QUANDRY) has been very successful for the static cases studied so far.

QUANDRY is currently being extended to do time-dependent problems using a semi-implicit time differencing technique. However, during the past year, we completed a preliminary study of a quasi-static synthesis approach to solution of space-dependent transient problems. This scheme permits the three-dimensional flux shapes to be computed only occasionally rather than at every time step. The savings in computer time is substantial.

One kinetics study completed during the past year dealt with a very specific and unusual reactor. The proposed Safety Test Facility involves a thermal or intermediate reactor surrounding a central fast reactor test section. Because of the dramatic change in the thermal neutron spectrum throughout such a reactor it appeared necessary initially to go to the expense of using four thermal groups in the analysis. We were able to devise a method for reducing this number to one.

Investigators: Professors K.F. Hansen, A.F. Henry; Messrs. S. Grill, R.A. Shober, R.N. Sims, W. Strohmayer.

Support: USERDA (approximately \$25,000/year), ANL (\$10,000/year), EPRI (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
- 22.22 Nuclear Reactor Kinetics
- 22.41 Numerical Methods of Radiation Transport
- 22.42 Numerical Methods of Reactor Analysis
- 22.43 Numerical Methods in Reactor Engineering Analysis

Recent References

R.A. Shober and A.F. Henry, "Nonlinear Methods for Solving the Diffusion Equation", MIT report, MITNE-196 (November 1976).

R.N. Sims and A.F. Henry, "A Coarse-Mesh Nodal Diffusion Method Based on Response Matrix Considerations", MIT report, MITNE-197 (March 1977).

R.A. Shober, R.N. Sims, and A.F. Henry, "Two Nodal Methods for Solving Time-Dependent Group Diffusion Equations", Nuc. Sci. & Eng., 64, 582 (1977).

S. Grill, "Methods of Switching from Point to Space-Dependent Kinetics in the Solution of the Time-Dependent Diffusion Equation", Ph.D. thesis, MIT, Nuclear Engineering Department (June 1977).

W. Strohmayer, "Approximate Representation of Thermal Neutron Spectra in Reactor Transients", S.M. thesis, MIT, Nuclear Engineering Department (June 1978).

S.A. Silling and K.F. Hansen, "Integration of the Kinetics Equations with Improved Steady-State Behavior", Trans. Amer. Nuc. Soc., 27 (November 1977).

3.2 Reactor Engineering

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

3.2.1. Subjects of Instruction

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

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

22.031, 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. Lectures 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 survey of engineering and physics aspects of current nuclear power reactors. Design details are discussed including requirements for safety of light and heavy water reactors high temperature gas-cooled reactors, fast reactors both liquid-metal and gas-cooled and the thermal breeder reactors. Reactor characteristics are compared both in class and by individual student projects. Development problems are discussed and potentials for future improvements are assessed.

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

objectives. The necessity for making trade-off decisions among conflicting requirements is stressed. During the past year, for example, the design project focused upon the feasibility of a nuclear-powered total energy system for the greater Boston area. The analyses included power plant siting, economics, power plant safety and environmental problems, LOCA-related risk analysis, and air pollution alleviation, among other topics.

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

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

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

22.38, 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 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.

3.2.2. Reactor Thermal Analysis

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

- 1) coolant and energy mixing in rod bundles,
- 2) fluid dynamic modeling of forced-buoyant flows in reactor vessel plenums,
- 3) theoretical determination of local temperature fields in LMFBR fuel rod bundles,
- 4) thermal design of fusion reactor blankets. (see Sec. 3.10.3)

1) Coolant and Energy Mixing in Rod Bundles

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

a) 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.

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. Based on this model, codes have been written for forced convection single assembly (ENERGY) and multi-assembly (SUPERENERGY) analysis in steady state and forced convection single and multiassembly analysis (TRANSENERGY-S) in transients. Additionally, this model was used to prepare an analysis method for the thermal-hydraulic behavior of the Clinch River Breeder Reactor secondary control assembly. These codes require input of the assembly flow distribution and one empirical sweeping flow constant for each of the two regions.

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, physical models were proposed for: (a) the sub-channel flows within the assembly and (b) the sweeping flow constants for turbulent flow.

The subchannel flow distribution model takes into account the effects of both the form drag induced by the wires and the skin friction pressure drop induced by the secondary flow in the determination of the interior and edge average subchannel flow rates. As a result, good agreement ($\pm 4\%$) between the predicted and the experimental subchannel flow rates is obtained for the bundles having the geometric characteristics ranging from $P/D = 1.067$ and $H/D = 4.0$ to $P/D = 1.25$ and $H/D = 52$ over the Reynolds number range $5,000 < Re < 73,000$.

The corner subchannel flow rates are not predicted by the proposed model because experimental data is lacking on the transverse and axial flow in the corner subchannels. However, when this information is available, the proposed model can be expanded to predict the corner subchannel flow rate.

For the sweeping flow models, two correlations are suggested for the two different types of gaps between subchannels, i.e. the gap between the interior subchannels and the gap between the wall subchannels. These two sweeping flow correlations are evolved by calibrating the constants in the proposed model against the available experimental data. Agreement between the correlations and all the experimental data of $\pm 35\%$ is obtained over the assembly design range of $1.315 > P/D > 1.067$ and $52 > H/D > 4$ in the turbulent flow regime.

b) Analysis and experimental water testing in small test sections representing a simple array of subchannels. In these test sections, wire-wrap or other means of pin mechanical support is not simulated. The investigations are aimed at providing a fundamental understanding of velocity and temperature fields in subchannels typical of rod arrays. These experimental investigations also make use of tracer techniques and the laser doppler system. Three studies have been carried out and results obtained on bulk mixing coefficients, wall shear stress, and the turbulent velocity field of a typical interior subchannel.

Bulk mixing coefficients were measured for single phase water flow in a simulated rod bundle with a pitch to diameter ratio of 1.10. A tracer technique employing Rhodamine B as the tracer and measuring fluorescence was used. Isokinetic sampling was achieved by using a pressure balance method. The results were corrected for both entrance effects and diversion crossflows. Our results showed a change in Reynolds number behavior as the laminar sublayer began to "choke" the turbulent mixing. This, and a review of other mixing experiments, suggested that secondary flows do not compensate for laminization and that turbulent mixing decreases as the pitch to diameter ratio decreases for values $P/D < 1.05$ in a manner similar to that predicted by Ramm *et al.* Concentration profiles were measured through the clearance gap and the values of the gradient were used to calculate the gap averaged circumferential eddy diffusivity for mass.

The wall shear stress distribution around the rod periphery, friction factors, static pressure distributions and turbulence intensity corresponding to various Reynolds numbers ranging from 4140 to 36170 in the central subchannel were measured. A simulated model of triangular array rods with pitch to diameter ratio of 1.10 (as a test section) and air as the fluid flow was used. Various approaches for measurement of wall shear stress were compared. The measurement was performed using the Preston tube technique with the probe outside diameter equal to 0.014". Our results showed that the nondimensional wall shear stress distribution is a monotonical function of the azimuthal angle, and its maximum value occurs at the largest flow area ($\theta = 30$ degrees): The friction factors calculated from the wall shear stress distribution results are less than the friction factors calculated from the pressure drop data measured at the rod gap. The former friction factor results agree with the results of pipe flow multiplied by a coefficient or the results of a calculation on an equivalent annular zone. The static pressure around the rod periphery is a function of the azimuthal angle, and decreases as the point moves away from the rod gap. The distribution becomes steeper as the Reynolds number increases. There were no detectable effects of secondary flow in the region very close to the rod surface.

Experimental measurements of the distribution of axial velocity, turbulent axial velocity, turbulent kinetic energy and radial Reynolds stresses were performed in the developing and fully developed regions. A 2-channel Laser Doppler Anemometer working on the Reference mode with forward scattering was used to perform the measurements in a simulated interior subchannel of a triangular rod array with $P/D = 1.124$. A 2-equation turbulence model -- a strong candidate for analyzing actual three dimensional turbulent flows -- was used to predict fully developed flow of infinite bare rod bundle of various aspect ratios (P/D). The model was modified to take into account anisotropic effects of eddy viscosity. Secondary flow calculations were also performed although the model seems to be too rough to predict the secondary flow correctly. Heat transfer calculations were performed to confirm the importance of anisotropic viscosity in temperature predictions. All numerical calculations for flow and heat were performed by two computer codes developed in the present work which were based on the TEACH code.

Comparisons between the analytical results and the results of this experiment as well as other experimental data in rod bundle array available in literature were presented. The predictions were in good agreement with the results for the high Reynolds numbers.

Investigators: Professors N.E. Todreas, W. Rohsenow; Messrs. K. Basehore, S. Glazer, C. Chiu, J. Kelly, J. Bartzis, M. Fakori-Monazah, A. Hanson

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:

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B. Mikic, E.U. Khan, and N.E. Todreas, "An Approximate Method for Predicting Temperature Distribution in Wire Wrapped Fuel Assemblies of a LMFBR," COO-2245-37TR, MIT, April 1977.

C. Chiu and N.E. Todreas, "Development of a Technique for Subchannel Flow Rate Measurements in LMFBR Wire Wrapped Assemblies," COO-2245-39TR, July 1977.

*Department of Mechanical Engineering

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- K.L. Basehore and N.E. Todreas, "Assessment of the Need to Incorporate A Variable Swirl Flow Model into the ENERGY Code," COO-2245-46TR, July 1977.
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- S. Glazer, N.E. Todreas, and W. Rohsenow, "TRANSENERGY S,M -- Computer Codes for Coolant Temperature Prediction in LMFBR Cores During Transient Events," COO-2245-52TR, January 1977.
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- C. Chiu, W.M. Rohsenow and N.E. Todreas, "Turbulent Sweeping Flow Mixing Model for Wire Wrapped LMFBR Assemblies," COO-2245-55TR, MIT, April 1978.
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3.2.3 Methods for Thermal/Hydraulic Analysis of LWR Cores

The goal of this project is to provide publicly available tools, primarily computer codes, for the analysis of operational transients in LWR cores. The focus of the previously reported effort was the development of a method for steady state PWR thermal analysis using publicly available computer codes. A one-pass analysis approach was developed and assessed. It was concluded that the one-pass method did give results of equal or better validity than the existing cascade method. Based on this conclusion, the optimum arrangement and size of fine (about the hot subchannel) and coarse (remainder of core) mesh zones for one-pass analysis were recommended for core MDNBR analysis.

The current effort was aimed at identifying those PWR transient conditions to which the one-pass method could be applied. PWR accident conditions and analysis methods were reviewed. Limitations of the simplified method with respect to analysis of these accident conditions were drawn and two transients (loss of coolant flow, seized rotor) identified as candidates for analysis by this method. These transients have been examined in detail by this one-pass approach. It was concluded that the steady state one-pass simplified method can be applied to the above two transient conditions.

Investigators: Professor N.E. Todreas, Research Associate
R. Bowring, Messrs. P. Moreno, C. Chiu, E. Khan, J. Liu

Support: New England Electric System and Northeast Utilities Service Company as part of the Nuclear Reactor Safety Research Program under the MIT Energy Laboratory's Electric Power Program (\$20,000/year for Thermal/Hydraulic Analysis of PWR Cores)

Related Academic Subjects:

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

Recent References:

P. Moreno, C. Chiu, R. Bowring, E. Khan, J. Liu, N. Todreas, "Methods for Steady State Thermal/Hydraulic Analysis of PWR Cores," Report MIT-EL-76-006, Rev. 1, July 1977 (Original March 1977).

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C. Chiu, P. Moreno, R. Bowring, N. Todreas, "Enthalpy Transfer Between PWR Fuel Assemblies in Analysis by the Lumped Subchannel Model," to be published in Nuclear Engineering and Design.

3.2.4 Fuel-Coolant Interactions in LMFBR's

In the context of reactor safety, various types of phenomena have been considered in the analysis of low probability accidents for both Light Water Reactors (LWR's) and the Liquid Metal Fast Breeder Reactor (LMFBR). These accidents are investigated because although their probabilities of occurrence are very small, the possible consequences to the public health and safety are large. One such phenomenon that is possible during these accident scenarios involves a thermal interaction when the more volatile coolant (e.g. sodium) and the hot core materials (e.g. UO_2) come into contact and become intermixed. High interaction pressures and disruptive mechanical work may be the result of this intermixing. This fuel-coolant interaction (FCI) may occur if the fuel is initially molten or if it is initially a two-phase expanding mixture of fuel vapor and liquid, and this is the logic for the division of the research into two areas.

(a) Physical Mechanisms for Molten Fuel-Coolant Interactions (MFCI)

The sequence of physical events leading to a coherent energetic MFCI are not completely known but could be characterized by a three-stage process: (1) coarse intermixing of the molten fuel and coolant without significant heat transfer; (2) a trigger mechanism that initiates the rapid heat transfer between the constituents, resulting in coolant vaporization at high pressures; (3) escalation and propagation of the interaction to an explosive nature (possible shock wave production). Simulant materials have been experi-

mentally used to investigate the MFCI phenomenon in the LMFBR. In particular small-scale experiments using molten metals as the fuel and water as the coolant were conducted at MIT to investigate the trigger phase of the interaction. The extent of fuel fragmentation, interaction, pressure, and the time to the interaction were monitored as the fuel temperature was varied at a fixed coolant temperature. The fuel was dropped into the coolant under air, nitrogen, and evacuated environments.

From these tests it was previously concluded that neither an acoustic cavitation mechanism nor a violent release of dissolved gas were responsible as the trigger of these fragmentation interactions. However, it was noted that these self-triggered MFCI's only occur in a specific range of initial fuel and coolant temperatures which is consistent with other small-scale dropping experiments throughout the world. Recent analysis of these experiments indicates: (1) The fuel surface temperature in the region of a self-triggered interaction is below the critical temperature of the coolant; and this is in agreement with the upper temperature bound for the spontaneous nucleation theory of MFCI's; (2) The upper diagonal portion of the fragmentation boundary for these small-scale self-triggered interactions can be explained by a non-condensable gas film. This film at high initial fuel and coolant temperatures allows coolant vaporization before film collapse and creates a thick film boiling regime which does not allow liquid-liquid contacts and precludes a self-triggered event.

(b) Two-Phase Fuel and Coolant Heat Transfer Modeling

A two-phase fuel source (UO_2) is envisioned to be formed by a low probability accident, identified as a Loss of Flow Transient with a failure to scram. This core disruptive accident (CDA) could cause destructive mechanical work within the reactor vessel, and the expansion work of this two-phase fuel up to the point where the upper plenum sodium coolant pool impacts the reactor vessel head is a measure of this work potential. The sodium coolant can interact with the expanding fuel by becoming entrained in the fuel bubble and receiving energy by some heat transfer mechanism. The key considerations for this process are: the amount of sodium entrained, the characteristic size of the entrained coolant (drop diameter), the heat transfer mechanism between fuel and coolant, and the potential for sodium vaporization. Sodium coolant vaporization is a concern because it can add to the expansion pressure and increase the expansion work.

The analysis of this phenomenon has led to a number of conclusions: (1) It appears a dominant mechanism for coolant entrainment into the expanding fuel bubble is due

to Taylor Instabilities. A model for this was developed by small-scale experiments performed here at MIT; (2) Modeling of small-scale heated experiments performed by SRI and P. Argonne indicate that the characteristic size of the entrained coolant in droplet form lies between the critical Taylor Instability wavelength (λ_c) and the fastest growing wavelength ($\lambda_m = \sqrt{3}\lambda_c$); (3) Full scale calculations indicate that radiation heat transfer controls the energy transfer process; and the fuel expansion work is reduced by a factor of 1.2 to 2.5 due to this process. The amount of reduction is dependent upon the radiative properties of the sodium surface; (4) The amount of coolant vaporized is small because the bulk of the coolant droplets do not become saturated and surface vaporization is very small due to mass diffusion effects. Thus, this initial research indicates that sodium coolant in this configuration has a quenching effect on the fuel expansion work.

Investigators: Professors N.E. Todreas, W.M. Rohsenow*, A.A. Sonin*, Messrs. M. Corradini, G. Shiralker, W. Lenz.

Support: Department of Energy (\$13,000/year for LMFBR Fuel Coolant Interaction work).

Related Academic Subjects:

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

Recent References:

M.S. Kazimi, et al., "Acoustic Cavitation as a Mechanism of Fragmentation of Hot Molten Droplets in Cool Liquids", MIT-COO-2781-6TR, November 1976.

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G. Shiralker, W. Rohsenow, A.A. Sonin, N. Todreas, "Experimental Investigation of Gas Evolution as the Mechanism for Free-Contact Fragmentation", Nuclear Science and Engineering, 66, 103-109 (1978)

*Department of Mechanical Engineering

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M. Corradini, W. Rohsenow, N. Todreas, "Application of Spontaneous Nucleation Theory to Tin-H₂O Interactions", MIT-COO-2781-11TR, January 1977.

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M. Corradini, W. Rohsenow, N. Todreas, "Effects of Sodium Entrainment and Heat Transfer with Two-Phase Fuel during an HCDA", Trans. of the ANS, 29, November 1978.

M. Corradini, W. Rohsenow, N. Todreas, "A Proposed Model for Tin/Water Interactions", presented at ASME Winter Meeting, San Francisco, December 1978.

3.2.5 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.

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

Investigators: Professor M.W. Golay; Messers. D. Boyle, S.H. Chang, and V. Manno.

Support: Energy Research and Development Administration (\$43,000).

Related Academic Subjects:

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

Recent References:

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

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L. Guillebaud and M.W. Golay, "Investigation of Iterative Methods for Solution of Large, Sparse Bandwidth Matrix Equations," MITNE-187, MIT-EPRI (1976).

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Y.B. Chen and M.W. Golay, "Validation of Turbulence Models for LMFBR Outlet Plenum Flows," 77-HT-34 (1977). Submitted to the J. Heat Transfer.

Y.B. Chen and M.W. Golay, "Coolant Mixing in the LMFBR Outlet Plenum", COO-2245-44TR, MIT-ERDA (1977).

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).

3.2.6 Multidimensional Fluid Flow and Heat Transfer Analysis for Finite LMFBR Bundles

Under this topic several aspects of multidimensional heat transfer in complex multiple connected geometry have been studied. The spectrum of the analyses performed ranges from 2-D and 3-D slug flow heat transfer analyses, 2-D laminar mixed convection analysis to 3-D turbulent velocity and temperature fields in characteristic coolant cells of hexagonal bundles. These studies were accompanied by additional thermoelastic and inelastic analyses which used the results of the aforementioned thermal analyses as input. Furthermore, lumped and distributed parameters approaches have been coupled for the first time to allow the user the evaluation of local temperatures at any position in the bundle with due regard of the information stemming from common subchannel codes.

An analytical two-dimensional, multiregion, multicell technique has been developed for the determination of local temperature fields of various unit cells and combinations thereof. Arbitrary power distributions and flow splits between interior cells and edge cells are allowed. The validity of the LOCAL code has been verified by the excellent agreement of its results with the THTB results obtained by finite difference technique. By comparing the calculated fully-developed circumferential clad temperature distributions with experimental evidence, an axial correction factor has been derived to account for the entrance effects for practical considerations. The knowledge of the local temperature field allows the analytic determination of the effective conduction mixing lengths for adjacent subchannels of various combinations. It could be shown that the implementation of these accurately determined parameters into the subchannel code COBRA-IIIC reduces over-conservatism.

For the first time a scheme has been proposed to couple the 2-D distributed and lumped parameter calculations. This approach has demonstrated its applicability for the analysis of a 7-pin bundle. These results were compared to experiments and a true three-dimensional analysis.

In addition, a three-dimensional single region slug flow heat transfer analysis of finite LMFBR rod bundles using a classic analytic solution method has been performed because the results of fully developed heat transfer analyses are too conservative. Results of isolated and coupled cell analyses were compared with three-dimensional clad temperature measurements and showed surprisingly good agreement which indicates that heat conduction is the dominant transport phenomenon in the thermal entrance region.

The effective conduction mixing length could be derived as a function of the axial coordinate. Fitted to an empirical equation and implemented into COBRA-IIIC it could be demonstrated that lumped parameter methods can be improved by virtue of the results of distributed parameter analyses.

Due to the multicell methodology developed during this research it was possible for the first time to analyze a complete internal cluster of coolant cells with power skews. It was demonstrated that the center pin experiences rather large azimuthal temperature gradients over its whole length which has major implications for the structural analysis of LMFBR bundles.

Due to the importance of low flow conditions in LMFBR bundles a two-dimensional analytical analysis of laminar velocity and temperature fields in characteristic coolant cells under the additional effect of natural convection was performed. It could be demonstrated that natural convection has a beneficial effect upon the reduction of azimuthal temperature gradients. The average Nusselt number increases from the pure laminar value up to a certain value at a critical Rayleigh number where it drops sharply below its laminar value. The onset of reversed flow in the wider parts of the coolant cells was determined as well as the associated changes in the pressure drop characteristics.

Two-dimensional thermoelastic and inelastic stresses and deformations of typical LMFBR claddings were evaluated by utilizing various codes developed at MIT and elsewhere. The primary objective of this study was to analyze the effect of various local perturbations in the clad temperature field,

namely eccentrically mounted fuel pellet, clad ovality, power tilt across the fuel and clad-coolant heat transfer variation on the cladding stress and deformation. The comparison of thermoelastic and inelastic results show that the former can be used effectively to analyze fuel pins during startup. Beyond that the inelastic solution must be used. The impact of the individual thermal perturbations and combinations thereof upon the structural quantities were shown. Finally, the effect of rod displacement on the two-dimensional thermal and structural characteristics of the LMFBR claddings were analyzed in an iterative way.

Efforts are now underway to develop a wire-wrap model from basic principles. Experience with the code RODBUN which evaluates local turbulent velocity and 3-D temperature fields in subchannels will help to support this important development.

Due to the importance of transient LMFBR bundle analysis, efforts have been devoted towards the extension of the LWR-COBRA-IIIP/MIT code to a liquid metal version which includes state-of-the-art wire wrap model, heat transfer coefficients and friction factors.

Investigators: Professor L. Wolf, Messrs. M.K. Yeung, C.N. Wong, J.Y. Kim, R. Karimi, F. Seifae

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:

M.K. Yeung, "A Multicell Slug Flow Heat Transfer Analysis for Finite LMFBR Bundles", Ph.D. Thesis, Department of Nuclear Engineering, July 1978.

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J.Y. Kim, "Fully Developed Mixed Convection Heat Transfer in Finite Hexagonal Bundles", S.M. Thesis, MIT, Department of Nuclear Engineering, February 1977.

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M.K. Yeung, L. Wolf, "Effective Conduction Mixing Lengths for Subchannel Analysis of Finite Hexagonal LMFBR Bundles" Trans. Am. Nucl. Soc., 26 (1977), 463-464.

R. Karimi, L. Wolf, "Two-Dimensional Structural Analysis of Reactor Fuel Element Claddings Due to Local Effects" Report No. COO-2245-59TR, April 1978.

L. Wolf, C.N. Wong, M.K. Yeung, "2-D Thermoelastic Analysis of LMFBR Fuel Rod Claddings", 4th SMIRT Conference, San Francisco, 1977, vol. c, paper C4/4.

F. Seifae, "An Improved Numerical Method for the Steady State and Transient Thermal-Hydraulic Analysis of Fast Breeder Reactor Fuel Pin Bundles", N.E. Thesis, MIT, Department of Nuclear Engineering, August, 1978.

3.2.7 Sensitivity Studies of the Thermal-Hydraulic Models of the MEKIN Code

The thermal-hydraulic models and solution schemes employed by the MEKIN computer code have been examined. The effects of the thermal-hydraulic input parameters on predicted fuel temperatures and coolant densities were determined with special consideration to a simulated PWR control rod ejection transient. The limitations to the use of MEKIN that arise because of the simplifying assumptions in the thermal-hydraulic models were examined. Computation time was reduced without altering the results of a transient analysis if appropriate MEKIN options were selected. Guidelines are presented to facilitate the selection of these options. Suggestions for improvement of the code were also made.

Coolant density and average fuel temperature, the neutronic feedback parameters, were found to be most sensitive to three T-H input options. These were:

- 1) the value of the gap heat transfer coefficient, h_{gap} used in the fuel conduction model;
- 2) the number of thermal-hydraulic channels used in the hot assembly; and
- 3) the use of a subcooled boiling correlation.

The neutronic feedback parameters were found to be insensitive to the convergence criterion, the number of radial fuel nodes used in a hot full power transient, the two-phase pressure drop correlation, and the value of the turbulent mixing parameters in single phase flow.

Formulas were presented which describe the response of the predicted fuel temperatures to changes in axial mesh and time step size. It was found that the transient volumetric flow weighted average coolant densities differ significantly from the area weighted average densities that should be used in neutronic feedback calculations. A method was proposed to adjust the coolant density for use in updating neutronic cross sections.

Sensitivity studies showed that the average fuel temperatures calculated with the parabolic averaging scheme used in MEKIN agreed well with analytic results and will provide acceptable results in all LWR transients if appropriate fuel mesh sizes are selected.

Many assumptions and approximations were made to arrive at the MEKIN thermal-hydraulic solution scheme. As a result, this scheme has a limited range of applicability. Analyses for a range of transients should be performed using the MEKIN solution scheme and less approximate codes.

A sensitivity study was performed for both steady state PWR and BWR operational and reduced flow conditions. The impact of various user options for the selection of appropriate correlations and empirical coefficients upon COBRA-IVC/MIT results was studied. An appropriate lumping scheme for the BWR option has been developed and recommendations given.

Due to the importance of a consistent fuel pin model this issue was studied separately by examining four finite difference conduction-convection schemes. Variable gas gap conductance, temperature dependent properties, consistent nodalization and strict energy conservation were analyzed and recommendations given for future implementation into thermal hydraulic codes.

Because other research had indicated the importance of a consistent heat transfer package a special study was entirely devoted to this issue alone which resulted in the implementation of a best estimate heat transfer package, BEEST, into the newly released computer code COBRA-IV-I. The new version, COBRA-IV-BEEST was tested for several types of transients such as power, flow, depressurization and pressurization transients. In addition, one semiscale Blowdown Test was used for comparison. The comparison with the originally built in RELAPY/MOD5 heat transfer package indicated that BEEST should be preferred. Furthermore, it was found that a package like this should be only used as an integrated part of a thermal hydraulic code and not as a stand alone version, as formerly suggested.

Investigators: Professor L. Wolf, Messrs. T. Rodack, F. Emami, M.A. Mehrabian, M. Massoud, D.Y. Hsia, D. Siggs.

Support: EPRI (\$45,000, as part of the MEKIN Sensitivity Study), Department of Energy (\$4,000 as part of the Thorium Fuel Project)

Related Academic Subjects:

22.33 Nuclear Reactor Design
 22.312 Engineering of Nuclear Reactors
 22.313 Advanced Engineering of Nuclear Reactors
 22.901 Special Problems in Nuclear Engineering

Recent References:

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M.A. Mehrabian, "Application of Numerical Methods in Steady-State and Transient Thermal Fuel Pin Modeling", S.M. Thesis, MIT, Department of Nuclear Engineering, May 1978.

M. Massoud, "Comparison of Conservative and Best Estimate Heat Transfer Packages with COBRA-IV-I", N.E. Thesis, MIT, Department of Nuclear Engineering, August 1978.

D.Y. Hsia, "A Sensitivity Study of the RELAP 3B Computer Code", Special Problem, Department of Nuclear Engineering, MIT, May 1978.

D. Siggs, "ATWS Analysis for PWRs", S.M. Thesis, MIT, Department of Nuclear Engineering, August 1978.

3.2.8 Assessment of the Range of Applicability of COBRA-IIIC/MIT

This research intended to investigate the range of applicability of various subchannel codes. The codes which were used included COBRA-IIIC/MIT, which is representative of many common subchannel codes and the newly released COBRA-IV-I code. Since the latter represents an improved code, its prediction was assumed to be the best estimate

for the cases considered in the study. Hence, through the comparisons of the two codes, the applicability of COBRA-IIIC/MIT was assessed with respect to COBRA-IV-I.

Both steady-state and transient analyses were performed with the two codes. The types of analysis included BWR bundle wide analysis, a simulated rod ejection transient and PWR loss of flow transients. In addition to these cases, comparisons of the two codes were made for actual core exit temperature measurements, bundle mixing experiments and subchannel blockage experiment.

While attempting to analyze a BWR pressurization transient, two severe problems were encountered which resulted in a breakdown of COBRA-IIIC/MIT when small step sizes were used. Solutions have been found which eliminated these breakdowns and other inconsistencies which were discovered in the BWR option. During this research it became apparent that the inclusion of a subcooled boiling model is mandatory for any realistic BWR analysis. Furthermore, it was realized that the explicit treatment of the energy equation in COBRA-IIIC/MIT poses certain limitations.

Problems also arose when PWR power transients were analyzed by using small time steps and Levy's model. Several changes were necessary to make COBRA-IIIC/MIT operational. After all these corrective measures have been implemented into the code, it is now believed that COBRA-IIIC/MIT is operational over the spectrum of transients it was supposed to handle in the first place.

It was found that, overall, COBRA-IIIC/MIT predicts most thermal-hydraulic parameters quite satisfactorily. However, the COBRA-IIIC/MIT clad temperature predictions differ from those of COBRA-IV-I and appear in error. These incorrect predictions are caused by the discontinuity in the heat transfer coefficient at the start of boiling. In fact, it was determined that the primitive logic in the heat transfer package is the major source for the discrepancies experienced with COBRA-IIIC/MIT. Hence, if the heat transfer package is corrected, the COBRA-IIIC/MIT should be just as applicable as COBRA-IV-I for a wide range of LWR thermal-hydraulic analyses.

One additional year of research on the problems revealed by the present analysis would certainly strengthen the reliability of COBRA-IIIC/MIT.

Investigators: Professor L. Wolf, Messers. J. Kelly,
J. Loomis.

Support: Nuclear Power Reactor Safety Program sponsored by New England Utilities under MIT Energy Lab. (\$35,000/year).

Related Academic Subjects:

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

Recent References:

J.E. Kelly, "Assessment of the Range of Applicability of Various Codes for Thermal-Hydraulic Design of Light Water Reactors, M.S. Thesis, Department of Nuclear Engineering, MIT, August 1978.

J.E. Kelly, J. Loomis, L. Wolf, "Range of Applicability of COBRA-IIIC/MIT, MIT Energy Lab. Report No. MIT-EL-78-026, September 1978.

J.E. Kelly, L. Wolf, "Investigation into the Failure of COBRA-IIIC/MIT while Analyzing a BWR Pressurization Transient," Report prepared for EPRI, Department of Nuclear Engineering, MIT, December 1977.

J.E. Kelly, L. Wolf, "Investigation into the Problems Associated with Using the Levy Model in BWR Analysis, " Report prepared for EPRI, Department of Nuclear Engineering, MIT, May 1978.

F. Emami, "Steady-State Thermal-Hydraulic Sensitivity Study of LWR Core Modeling with COBRA-IIIC/MIT," S.M. Thesis Department of Nuclear Engineering, MIT, August 1977.

3.2.9 Alternative Solution Scheme for the COBRA-Code

The purpose of this research was the development of two new and extremely efficient numerical methods for the steady state and transient two-phase lumped-parameter thermal hydraulic analysis of fluid flow distributions in fuel pin bundles and nuclear reactor cores.

These methods use the same physical model as the COBRA-IIIC code but are based on the alternative numerical concept of generating a system of semi-implicit difference equations for the pressure field by using a spatial differencing scheme which is different, than previously used by subchannel analysis codes. The flow and enthalpy distributions in the

lattice are found by marching downstream several times in succession between adjacent computational planes and by combining the computed pressure fields from these planes together into a composite pressure field, which is then used as the driving force for the crossflow distribution is a reformulated form of the transverse momentum equation. Both methods are extremely efficient from a computational point of view and are compatible with a variety of iterative solution techniques because the coefficient matrices governing the computation of the pressure fields can be shown to be Stieltjes matrices. This property results in further savings of computation time.

These numerical methods have been integrated into the computational framework of the COBRA-IIIC code and a new computer program has been devised which is called COBRA-IIIP/MIT (P for the pressure solution). The code is considerably faster and more powerful than other programs and has the capability to solve extremely large and complex problems with great speed. Most importantly, the predictions of the code proved to be within a few tenths of one percent compared to those of COBRA-IIIC. Moreover, COBRA-IIIP/MIT does not appear to suffer from drawbacks inherent to COBRA-IIIC. Rather it converges very rapidly to an asymptotic crossflow distribution without spurious oscillations as additional iterations are performed.

More recently, additional features have been added to COBRA-IIIP/MIT which allow the analysis of hexagonal liquid metal cooled fuel pin bundles. Comparison with other available codes show the superiority of this extended version especially under transient conditions such as combined power and flow transients.

Investigators: Professor L. Wolf, Messers, R.E. Masterson,

Support: EPRI (\$2,000/year).

Related Academic Subjects:

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

Recent References:

R.E. Masterson, L. Wolf, "An Efficient Multidimensional Numerical Method for the Thermal-Hydraulic Analysis of Nuclear Reactor Cores," ANS Topical Meeting, Tuscon, Arizona March, 1977, Nuclear Science and Engineering.

R.E. Masterson, L. Wolf, "Improved Multidimensional Numerical Methods for the Steady State and Transient Thermal-Hydraulic Analysis of Fuel Pin Bundles and Nuclear Reactor Cores", Department of Nuclear Engineering, MIT, MITNE-203, June 1977.

R.E. Masterson, L. Wolf, "COBRA-IIIP: An Improved Version of COBRA for Full-Core Light Water Reactor Analysis," Nuclear Engineering Design, 48, pp 293-310, 1978.

3.2.10 Drift-Flux Concept Applied to BWR Subchannel 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.

The code WOSUB has the following features:

- (1) it uses the Zuber-Findlay drift flux model of two-phase flow;
- (2) a vapor diffusion model is included, which accounts for an affinity of the vapor to redistribute into channels with higher velocities;
- (3) thermodynamic nonequilibrium effects are accounted for in the subcooled region;
- (4) boiling length and critical power are calculated;
- (5) and a novel collocation method is used for calculating the steady-state and transient fuel pin temperatures.

The code has been extensively tested against local quality, mass flux and void fraction measurements in the individual subchannels and compared to a wide variety of well-known subchannel codes which use the homogeneous two-phase flow model. These comparisons showed that an improved two-phase flow modeling leads indeed to substantial improvement in the calculated results. It could be shown at the same time that the codes with the

homogeneous model cannot predict the correct trend of the data no matter what numerical scheme was used. Work in this area is continuing. Unpublished data have been received which will be used to improve the empirical vapor diffusion model.

Investigators: Professor L. Molf, Messers. L. Guillebaud, A. Boyd, A. Faya.

Support: Nuclear Power Reactor Safety Program sponsored by New England Utilities under MIT Energy Laboratory Program (\$26,000/year).

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, MIT-EL-78-025, August 1977.

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

J.E. Kelly, L. Wolf, "Investigation into the Failure of COBRA-IIIC/MIT While Analyzing a BWR Pressurization Transient", Report prepared for EPRI, Department of Nuclear Engineering, MIT, December 1977.

J.E. Kelly, L. Wolf, "Investigation into the Problems Associated with Using the Levy Model in BWR Analysis" Report prepared for EPRI, Department of Nuclear Engineering MIT, May 1978.

F. Emami, "Steady-State Thermal-Hydraulic Sensitivity Study of LWR Core Modeling with COBRA-IIIC/MIT," S.M. thesis, Department of Nuclear Engineering, MIT, August 1977.

3.2.11 Thermal Phenomena in LMFBR Safety Analysis

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

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

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

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 so far can be summarized as follows:

1. In-Core Phenomena

- a) Plugged-up Core: A simplified analysis of a fuel pool under plugged-up core conditions has been performed to estimate the potential for heat transport to the structures surrounding the core. The results indicate that under decay power density conditions, the heat transport to the surrounding structures around the core will govern the pressure in the sealed core region and in fact, may eliminate overpressure development. Under operating power density conditions, the heat transport to the surrounding structures is not sufficient to influence the pressure build-up in the sealed region.

b) Fuel-to-Steel Heat Transfer: Modeling of the volumetric heat transfer coefficient from fuel to steel has been initiated. The model is based on an extension of the single 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 test the model.

2. Out-of-Core Phenomena

b) Bubble/Jet Expansion in a Pool: An experiment has been performed to investigate the rate of entrainment of a liquid into a penetrating jet under transient conditions. The experiment is two-dimensional and is designed to simulate the conditions of a segment of the upper plenum of an LMFBR. Two series of experiments have been performed using this apparatus: a hydraulic series and a thermal hydraulic one. The hydraulic series showed significant entrainment of the liquid in the penetrating gas, which may be explained by Taylor instability. This will enhance condensation of fuel vapor.

Investigators: Professor M.S. Kazimi, W.M. Rohsenow, Messrs. R.A. Rothrock, R. Smith, K. Araj.

Support: NRC (approximately \$70,000/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, "On the Limits of Stability of Internally Heated Pools", Trans Am. Nucl. Soc., 26, 362 (June 1977).

M.S. Kazimi, "The Potential for Fuel Boiling Under Decay Heat Conditions", presented at Third PAHR International Information Exchange Meeting, Argonne National Laboratory (November 2-4, 1977).

R.A. Rothrock and M.S. Kazimi, "On the Potential for Plugged Core Pressurization Following a Hypothetical Accident in LMFBR", submitted to Nucl. Eng. Design (March 1978).

M.S. Kazimi and J.C. Chen, "Void Distribution in Boiling Pools with Internal Heat Generation", Nucl Sci. Eng., 65, 17-27 (1978).

3.2.12 Development of Two-Fluid Models for Sodium Boiling

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 models will be pursued: a one-dimensional model (NATOF-1D), and a two-dimensional model (NATOF-2D). The models will be verified by comparison to existing experimental results on sodium boiling. Where needed, additional experimental results will be defined.

For the one-dimensional approach, there already exists a computer code which demonstrates a working numerical method for a broad range of difficult flow conditions with no convergence, stability, or other numerical difficulties.

The one-dimensional code is, however, in a relatively primitive state as regards physical realism. Thus, implementation of the correlations necessary to bring realism into this 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 superheat is important), interphase heat and mass transfer rate models.

The NATOF-2D two-fluid two-dimensional model is now at an initial state of development (Item (1) above). Hence, development of this model will lag behind the 1D model. However, the importance of the 2D effects under some transient conditions imply that development of this model should be pursued at the same time so that comparison of the 1D and 2D models will be helpful in verification of the 1D model.

The development of the 2D model will also 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: Professor M.S. Kazimi, Dr. W.D. Hinkle, Messrs. M. Granziera, M. Autruffe.

Support: DOE (approximately \$60,000/year).

Related Academic Subjects:

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

Recent References:

M. Autruffe, "Analysis of Some Thermal Phenomena in LMFBR Safety", M.S. Thesis, Mech. Eng. Dept. (August 1978).

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 starting at the TOP successively 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 modularization methodology has been implemented into the PL-MOD computer code, written in PL-1 language in order to take advantage of its list-processing capabilities. In particular, extensive use was made of based structures, pointer variables and dynamic storage allocation. Moreover, the main treatment of Boolean state vectors, required to handle higher order modular structures was conveniently performed using bitstring variables.

PL-MOD was used to analyze a number of nuclear reactor safety system fault trees, and its performance was tested against that of minimal cut-set generation codes. It could be demonstrated that its execution time to modularize large fault trees is significantly smaller than what it takes to generate the high amount of minimal cut-sets. Thus, the execution time to modularize the High Pressure Injection System was twenty five times faster than that necessary to generate its equivalent minimal cut-set description using MOCUS, a code considered to be fast by present standards.

PL-MOD has generated substantial interest, especially by the Nuclear Regulatory Commission.

Investigators: Professor L. Wolf, Dr. J. Olmos

Support: Nuclear Regulatory Commission (\$2,500/year).

Related Academic Subjects:

22.38 Reliability Analysis Methods

Recent References:

J. Olmos and L. Wolf, "A Modular Approach to Fault Tree and Reliability Analysis", Trans. Am. Nuclear Society, 26, pp 395-396, 1977.

J. Olmos and L. Wolf, "A Modular Approach to Fault Tree and Reliability Analysis," MITNE-209, August 1977.

J. Olmos and L. Wolf, "PL-MOD -- A Complete Code for Modular Fault Tree Analysis and Evaluation," Topical Meeting on Probabilistic Analysis of Nuclear Reactor Safety, May 8-11, 1978, Los Angeles, Vol. 3, XIII - 4.1/4.12.

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

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

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

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

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

Given the efficient recursive computational procedure, the inclusion of a time-dependent tree analysis capability was thought to be justified. This has already led to the development of the extended version PL-MODT, which allows the determination of time-dependent point unavailabilities for a system comprising non-repairable, repairable, tested and maintained components. PL-MODT has been successfully

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, PL-MODT 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 PL-MOD 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 will be issued early in 1979 which comprises PL-MOD, PL-MODT, and PL-MOD-MC.

Investigators: Professor L. Wolf, Mr. M. Modarres

Support: Nuclear Regulatory Commission (\$35,000)

Related Academic Subjects:

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 Evaluation Code," Trans. Am. Nucl. Soc. 28 510-511

M. Modarres, L. Wolf, "Automatic Reduction of Complex Fault Trees by PL-MODT," accepted for presentation at the American Nuclear Society Winter Meeting, Washington, D.C. November 1978.

3.2.15 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 operation 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 a 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; Dr. R. Karimi.

Support: Nuclear Power Reactor Safety Research Program, sponsored by New England Utilities under the MIT Energy Laboratory (\$48,000)

Recent References:

R. Karimi, L. Wolf, "BIT-FRANTIC: A Convenient and Simple Code Package for Fault Tree Analysis and Unavailability Calculations," accepted for presentation at the American Nuclear Society Winter Meeting, 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.

3.2.16 Structural Mechanics

Nuclear power plants contain components requiring a wide variety of applications 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).

Theses have been completed on several such topics and are listed below as recent references.

Investigators: Professor J. Meyer, Messrs. H. Alesso, M. Fardis, G. Garner, W. Michell, R. Racana, T. Tokunaga

Support: Some funds for computer from other research topics (§3.11.3, Fusion Reactor Technology and §3.3.4, Light Water Reactor Fuel Performance Analysis)

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:

T. Tokunaga, "Important Structural Considerations in Design of Prestressed Concrete Reactor Vessels," S.M. Thesis, MIT Nuclear Engineering Dept., May 1977.

M.N. Fardis, C.A. Cornell, and J.E. Meyer, "A Probabilistic Seismic Analysis of Containment Liner Integrity," Trans. 4th Intl. Conf. Str. Mech. in Reactor Tech. K(b), Paper K4/16 (1977).

W.R. Michell, "Significant Structural Design Considerations in Welded Components," S.M. Thesis, MIT Nuclear Engineering Dept., September 1977.

M.N. Fardis, "An Accident and Seismic Containment Reliability Study Including Statistical Uncertainty," S.M. Thesis, MIT Nuclear Engineering Dept., January 1978.

R. Racana, "Analysis of Structures Operating at High Temperatures in a High Radiation Field," Nuclear Engineer Thesis MIT Nuclear Engineering Dept., May 1978.

H.P. Alesso, "Elementary Catastrophe Theory Modelling of an End Loaded Ring in a Rigid Cavity," Nuclear Engineer Thesis MIT Nuclear Engineering Dept., May 1978.

G. Garner, "Flow Induced Vibration of Tubular Components of Nuclear Power Plants," S.M. Thesis, MIT Nuclear Engineering Dept. and Mechanical Engineering Dept., August 1978.

3.2.17 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 like 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 thoroughly tested, verified and qualified for PWR facilities. Its usefulness has been demonstrated with numerous studies which can be done quickly and easily.

Proposed continued work on the FLAC code includes extension to BWR facilities and incorporation of simple estimates of peaking and reactivity limits. Also, an economics analysis can be incorporated into the code.

Investigators: Professors D.D. Lanning, M.J. Driscoll, Mr. C.L. Beard.

Support: Yankee Atomic Electric Company (\$1,000/year), Proposal pending for further Electric Utilities Support.

Recent Reference:

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

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

3.3.2 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, long time (creep), and irradiation creep behavior. Irradiation creep tests are being simulated using energetic protons. 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. G.E. Lucas, R. Ballinger.

Support: Electric Power Research Institute

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:

R.G. Ballinger, "The Anisotropic Mechanical Behavior of Zircaloy-2," S.M. Thesis, Department of Nuclear Engineering, August 1977.

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

R. Ballinger, R.M.N. Pelloux, "The Anisotropic Mechanical Behavior of Zircaloy-2," The Third International Conference on Mechanical Behavior of Materials, Cambridge, U.K., to be presented in August, 1979.

3.3.3 Hydrogen Embrittlement and Corrosion 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 temperature and at nuclear steam generator operating conditions. This investigation will aid in the understanding of several phenomena, including denting, and stress corrosion cracking, which have led to a loss in availability of many nuclear electric generating stations.

Investigators: Professors R.M. Latanision, R.M.N. Pelloux, Messrs. 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 conjunction 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 irradiated 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 displacements/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 M. Rechter

Support: National Science Foundation

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, (in press).

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 (in press).

3.3.5 Simulation of Oxide Dispersoid Stability in Irradiated Alloys.

The Maydet-Russell theory for irradiation-altered stability of incoherent precipitates has been applied to two dispersoid strengthened alloys of interest as first wall materials, Cr₂O₃ - strengthened austenitic stainless steel and Al₂O₃ strengthened aluminum.

Dispersoid stability under irradiation was found to be crucially dependent on whether the oxygen forms an interstitial or substitutional solid solution in the matrix.

In the former case growth of the oxide particle requires vacancy capture to prevent prohibitive transformation strains. Irradiation induced vacancies markedly stabilize the particles, giving a smaller critical size (as compared to thermal conditions) and under a range of conditions give stable particles in an undersaturated matrix. In the case of substitutional oxygen, dispersoid particles must emit vacancies to grow, and are destabilized by irradiation. The destabilization is strongest at lower temperatures, and up to ca. $0.4T_m$ irradiation will cause particles to dissolve in the presence of a ten-fold solute supersaturation.

Investigators: Professor K.C. Russell and Mr. M.S. Saiedfar

Support: Department of Energy

Related Academic Subjects:

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

Recent References:

"Effects of Irradiation on the Stability of Alloy Phases", Proceedings of International Conference on Radiation Effects in Breeder Reactor Structural Materials, edited by M.L. Bleiberg and J.W. Bennett, AIME, New York, 1977 (821-840).

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

M. Mruzik and K.C. Russell, "The Effect of Irradiation on the Nucleation of Incoherent Precipitates", J. Nuclear Mats. (in press).

M. Saiedfar, "Simulation of Oxide Dispersoid Stability in Irradiated Metals", S.M. thesis, M.I.T. Department of Materials Science and Engineering, 1978.

3.3.6 Theory of Void Nucleation at Heterogeneities

Voids have been observed to form in many irradiated metals; in many instances the distribution is heterogeneous, with decoration of dislocations and interphase boundaries. A theory for homogeneous void nucleation with or without inert gas (typically helium) has been extended to such heterogeneous void nucleation. Dislocations catalyze void nucleation because of release of strain energy and collection of and rapid diffusion of inert gas, if present. However, only dislocations which cannot climb, and therefore maintain the vacancy supersaturation, function as optimal sites. Cal-

culations (based on austenitic stainless steel parameters) show such dislocations to be excellent void nucleation sites. Much the same considerations were found to apply to void nucleation at interphase boundaries. The boundary reduces the energy of void nucleation, and acts as a very efficient collector rapid diffusion path for any inert gas present. The condition for non-climbing interphase boundary dislocations is fairly commonly met, and calculations show that such interphase boundaries should be excellent void nucleation sites.

Investigators: Professor K.C. Russell, Messrs. S.A. Seyyedi, M. Hadji-Mirzai

Support: National Science Foundation

Related Academic Subjects:

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

Recent References:

S.A. Seyyedi, "Theory of Void Nucleation on Dislocations", S.M. thesis, M.I.T., Department of Nuclear Engineering, 1978.

M. Hadji-Mirzai, "Effects of Material and Microstructural Parameters on Void Nucleation in Irradiation Metals", S.M. thesis, M.I.T. Department of Nuclear Engineering, 1978.

3.3.7 A Dimensionless-Parametric Analysis of Void-Swelling Susceptibility in Irradiated Metals

Irradiation induced voids form via two distinctly different mechanisms, depending on whether or not inert gas (in particular helium) is present. In the absence of helium, void nucleation requires the overcoming of activation barrier $\Delta G^*/kT$. In the presence of inert gas, void nucleation involves no activation barrier if a certain dimensionless parameter $\psi > 1$. Both ψ and ΔG^* depend crucially on the grouping of variables $\gamma\Omega^{2/3}/T$, and the vacancy supersaturation, where γ = surface energy, Ω = atomic volume, and T = absolute temperature. The vacancy supersaturation is determined by the diffusion coefficient, dislocation density, and atomic displacement rate.

Values of ψ and $\Delta G^*/kT$ have been calculated for a number of metallic elements at 0.35 of the absolute melting point for heavy ion accelerator and breeder reactor or fusion first-wall irradiation conditions. The results, when normalized to nickel, are found to predict observed swelling behavior very well, especially the high swelling resistance of zirconium and titanium, and the high swelling susceptibility of magnesium.

*MIT Reactor Laboratory

Investigators: Professor K.C. Russell and Mr. M. Hadji-Mirzai

Support: National Science Foundation

Related Academic Subjects:

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

Recent References:

K.C. Russell, "Theory of Void Nucleation in Irradiated Metals," Acta Met. (in press).

3.3.8 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, Messers. H. Andresen, Drs. M.T. Thomas, D.L. Styryus.

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 Device, 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. Jenkins, 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.

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

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

Investigators: Professors O.K. Harling, K.C. Russell, A.S. Argon, Ms. S. West, Messers, E. Daxon, H. Andresen, G. Dansfield, and A. Fadaai.

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 References:

A. Fadaai, "Determination of 3-D Boron Distribution,"
 S.M. Thesis, Departments of Nuclear Engineering and
 Materials Science and Engineering, June 1978.

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

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

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

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

Related Academic Subjects:

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

3.3.11 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 of 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, "Characterization of MITR-II Facility for Neutron Activation Analysis," M.S. Thesis in Nuclear Engineering, August 1978.

3.3.12 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. mechanical property testing of unirradiated material,
5. modeling of mechanical behavior, and
6. irradiation, testing, and modeling of the best candidate alloys.

Investigators: Professor O.K. Harling, N.J. Grant, A.S. Argon, R. Lantianision, K.C. Russell, J.E. Meyer, R. Pelloux, and J. VanderSande, Dr. J. Megusar, Messers. 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

3.3.13 Light Water Reactor Fuel Performance Analysis

The fuel rods in light water reactors must perform well 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.

We have available several fuel rod modeling codes, have improved these to incorporate new physical models and better numerical methods, and have applied these techniques to several problems of interest in light water reactor design/operation.

Investigators: Professor J. Meyer, Ms. M. Dashti, Messrs. G. de Andrade, M. Krammen, Y. Liu, J. Maki, S. Schultz, and O. da Silva

Support: Several electric utilities under the MIT Energy Laboratory Electric Power Program (\$46,000/yr)

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:

S.P. Schultz, "The Utilization of Fuel Integrity Prediction in Light Water Reactor Fuel Management," Sc.D. Thesis, MIT Nuclear Engineering Dept., May 1977.

J.E. Meyer, A.S. Hanson, M. Pitek, and S.P. Schultz, "Utility Needs for Fuel Rod Modeling Capability," Trans. Am. Nucl. Soc. 26, 219-220(1977).

M.M. Dashti, "Effect of Pre-Pressurization of Fuel Rods on Steady State and Transient Rupture Behavior," Nuclear Engineer Thesis, MIT Nuclear Engineering Dept., July 1977.

Y.Y. Liu and A.L. Bement, "A Regression Approach for Zircaloy-2 In-Reactor Creep Constitutive Equations," Trans. 4th Intl. Conf. Str. Mech. in Reactor Tech. C, Paper C3/3 (1977).

Y.Y. Liu and A.L. Bement, same title, more detail, Energy Laboratory Report No. MIT-EL 77-012, December 1977.

S.P. Schultz, A.L. Bement, and J.E. Meyer, "Using Fuel Performance Prediction in Light-Water Reactor Fuel Management," Trans. Am. Nucl. Soc. 27, 730-731(1977).

O.L.P. da Silva, "Fuel Element Performance Maps for Nuclear Reactor Operational Decisions," Nuclear Engineer Thesis, MIT Nuclear Engineering Dept., December 1977.

G.G. de Andrade, "Load-Following Operation of Pressurized Water Nuclear Reactors," Nuclear Engineer Thesis, MIT Nuclear Engineering Dept., January 1978.

M.A. Krammen, "Calibration of the CYGRO and LIFE Fuel Element Modeling Codes," Nuclear Engineer Thesis, MIT Nuclear Engineering Dept., January 1978.

Y.Y. Liu, "A Mechanistic Study of Light Water Reactor Fuel Element Failures," Sc.D. Thesis, MIT Nuclear Engineering Dept., February 1978.

G.G. de Andrade and J.E. Meyer, "Load-Following Operation of a Pressurized Water Nuclear Power Plant," Trans. Am. Nucl. Soc. 28, 597-598(1978).

3.4 Nuclear Chemical Technology

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

3.4.1 Subject of Instruction

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

3.4.2 Recovery of Uranium from Seawater

Funded by seed money from the MIT Energy Laboratory, a small project has been initiated to evaluate the economic prospects for the recovery of uranium from seawater. Since the ocean contains some 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 (the breakeven price versus coal-fired units or breeder reactors) could have a profound influence on energy planning. The resource is extremely dilute, however, and only a carefully designed and optimized process can have a chance at success. Work to date has focussed on the cost of pumping systems and pumping power, including the use of exotic energy sources such as ocean thermal gradients, and on the application of engineering principles to define the envelope of characteristics which would permit an attractive overall system design. Possible experimental work is in an early planning stage.

Investigators: Professor M.J. Driscoll, Messrs. F.R. Best, M.R. Broussard, S.J. Oliva

Support: MIT Energy Laboratory (\$20,000/year)

Related Academic Subjects:

22.033/ Nuclear Systems Design Project/Nuclear Reactor
 22.33 Design (under Prof. M.W. Golay--the Spring 1978 design project topic was uranium from seawater)
 22.76J Nuclear Chemical Engineering

Recent Reference:

M.R. Broussard "Alternative Energy Sources: Application to the Extraction of Uranium from Seawater," S.M. Thesis, MIT Nuclear Engineering Department, May 1978.

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. Operation up to power levels of 2,500 kw were continued until November, 1976. Since November, 1976 the reactor has been in routine operation at the 5,000 kw power level.

The modified reactor core is more compact than the former core, and is cooled by light water instead of by heavy water. The new core is surrounded by a heavy water reflector. The core is undermoderated and delivers a high output of fast neutrons to the heavy water reflector, where the neutrons are moderated and the resulting thermal neutrons trapped to 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-faculty design, fuel management, and advanced control systems.

Investigators: Professors M.J. Driscoll, S.-H. Chen, O.K. Harling, D.D. Lanning, N.E. Todreas, Messrs. L. Clark, Jr., H. Andersen, A. Adegbulugbe, R. Chin, F. Bamdad-Haghighi, K. Collins; Ms. S. West

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
- 22.901 Special Problems in Nuclear Engineering
- 22.904

Recent References:

MIT Reactor Staff, "MITR-II Startup Report", MITNE-198, January 1977.

D. Lanning, L. Clark, Jr., J. Gosnell, G. Allen, Jr., "MIT Reactor Modification", Trans. Am. Nucl. Soc., November 1976.

R.J. Chin, "DEPLESYN: A Three-Dimensional Discontinuous Synthesis, Diffusion-Depletion Code", Ph.D. thesis, MIT, Department of Nuclear Engineering, 1977.

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

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

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, an introductory subject to nuclear physics and neutron physics with emphasis on those aspects of the subject which are applied in nuclear engineering. Elementary results of quantum theory and special relativity. Detection of atomic and nuclear particles. Properties of atomic nuclei: isotopes and isotopic masses; nuclear reactions; natural and artificially induced radioactivity; cross sections for nuclear reactions; alpha-, beta- and gamma-decay. Nuclear models; shell-model; liquid-drop model. Nuclear fission: properties of fission and their relation to the feasibility of nuclear power and to its problems. Slowing down and diffusion of neutrons. Neutron induced chain reactions. Thermonuclear reactions and the possibility of energy from nuclear fusion.

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 M.I.T. 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-Müller 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 basic 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, multichannel 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 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, principles of radiation production and interactions. Radiation dosimetry with emphasis on applications and health hazards. Shielding of beta, gamma, and neutron radiation from isotope and machine sources. Detection and spectroscopy of beta, gamma, and neutron radiation. Neutron activation analysis. Production of radioisotopes and radiopharmaceuticals. Principles of nuclear medicine.

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

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-Feshbach 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 Angstrom).

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 2000 atmospheres. The density dependence of the self-diffusion coefficient was studied through the observed quasielastic line width, and the data confirmed the recent prediction (based on computer molecular dynamics simulation results) of correlation effects in dense fluids. The wave number dependence of the observed line width clearly showed deviations from behavior 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

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 framework of Born-von Karman theory. A number of less ambitious computer codes have been used to study individual molecules and single-chain polymers.

Investigators: Professors S.-H. Chen and S. Yip; Dr. C.V. Berney, Mr. D.H. Johnson.

Support: National Science Foundation (cumulative support since 1973, \$540,000)

Related Academic Subjects:

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).

made at Argonne to investigate the process of two-dimensional diffusion on the surface. It is expected that neutron studies will yield valuable information on the relation between the macroscopic properties of adsorbed phases and the molecular interactions of surfaces.

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

Investigators: Professors S.-H. Chen, S. Yip.

Support: U.S. Energy Research and Development Administration (cumulative since February 1969, \$815,684; new proposal pending).

Related Academic Subjects:

22.51 Radiation Interactions and Applications

Recent References:

S.-H. Chen, T.A. Postal and K. Skold, "Study of Self-Diffusion in Dense Hydrogen Gas by Quasielastic Incoherent Neutron Scattering", Phys. Rev. 16A, 2112 (1977).

J.C. Castresana, G.F. Mazenko and S. Yip, "Thermal Fluctuations in a Mixture of Hard Spheres", Phys. Rev. 14A, 1814 (1976)

J.C. Castresana, G.F. Mazenko and S. Yip, "Thermal Fluctuations in Gas Mixtures", Ann. Phys. 103, 1 (1977).

J. Rouch, C.C. Lai and S.-H. Chen, "Brillouin Scattering Studies of Normal and Supercooled Water", J. Chem. Phys. 65, 4016 (1976).

J. Rouch, C.C. Lai and S.-H. Chen, "High Frequency Sound Velocity and Sound Absorption in Supercooled Water and the Thermodynamic Singularity at 228°K", J. Chem. Phys. 66, 5031 (1977).

S.-H. Chen, C.C. Lai and J. Rouch, "Hypersonic Sound Velocities in Aqueous Salt Solutions", J. Chem. Phys. 67, 5080 (1977).

3.6.3 Neutron Molecular Spectroscopy

The primary purpose of this program is to apply the technique of incoherent inelastic neutron scattering to

C.V. Berney and A.D. Cormier, "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, 1977, Vol. I, pp. 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)

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, 1978.

3.6.4 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 fluctuations 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:

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

P.M. Furtado, G.F. Mazenko and S. Yip, "Effects of Correlated Collisions on Atomic Diffusion in a Hard-Sphere Fluid", Phys. Rev. A14, 869 (1976).

G.F. Mazenko and S. Yip, "Renormalized Kinetic Theory of Dense Fluids", a chapter in Modern Theoretical Chemistry: Statistical Mechanics, Part B, B.J. Berne, ed. (Plenum Press, New York, 1977), p. 181.

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, p. 81.

3.6.5 Computer Molecular Dynamics Studies

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

A 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.

Another objective of the project is to study problems involving chemical reactions. A simulation program for hard spheres is being used to investigate nonlinear behavior of model systems where molecules can convert from one species to another by prescribed reactions. Calculations are in progress to elucidate the nature of thermal instability in a system where molecules can react upon sufficiently energetic collisions and release internal energy.

Investigators: Professor S. Yip; Messrs. T. Kwok and D. Chou.

Support: Army Research Office - Durham (continuing support since July 1974, current contract period extends to December 1980 at an annual level of about \$55,000)

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 Proceedings of Symposium on Nonlinear (Soliton) Structures and Dynamics in Condensed Matter, Oxford, England, June 27-29, 1978 (to be published by Springer-Verlag).

3.6.6 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 spectroscopy" is a completely digital technique in the time domain whereby the intensity correlation function of the scattered light $\langle I(t) I(t+\tau) \rangle$ can be simultaneously measured at 256 values of the delay time τ by using a delay coincidence method. The accessible range for τ in this instrument is from 1 sec to 1 μ sec 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. M. Holz

Support: National Institutes of Health, Energy Research and Development Administration, Sloan Fund, National Science Foundation (proposal under review).

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).

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, Biological and Medical Applications of Radiation and Radioisotopes II, includes advanced topics and may be taken after 22.55J or separately. Radiation biology including radiation chemistry and cellular and mammalian radiation effects. Stable and radioactive isotope tracer applications. Principles of radiological imaging including computerized tomography and ionography. Advanced topics in nuclear medicine including transverse section and positron imaging. A high level experimental laboratory is an integral part of this course. Experiments include nuclear spectroscopy, γ - γ coincidence methods, neutron activation analysis with off-line analysis, and mixed field dosimetry of the MITR-II therapy beam.

This summer a successful one-week special program was offered by Professor Gordon Brownell, Dr. Brian Murray, and Mr. R.E. Zimmerman, Department of Radiology, Harvard Medical School entitled Transverse Section Imaging in Radiology (TCT) and Nuclear Medicine (EZT), (22.85s) which covered those fields required for an understanding of computerized axial tomography.

3.7.2 In Vivo Neutron Activation Analysis

Using the refurbished pulsable Cockcroft-Walton neutron generator, Dr. R.G. Zamenhof conducted a thorough study of prompt gamma-ray activation analysis using tissue-like phantom targets for the pulsed 14 MeV neutrons. The experimental portion of this study was correlated to a time-dependent calculation using ANDY, an advanced Monto-Carlo transport code and a 42 group neutron-gamma ray coupled cross section data file from the Los Alamos Scientific Laboratory. The experiment and calculations correlate well.

We have also designed an in vivo total body activation system to quantitate nitrogen in cancer patients as part of their therapy and management. The prompt gamma ray studies noted above were instrumental in planning our proposal to the NIH. At the moment, the funding for such a grant application is unclear. Professor Vernon Young, Department of Nutrition and Food Science, is acting as principal investigator for this interdisciplinary program.

Investigators: Dr. B.W. Murray, Professor G.L. Brownell, Ms. K. Kearfott.

Support: National Institutes of Health.

Related Subjects:

- 22.111 Nuclear Physics for Engineers I
- 22.112 Nuclear Physics for Engineers II
- 22.29 Nuclear Measurements Laboratory
- 22.55J Biological and Medical Applications of Radiation and Radiosotopes I
- 22.56J Biological and Medical Applications of Radiation and Radiosotopes II

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).

B.W. Murray, K.A. Klein, M.A. Campbell, and R.D. Hunt, "Total Body in vivo Neutron Activation Analysis of Rhesus Monkeys with Induced Bone Disease", in Proc. Second. E. Kilbride, Conf. Prog. Prob. of in vivo Neutron Activation Analysis, Glasgow, Scotland (1976).

R.I. Pettigrew, O.L. Deutsch, and B.W. Murray, " ^{252}Cf Partial Body in vivo Neutron Activation Analysis", ibid.

R.G. Zamenhof and B.W. Murray, "The Measurement of Whole Body Elemental Composition by Radiative Capture in vivo Neutron Activation Analysis", ibid.

3.7.3 Boron Neutron Capture Therapy -- Preclinical Studies

During the past two years, preclinical studies of BNCT have progressed in several areas. The new MITR-II Medical Therapy Facility now provides an optimized beam essentially free of fast neutron contamination, and with a minimum of incident gamma rays. A small number of animal irradiation studies has shown that this therapy modality has far less risk for producing radio necrosis than has X-ray therapy at the same dose level. We have written a significant renewal proposal seeking funds to conduct a large scale animal therapy and irradiation study as an essential part of a preclinical evaluation plan.

Investigators: Dr. B.W. Murray, Professor G.L. Brownell, Messrs. M. Lussier, J. Pasztor, Dr. James Murphy and Dr. M. Shalev (Division of Laboratory Animal Medicine, MIT).

Support: National Institutes of Health

Related Academic Subjects:

- 22.111 Nuclear Physics for Engineers I
- 22.112 Nuclear Physics for Engineers II
- 22.55J Biological and Medical Applications of Radiation and Radioisotopes I
- 22.56J Biological and Medical Applications of Radiation and Radioisotopes II

Recent References:

R.I. Pettigrew, "The Development and Evaluation of ^{252}Cf Neutron Irradiation Facilities for Two Biomedical Applications Using Discrete Ordinates, Monte Carlo, and Experimental Methods", Ph.D. thesis, MIT, Nuclear Engineering Department (1977).

B.W. Murray, O.L. Deutsch, and G.L. Brownell, "The MITR-II Medical Therapy Facility", in Proc. 3rd. Symp. Neutron Dosimetry in Biol. Med., Munich, Germany (1977).

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 Thrombus Detection Studies

A multiwire proportional detector imaging system has been designed, constructed, and tested for monitoring forming thrombi (clots) in legs of surgical patients, after being administered ^{125}I labeled fibrinogen. Mr. Joel Lazewatsky is the student responsible for much of the technical effort. This is a one-of-a-kind prototype instrument, now being clinically evaluated on patients at the Massachusetts General Hospital, in collaboration with Dr. W. Harris.

Investigators: Mr. J.L. Lazewatsky, Drs. B.W. Murray, Dr. W. Harris (MGH).

Funding: Health Sciences Fund (MIT).

Related Academic Subjects:

- 22.29 Nuclear Measurements Laboratory
- 22.55J Biological and Medical Applications of Radiation and Radiosotopes I
- 22.56J Biological and Medical Applications of Radiation and Radioisotopes II

3.7.5 Collaborative Projects with MGH

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 the heart, lung and brain.

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.

Computers in Nuclear Medicine: A joint project in conjunction 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; Drs. B. Murray, D. Hnatowich; Mr. D. Laning.

Support: National Institutes of Health, Department of Energy

Related Academic Subjects:

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

Recent References:

D.J. Hnatowich, S. Kuprathipanja and S. Treves, "An Improved ^{191}Os - $^{191\text{m}}\text{Ir}$ Generator for Radionuclide Angiocardiology" Radiology, 123, 189 (1977)

D. J. Hnatowich, S. Kulprathipanja, D.R. Elmaleh and G. Evans, "A Comparison of Positron Emitting Blood Pool Agents. J. Nucl. Med. (1977).

S. Kulprathipanja, D.J. Hnatowich and G.L. Brownell, "A Novel Method for Removing Aluminum from Spallation-Produced $^{82}\text{-Sr}$," J. Radioanal. Chem. (1977).

S. Kulprathipanja, D.J. Hnatowich and G. Evans, "The Effect of pH on the In Vitro and In Vivo Behavior of Complex-Free ^{68}Ga and $^{113\text{m}}\text{In}$," Int. J. Nucl. Med. and Bio. (1977)

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.

3.8.1 Subjects of Instruction

22.571J, General Thermodynamics I -- Presentation of 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 -- continuation of 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 -- 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 areas of energy policy, environmental effects, national security, studies of the overall health of the nuclear industry, power plant siting policies, critiques of regulatory procedures, and so forth.

During the past year, these activities have grown substantially.

3.9.1 Subjects of Instruction

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

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

22.38, 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 discussed.

22.80, National Socio-Technological Problems and Responses, A subject designed to acquaint the student with large socio-technological problems and our capabilities regarding them, in ways beyond discipline oriented research. The structure and

content of national problems; connectivity between problems and sectors. Review of present organizations at the working level (universities, national laboratories, industrial laboratories, etc.) the extent to which they relate to the decision-making levels, and the extent to which they match or mismatch their programs to the true scale of problems. Recent efforts to make new organizations or to re-orient present ones. Recent debates, programs, and proposals related to energy and the environment used as particular examples.

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

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

22.913, Graduate Seminar in Energy Assessment, Primarily designed as a communication medium among students conducting research in energy related areas, and as a means for obtaining critical evaluation of their 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

The largest activity of this sort is a study of 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 jeopardizing 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 identified in detail and are being studied for DOE.

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

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
- 22.81 Energy Assessment
- 22.85J Introduction to Technology and Law

Recent Publications:

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).

3.9.3 Nuclear Power, Nuclear Weapons and Internationally Stable Societies

The topic has produced major results in the past year, and our writings have contributed to a sharp international debate about the future of nuclear power, and about what the consequences of various United States attitudes toward energy use, and nuclear power in particular are likely to be. Our own general conclusions are that the present U.S. policy with respect to nuclear power, taken as a whole and if continued, is liable to cause the domestic industry to wither away. Unless the U.S. simultaneously reduces its oil imports substantially, the U.S. international position in the nuclear field, in the energy field, and as an international leader in the search for a more just and sustainable world society, will suffer badly. Our conclusions have received considerable international notice and commendation.

Support: MIT General.

Recent References: D.J. Rose "*Energie für eine gerechte und zukunftsichere Welt*" (Energy for a Just and Sustainable World), in *Probleme der Kernenergie: Chancen, Risiken und Perspektiven in einer sich wandelnden Energiewirtschaft*, Verlag Neue Gesellschaft, Bonn (1977).

D.J. Rose and R.K. Lester, "Nuclear Power, Nuclear Weapons and International Stability," Scientific American, 238, 45-57 (April 1978).

D.J. Rose, "Is there a Role for Fusion?" Proc. International Scientific Forum on Acceptable Nuclear Energy Future of the World, U. of Miami, Coral Gables, Florida (November 1977).

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) Nonproliferation Alternative Systems Assessment Program (NASAP) and the United State contribution to the International Nuclear Fuel Cycle Evaluation (INFCE). During the past year work has been performed in the following areas:

1. Development of a decision theory methodology for assessing the proliferation vulnerabilities of alternative nuclear fuel cycles.
2. The technical alternatives and constraints involved in international management of spent fuel.
3. The proliferation implications of the denatured thorium cycle.

Work to be performed during the coming year includes the following:

1. Country capabilities, incentives and disincentives for indigenous development of uranium enrichment and heavy water production facilities.
2. Proliferation resistance in a constrained nuclear power environment.

Investigators: Professors M. Benedict, E. Gyftopolous, N. C. Rasmussen, D. Rose; Drs. I. Papazoglou, C. Heising, M. Miller (Energy Laboratory), Professor G. Rathjens (Political Science), and Mr. R. Lester.

Support: U.S. Department of Energy contract through MIT Energy Laboratory (\$224,970).

Related Academic Subjects:

- 22.003J In Pursuit of Arms Control
- 22.38 Reliability Analysis Methods

Recent References:

M.M. Miller, "International Management of Spent Fuel Storage: Technical Alternatives and Constraints", MIT Energy Lab report MIT-EL- 78-012 (June 1978)

I. Papazoglou, E. Gyftopoulos, M. Miller, N. Rasmussen and H. Raiffa, "A Methodology for the Assessment of the Proliferation Resistance of Nuclear Power Systems", MIT Energy Laboratory Report Nos. MIT-El 78-021 and 78-022, 1978.

3.9.5 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 non-transportation energy demand for large (50,000 population) military installations are examined. In that demand schedules and energy consumer groups in such installations are quite similar to those encountered in the civilian sector, the results and analytical methods of this work are generally applicable to a broad range of situations.

The most recent and most important product of this work is an analysis of the optimal total energy system (TES) for Ft. 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 power system, and thermal power in a high temperature water (HTW) thermal utility system. For each power station type the optimal (minimum TES cost-over-life) configuration is obtained by varying the thermal to electrical utility system load capacity. For each utility system configuration a year-long operational numerical simulation of consumer power demands, and of the dynamic response of the TES (including a large HTW storage reservoir-in meeting these demands) is performed using a computer program (named TDIST), which was developed in this project for that purpose. This simulation provides estimates of the required power station thermal and electrical capacities, HTW storage reservoir capacity, annual fuel consumption, and TES capital costs.

In the Ft. Knox analysis (and previously in a 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.

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

L.R. Metcalfe and M.W. Golay, "Final Report: Storage of Off-Peak Nuclear Power Through Hydrogen Generation," FESA-RT-2005, 1975.

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

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S.B. Goldman, F.R. Best, and M.W. Golay, "Energy Production by Solid Waste Incineration," FESA-RT-2022, 1977.

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," Submitted to Energy, 1978.

3.9.6 Analysis of the MIT Total Energy System

An effort directed toward better definition of energy conservation possibilities for the Institute through cogeneration has been completed recently. In this work, the feasibility of cogeneration using either steam, gas turbine, or deisel-powered systems was examined. The deisel system was found to have the most favorable economic position with a seven-year payback period. However uncertainties regarding future environmental protection requirements, fuel prices, utility rate schedules, and costs of backup service are sufficiently great that the prospects for cogeneration at MIT remain poor.

Investigators: Professor M.W. Golay, Mr. G. Was.

Support: MIT Physical Plant

Related Academic Subjects:

- 22.312 Engineering for Nuclear Reactors
- 22.313 Advanced Engineering of Nuclear Reactors
- 22.34 Economics of Nuclear Power
- 22.37 Environmental Impact of Power Production

Recent References:

G.S. Was and M.W. Golay, Economic Feasibility Study of Total Energy System Options for the Massachusetts Institute of Technology, MIT Department of Nuclear Engineering, MITNE-218, 1978.

G.S. Was and M.W. Golay, "Cogeneration--An Energy Alternative for the United States?", Submitted to Science, 1978.

3.9.7 Buoyant Atmospheric Plume Modeling

Over the past two years an effort concerned with numerical simulation 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 viscous energy dissipation rate data; and it provides a three-dimensional prediction of plume velocities, temperatures, pollutant concentration, moisture, and turbulence fields. In doing this it uses 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: Professor M.W. Golay, Mr. Ralph Bennett.

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

3.9.8 Waste Heat Disposal

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

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

A) Cooling Tower Drift Propagation and Effluent Reduction

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

1) Drift Eliminator Performance

An experimental and analytical effort has recently been completed which permits improved drift eliminator design to be

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

2) Droplet Captive

In new work an experimental investigation of the dynamics of droplet impacts upon water films is being conducted, with analytical models to be developed based upon the resulting empirical data. In this work small droplets will be projected towards a horizontal water surface. The resulting effects (capture, splashing, or reflection) are recorded photographically, and the data regarding velocity, droplet size, and rate are used in formulation of a droplet capture model to be used in drift elimination analysis. This work is also applicable to problems of droplet capture in sulfur scrubbers, steam generators, and other liquid processing apparatus.

3) Drift Measurement

In new work the Drift Elimination Wind Tunnel will be used in testing alternative drift elimination methods. Each method will be used to measure drift in a spectrum of cases, and this performance will be compared to that of a laboratory standard method. This will permit a ranking to be made of the competing methods, with the goal being identification of a standard method to be used in field measurements.

B) Economics and Technical Innovations

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

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

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

Investigators: Professor M.W. Golay; Messrs. J. Chan, E.C. Guyer, T. Johnson, and Ms. E. Ward.

Support: MIT Energy Laboratory (\$30,000/year). EPRI (\$100,000/year), ERDA (\$31,000/year).

Related Academic Subjects:

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

Recent References:

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

J. Chan and M.W. Golay, "Numerical Simulation of Cooling Tower Drift Eliminator Performance," Numerical/Laboratory Computer Methods in Fluid Mechanics, Symp. Proc., A.A. Pouring, ed., Amer. Soc. Mech. Engrs., 229 (1976).

E.C. Guyer and M.W. Golay, "An Engineering and Economic Evaluation of Some Mixed-Mode Waste Heat Rejection Systems," MITNE-191, ERDA-EPRI (1976).

E.C. Guyer and M.W. Golay, "Mathematical Models for Predicting the Thermal Performance of Closed-Cycle Waste Heat Dissipation Systems," MITNE-192, ERDA-EPRI (1976).

J. Chan and M.W. Golay, "Comparative Performance Evaluation of Current Design Evaporative Cooling Tower Drift Eliminators," Atmospheric Environment, 11,775 (1977).

E.C. Guyer and M.W. Golay, "Evaluation of Combined Thermal Storage Pond/Dry Cooling Tower Waste Heat Disposal Systems," 77-HT-57, Nat. Heat Transfer Conf. (1977). Submitted to J. Engineering for Power.

E.C. Guyer and M.W. Golay, "Investigation of the Fluid Mechanical Behavior of a Thermal Storage Reservoir for Dry Cooled Central Power Stations," Waste Heat Management and Utilization S.S. Lee, ed. 7-C-209, U. of Miami (1977). Submitted to J. Fluids Engineering.

J.K. Chan and M.W. Golay, "Design Study of Cooling Tower Drift Eliminators," Trans. Amer. Nucl. Soc., 26, 113 (1977).

J.K. Chan and M.W. Golay, "Comparative Evaluation of Cooling Tower Drift Eliminator Performance," MIT Energy Lab. Report, MIT-EL 77-004 (1977).

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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 reactor fueling experiment funded by the Oak Ridge National Laboratory. 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 this effort have been singled out for further research.

The most noteworthy single project carried out in the last year was the demonstration that the force-reduced torsatron configuration offered substantial potential benefits as the basis for a fullscale 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 and substantial OFE funding has been secured for continuation of torsatron reactor design studies.

The T-1 Reference Design Project has had substantial impact on the National Fusion Program and inspired the PFC proposal for construction of TOREX-4, a major new experiment to be carried out with the Plasma Fusion Center. An intensive \$215,000 for a 5 month design study funded by OFE is in progress. The design will be reviewed and a decision made to the funding of TOREX-4 in November and December of 1978. TOREX-4, described in more detail below, would be the largest fusion related project ever carried out at MIT and would play a substantial role in the development of the Plasma Fusion Center as well as the direction, size, and staffing requirements of the Nuclear Engineering Department's Controlled Fusion Group.

3.10.1 Subjects of Instruction

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

22.069, Undergraduate Plasma Laboratory, is the basic engineering and scientific principles associated with experimental plasma physics. 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, which introduces the fusion processes and potential for energy production. Physical processes in ionized gases and discussion of the natural occurrence of plasmas in the universe. Basic concepts of plasma physics and introduction to the elementary electro-magnetic theory needed to describe plasma behavior. Elementary theory of plasma stability and transport.

22.610, Controlled Fusion Power, Survey of energy for the future, including resources, demand and cost, with emphasis on the 21st century. Introduction to controlled fusion concepts: fusion reactions, basic methods of producing and confining fusion plasmas; extraction of energy and regeneration of fuel. Introduction to technologies related to controlled fusion power: large magnetic field structures, lasers, heat transfer, materials. Description and critique of proposed fusion reactor schemes. The outlook for controlled fusion power, in the post-AD 2000 period. This course will include appropriate reviews of 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, Introduction to plasma phenomena, the occurrence and generation of plasmas with applications to thermonuclear fusion, gas lasers and astrophysics. Motion of charged particles in electric and magnetic fields; drifts; adiabatic invariants. Plasma models: kinetic equations, MHD and fluid approximations. Wave propagation in cold and warm plasmas; Landau damping. Simple equilibrium and stability analysis. Introduction to collisions and transport processes.

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

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

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

22.63, Engineering Principles for Fusion Reactors, Introductory course in engineering principles and practices of systems relevant to controlled fusion. Mechanism and technique for plasma production. Vacuum engineering based on considerations of free molecular flow, surface physics and standard design practices. Magnetic field generation by normal, cryogenic and superconducting coils: electrical, heat transfer and structural requirements. High voltage engineering and practices. Methods of plasma heating: ion, electron and neutral beam production, microwave and laser systems. Applications to fusion systems.

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

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

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

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

22.68J, Introduction to Plasma Kinetic Theory, 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 Applied Plasma Physics Experimental Program

The Plasma Physics and Controlled Fusion Group maintains a continuing program of experiment research and development in several areas supportive of the Controlled Fusion effort. This work is directed along two major lines, diagnostic and highly ionized plasma experiments. We are engaged in the development of diagnostic techniques for measurement of plasma parameters in large scale research devices, both those presently in operation (e.g., Alcator) and larger proposed facilities. New diagnostic techniques are needed because fusion research devices are approaching new regimes of plasma density and temperature in which many of the methods presently in use are no longer applicable. Furthermore, more detailed and accurate measurements are needed for comparison with new theoretical models of "reactor grade" plasmas. Fortunately, the energy density in these devices is high enough to facilitate new measurement techniques.

The second major area of experimental research involved the testing, in laboratory scale experiments, of the predictions of theories of plasma behavior. These tests are needed both to verify the theories which are being used in the design of large scale devices, and to provide information which will lead to further development of the plasma theoretical models.

A) Diagnostic and Confinement Studies on ALCATOR

The Nuclear Engineering Department now has a substantial tie with the ALCATOR program through Professor Louis S. Scaturro. Several diagnostic projects are underway regarding the interaction of plasma with the containment wall and limiter in a Tokamak confinement system. These projects include:

- 1) bolometric studies of plasma energy loss to the walls;
- 2) plasma energy conduction losses to the limiter; and
- 3) measurements of plasma edge conditions and particle diffusion times with a Langmuir probe. A more detailed description of these projects follows.

1) Bolometric Studies of the Plasma Energy Loss to the Walls

During a typical discharge in ALCATOR the ohmic power input is approximately 400-500 kilowatts during the time when the contained plasma energy is constant. This input power must either impinge on the wall of the Tokamak or be conducted directly to the limiter. A bolometric system has been installed on the ALCATOR system to measure the

temporarily and spatially resolved energy flux to the wall. This loss comes in the form of neutral particles and electromagnetic radiation. Data to date indicates that only 25-35% of the ohmic input power appears on the walls during a typical high density discharge. The insertion of thin metal foils in front of the bolometers will determine the fraction of this energy that is carried by particles as opposed to the energy leaving in the form of radiation. This work will be reported at the 1978 APS Plasma Physics Division Meeting in November 1978, and in a forthcoming publication in Nuclear Fusion.

2) Conduction Losses to the Limiter

Since only 25-35% of the ohmic input power can be accounted for in losses to the walls, an accurate measurement of the energy loss to the limiter is necessary to complete an overall power balance measurement. A simple optical system and new limiter configuration for ALCATOR have been designed that will allow a quantitative measurement of plasma energy conduction losses. This diagnostic tool is under construction and will be implemented before the end of 1978.

3) Plasma Edge Conditions

A Langmuir probe has been used to measure the ion density and electron temperature at plasma edge. This region, the so called magnetic shadow of the limiter, is an important one to understand from a standpoint of reactor fueling by neutral gas blankets. The measurement of these edge conditions has shown that the edge particle diffusion coefficient is a turbulent one.

In addition to these diagnostic programs, there are several other areas relating to confinement studies where the Department plays an active role. Following is an outline of these areas.

I. High-Energy Diagnostic Neutral Beam

TRW systems has submitted a proposal to the National Magnet Laboratory and the ALCATOR project for the construction of a 200 KeV, 1mA, 1mA/cm² diagnostic neutral beam that can create a tritium, deuterium or hydrogen beam. This project would be funded by DOE through the ALCATOR project. Professor Louis S. Scaturro is involved in coordinating ALCATOR'S effort involving utilization of this beam. These projects include:

1. The temporarily and spatially resolved measurement of plasma ion temperature by Doppler shift. The ALCATOR project would purchase a high-resolution, high dispersion

spectrometer that would be used to measure the Doppler width of the Lyman- α line at 1215\AA . The neutral beam is used to modulate and enhance the source of these neutrals at the center of the plasma so a measurement of the ion temperature profile is possible.

2. The use of tritium in the beam produces high fluxes of 14 MeV D-T fusion neutrons and 3.5 MeV α -particles. A collimated neutron detector system will be built that monitors the production of these neutrons with good spatial resolution. This allows a measurement of the slowing-down rate of fast tritons in the plasma and tritium diffusion processes. In addition the tritium beam will produce enough neutron energy out such that $Q=1$. That is, Q , the ratio of beam power into the Tokamak to fusion power out will be unity. This represents a significant scientific milestone in the Tokamak program.

3. Numerous other experiments are possible with this high energy beam including measurements of Q profiles in the plasma and beam attenuation measurements to determine the ion density profiles.

II. Pellet Fueling

The Alcator project in planning an experiment in conjunction with the University of Illinois that involves injection of deuterium ice pellets into the plasma for the purpose of refueling the lost plasma particles. ALCATOR plasmas provide a unique combination of density and temperature that would allow the scaling pellet-fueling schemes to reactor regimes. Professor Scaturro is involved in the interface of this project with the ALCATOR system.

The ALCATOR project is currently supporting four Nuclear Engineering graduate students on either a full time or part time basis.

B) Wave Particle Interaction Experiments

The study of nonlinear interactions between electromagnetic waves and plasmas is a major area of current plasma physics research. It is important both to further our understanding of the fundamental plasma processes, and in application to the improvement of confinement and plasma heating in fusion devices. We have developed a unique experimental facility for the study of non-linear phenomena. This device confines a dilute electron plasma whose initial state

is very well known. We can apply to this plasma a controlled spectrum of electric field fluctuations and directly observe the evolution of the electron velocity distribution in time. This allows us to make direct comparisons between the various theoretical models which have been developed to describe turbulence in plasmas and the experimental observations.

This device has recently been modified to permit us to measure the electron velocity distribution in two dimensions, rather than one. We plan a number of experiments to attempt to observe the phase space granulation that is predicted, particularly in Professor Thomas Dupree's models of strong turbulence. In the presence of turbulent fields, the particle velocity distribution should go from the monotonic smooth function of energy characteristic of the equilibrium state to a function which shows a great deal of structure. This state should persist long after the driving turbulence is removed, and is predicted to have important observable consequences. Such behavior has been observed in computer simulations of plasmas and we hope to identify this phenomenon in an experimental plasma. Another experiment we are undertaking with this device is a test of the prediction that, due to non-linear effects, a sufficiently strong, monochromatic wave will produce stochastic behavior in the orbits of individual particles. If confirmed, this has significant implications for possible plasma heating methods.

Investigators: Professors L.S. Scaturro, P.P. Politzer, L.M. Lidsky.

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

3.10.3 Fusion Reactor Technology

The demonstration of the scientific feasibility of controlled fusion power--a milestone that might possibly be reached within ten years--is not sufficient to ensure that fusion will become ultimately a significant contributor to our energy requirements. The development of controlled thermonuclear reactors for commercial power generation will require also the solution of many extraordinarily difficult technological problems. Many of these problems are similar to, but more difficult than, those associated with fission reactor technology. Thus, the Nuclear Engineering Department with its unique combination of skills and fission reactor expertise, is the ideal locus for a balanced attack for these problems.

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 as 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-B 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-II. Volatile oxidation of the first wall during a lithium fire appears to be a primary means of disrupting induced activity, and the molybdenum alloy. TZM (UWMAK-III) tends to be more susceptible than 316 stainless steel (UWMAK-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 spilled 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 subatmospheric 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 maximum flame temperature resulting from lithium fire indicate that none of the radioactive first wall materials under consideration would vaporize, and only a few could possibly melt.

Investigators: Professors M.S. Kazimi, L.M. Lidsky, N.C. Rasmussen, Messrs. D.A. Dube, R.W. Sawdye, J. Sefcik, R. Green.

Support: Department of Energy (approximately \$60,000/year).

Related Academic Subjects:

22.38 Reliability Analysis Methods
22.621 Thermonuclear Reactor Design

Recent Publications:

R. Sawdye, J. Sefcik, and M.S. Kazimi, "Reliability Requirements for Admissible Radiological Hazards from Fusion Reactors", Trans. Am. Nucl. Soc., 27, pp 65-66, November 1977.

M.S. Kazimi et al., "Aspects of Environmental and Safety Analysis of Fusion Reactors", MIT Report MITNE-212, Department of Nuclear Engineering, October 1977.

D.A. Dube, M.S. Kazimi, and L.M. Lidsky, "Thermal Response of Fusion Reactor Containment to Lithium Fire", Paper presented at Third Top. Meeting on Fusion Reactor Technology, Sante Fe, New Mexico, May 1978.

R.W. Sawdye and M.S. Kazimi, "Application of Probabilistic Consequence Analysis to the Assessment of Potential Radiological Hazards of Fusion Reactors", MIT Report MITNE-220, Department of Nuclear Engineering, July 1978.

D.A. Dube and M.S. Kazimi, "Analysis of Design Strategies for Mitigating the Consequences of Lithium Fire Within Containment of Controlled Thermonuclear Reactors", MIT Report MITNE-219, Department of Nuclear Engineering, July 1978.

C) Fusion Reactor Blanket Design

Previous work in the area was on the Breeder Rod Shim Rod solid breeder reactor concept. It was found that adequate breeding could not be demonstrated with lithium aluminate as the breeding material. A design methodology however was established that appears useful and applicable to other concepts. It consists of first establishing a desired set of parameters and constraints and then finding the allowable range, or design window, for the remaining free variables.

It was decided to next investigate the performance of stagnant lithium blankets with heat removal by distributed tubes. The objective was to determine the functional relations between the major parameters and constraints and the associated heat removal capacities. Two parallel investigations were made, one for the conducting coolant lithium, and the other for the non-conducting coolants helium and flibe. The first wall and interior blanket regions were studied separately because of the very different requirements for each region.

For the interior blanket region, procedures have been found for establishing a design window in terms of coolant tube diameter and length and first wall neutron loading for all coolants considered. In the analysis two types of coolant tube distributions were examined. The first assumed the tubes to be distributed such that each removed the same amount of heat with the coolant tube density proportional to the volumetric energy generation rate. A new distribution was also proposed in which parallel banks of tubes forming walls were located at only a few radial positions. The main advantage of this arrangement is that flow blockages in individual tubes could be easily tolerated without exceeding structural temperature limits. For the lithium coolant a radial header system was employed with the primary heat removal by tubes running in the toroidal direction. With this system MHD pressure drops were found to be tolerable at the expected magnetic field strengths. For helium and flibe coolants functional relations were also found and typical design windows calculated. These

methodologies developed should be very useful in parametric reactor studies for estimating blanket requirements.

In addition to the thermal hydraulic analysis a full neutronic capability for calculating breeding, heating, and radiation damage rates through the use of ANSIN has been established. The capability was used to investigate the effect of spatially non-uniform structural material distribution on tritium breeding. The effect compared to a uniform distribution was found to be generally small for the required coolant tube distribution.

The current emphasis is on first wall design. Tubular walls have been examined to date and analytic expressions for the temperature field and thermal stresses found for both clad and unclad tubes. It was shown that copper cladding can significantly reduce the peak stress for a 316 stainless steel radiation shield tube. Another concept under development is a relatively thick first wall to serve as a protective "armor" with coolant tubes welded or brazed to the rear surface. To reduce the stresses grooves would be cut or forged in a checkerboard pattern most of the way through the block.

Investigators: Professor N.E. Todreas, B. Mikic, P. Griffith; Messrs. J. Chao, F. Chen, T. McManamy, G. Was.

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

Recent References:

F. Chen, et al. "A Solid Breeder TOKAMAK Blanket Designed for Failure Mode Operations", MITNE-213, Department of Nuclear Engineering, 1977.

J. Chao, et al. "A Parametric Study of A Lithium Cooled TOKAMAK Blanket", Nuclear Technology Accepted, August 24, 1978.

J. Chao, et al. "Neutronic Performance of Fusion Reactor Blankets with Different Coolants and Structural Arrangements", submitted for publication in Nuclear Technology, August 1978.

F. Chen, et al. "A Thermal Hydraulic Study and Failure Analysis of The Breeder Rod Shim Rod Solid Blanket Design (BRSR)", Second Top. Meeting on Fusion Technology, Richland, Washington, April 1976.

T. McManamy et al. "Helium or Molten Salt Cooling of a Static Lithium Blanket with Distributed Tubes", Submitted for publication in Nuclear Technology, October 1978.

T. McManamy et al. "Thermal Stress Reduction for 316 Stainless Steel Coolant Tubes in a Fusion Reactor First Wall", submitted for publication in Nuclear Engineering and Design, October 1978.

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 compatible 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 $\bar{n}\tau_e = 3 \times 10^{20}$ 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 access 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, and 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/m²

and "Alcator Empirical Scaling" the optimized choices for this reactor are $\ell = 3$, $a_c = 4.0\text{m}$, and $p = 27.5\text{m}$. 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 sufficiently 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 multidisciplinary projects furnish an excellent medium for motivating 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.P. Politzer, M. Kazimi, N.E. Todreas, B. Mikic; Dr. D.B. Montgomery.

Support: Department of Energy, EPRI.

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: Professors T.H. Dupree, Drs. D.J. Tetreault, R.H. Berman, Messrs. T. Boutros-Ghali, and P. Diamond.

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

Related Academic Subjects:

22.64J Plasma Kinetic Theory
 22.65J Advanced Topics in Plasma Kinetic Theory
 22.68J Introduction to Plasma Kinetic Theory

3.10.5 Torex

We are designing a torsatron confinement experiment, TOREX, to be built at MIT in the Plasma Fusion Center. At present, we are preparing a detailed, formal proposal for the construction of TOREX which will be presented to the Department of Energy in December. TOREX is the logical extension of presently operating stellarator, torsatron and heliotron devices around the world to plasma regimes of interest for fusion reactors. This project is an outgrowth of our design work on the T-1 torsatron reactor, and embodies many of the features which would be found in such a reactor.

The TOREX Project is a collaborative effort involving the Nuclear Engineering Department fusion group and the engineering staff of the National Magnet Laboratory, with assistance from the Grumman Aerospace Corporation. If approved, we expect that construction of this device will take approximately thirty-six months and will cost about \$20M. This project is comparable in scale of effort to the ALCATOR program, and will involve large numbers of MIT staff and students. It will place MIT in the forefront of work on alternative fusion confinement concepts and will complement the MIT efforts in the tokamak program.

The principal purposes of the TOREX experiment are to test the equilibrium and stability limits on plasma β in the three dimensional torsatron configuration, and to extend measurements of the confinement properties of this type of device to the ranges of plasma parameters important for fusion reactors. We anticipate that, on the basis of conservative plasma physics assumptions, TOREX will be able to achieve plasma densities of up to $\bar{n} = 4 \times 10^{20} \text{m}^{-3}$; temperatures in the range $\bar{T} = 650\text{-}2200 \text{ eV}$, and $\bar{\beta} = 2.5 - 8\%$. The energy confinement time should exceed 40 msec.

TOREX, is an $\ell = 4$ Torsatron, with a major radius of 2.06m, and an average plasma minor radius of 0.22m. Both the helical windings and the circular compensation coils are constructed of LN_2 cooled copper. These coils will be driven by the large alternator now being installed for Alcator C. They will provide a magnetic field in excess of 3T, for a flat-top pulse of more than 0.5 sec.

The primary heating system for TOREX will be energetic neutral beams. The neutral beam system will provide 6 MW of beam power at 50 keV. This system is essentially a duplicate of the beam system now being built for the PDX tokamak, and thus will help to reduce the TOREX cost. These beams will likely be supplemented by the shared use of the Alcator C rf heating system.

A primary consideration in the design of TOREX has been to utilize the resources available on the MIT campus to the fullest extent possible. This includes both physical resources, such as the facilities in place or being constructed for use by the ALCATOR project, and personnel. The staffs of the Nuclear Engineering Department, the Plasma Fusion Center, the Bitter National Magnet Laboratory, and the ALCATOR project are being called upon for assistance. The relationship between TOREX and ALCATOR is mutually beneficial. The facilities and expertise of the ALCATOR group will contribute greatly to the development of operation of TOREX. The presence of TOREX will, in turn, provide a strong stimulus for expanded work in toroidal confinement devices. The sharing of physical resources will make both programs more effective and efficient, and interchange of ideas and techniques will be extremely beneficial.

In addition to the involvement of the MIT fusion community in the TOREX project, we have begun discussions with the principal Japanese laboratory working in this field, the Plasma Physics Laboratory of Kyoto University. They are presently building a large torsatron-like device, Heliotron E, which is comparable to TOREX in size, but differs in many important parameters. We have discussed, and hope to implement exchanges of information and personnel as TOREX begins construction and Heliotron E begins operation.

Investigators: Professors P.P. Politzer, L.M. Lidsky; Dr. D.B. Montgomery

4. CURRICULUM

4.1 Degree Programs

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

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

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

The objective of the Nuclear Engineer's program is to educate students for a creative career in the design aspects of nuclear engineering. Minimum requirements are four semesters of full-time graduate instruction, including a substantial thesis concerned with engineering analysis,

engineering design or construction of a nuclear facility or device. Students in this program have sufficient time to learn advanced techniques for engineering analysis and design, and their creative abilities in these areas are developed through participation in engineering projects under faculty supervision.

The objectives of the doctoral program are to provide an advanced education in nuclear engineering and to challenge the student to become a leading and original contributor to her or his professional field. Students in this program are required to pass a searching and difficult general examination and then to complete a major research investigation of sufficient scope and originality to constitute a contribution of permanent value to science and technology. Although no set time is specified for completion of the doctoral program, most students require from three to five years. Students completing the Doctor's program in Nuclear Engineering are prepared and motivated to work on the frontiers of nuclear technology.

4.2 Fields of Study

Although each student's program of study is arranged to suit her/his individual interests and objectives, most programs fall into one of the six fields of study mentioned in the introduction:

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

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

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

All six fields are appropriate for candidates for the Doctor's degree. Doctoral candidates taking the General Examination required for that degree have the option of being examined in any one of these six fields.

4.3 Subjects of Instruction

Subjects of instruction currently offered by the Nuclear Engineering Department are listed below. The subjects are divided into different areas for convenience. The introductory subjects 22.89 Basic Electronics, 22.311 Engineering Principles for Nuclear Engineers, and 22.71 Physical Metallurgy Principles for Engineers, are intended for graduate students who did not have the material as an undergraduate but need the material for graduate work.

Subjects designated "J" are taught jointly with other Departments, e.g. 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
22.003J	In Pursuit of Arms Control
22.005	Dynamics of Physical and Social Systems
22.006	Computer Models of Physical and Engineering Systems I
22.02	Introduction to Applied Nuclear Physics
22.021	Nuclear Reactor Physics
22.03	Engineering 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
22.09	Introductory Nuclear Measurements Laboratory
22.092	Engineering Internship
22.85	Introduction to Technology and Law I
22.916	Management in Engineering

Nuclear Physics

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

Nuclear Reactor Physics

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

- 22.22 Nuclear Reactor Kinetics
 22.29 Nuclear Measurements Laboratory

Nuclear Reactor Engineering

- 22.311 Engineering Principles for Nuclear Engineers
 22.312 Engineering of Nuclear Reactors
 22.313 Advanced Engineering of Nuclear Reactors
 22.314J 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 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 Biological and Medical Applications of Radiation
 and Radioisotopes II

Plasmas and Controlled Fusion

- 22.610 Controlled Fusion Power
 22.611J Introduction to Plasma Physics
 22.612 Plasmas and Controlled Fusion
 22.621 Thermonuclear Reactor Design
 22.622 Special Topics in Thermonuclear Reactor Design
 22.63 Engineering Principles for Fusion Reactors
 22.64J Plasma Kinetic Theory
 22.65J Advanced Topics in Plasma Kinetic Theory
 22.66 Transport Phenomena in Torodial 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
22.901-}	Special Problems in Nuclear Engineering
22.904	
22.911-}	Seminar in Nuclear Engineering
22.912	
22.913-}	Graduate Seminar in Energy Assessment
22.914	
22.915	Seminar in Reactor Safety
22.917	Entrepreneurship
22.92	Advanced Engineering Internship

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
2.06	Vibration and Sound
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
- 3.25J 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
- 3.144J Deformation and Failure of Engineering Alloys in Service

Electrical Engineering and Computer Science

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

Physics

- 8.312 Electromagnetic Theory
- 8.321} Quantum Theory
- 8.322}
- 8.341} Methods of Theoretical Physics
- 8.342}
- 8.511} Theory of Solids
- 8.512}
- 8.641} Physics of High Temperature Plasmas
- 8.642}

Chemical Engineering

- 10.38 Analysis and Simulation of Chemical Processing Systems
- 10.39 Energy Technology
- 10.47 Ion Exchange
- 10.50 Heat and Mass Transfer
- 10.52 Mechanics of Fluids
- 10.56 Chemical Engineering in Medicine
- 10.70 Principles of Combustion
- 10.72 Seminar in Air Pollution Control

10.73 Seminar in Fuel Conversion and Utilization
 10.86 }
 10.87 } School of Chemical Engineering -- Oak Ridge
 10.88 }

Ocean Engineering

13.21 Ship Power and Propulsion
 13.26J Thermal Power Systems

Economics

14.23 Economics of Fuel and Power

Management

15.065 Decision Analysis
 15.081J Introduction to Mathematical Programming
 15.084J Nonlinear Programming and Discrete 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 minicourses 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 1978, the Nuclear Engineering faculty offered 10 activities, and 7 additional activities were arranged by nuclear engineering students. Professor L. Scaturro conducted a "Fusion Open House" to display the controlled fusion and plasma physics facilities of the department, Professor M. Kazimi gave a seminar on "Environmental and Safety Analysis of Fusion Reactors", and Professor D. Lanning organized a seminar entitled, "What Is An Electronuclear Breeder?" Professor I. Kaplan gave a series of talks on the history of nuclear power entitled "The Search for the Nuclear Grail". A seminar entitled "The Future of Nuclear Power", honoring Professor Irvine Kaplan's numerous contributions to the nuclear industry and education was given by Dr. Herbert Kouts of the Brookhaven National Laboratory and by Professor N. Rasmussen. Professor E. Gyftopoulos gave a seminar entitled, "Is Macroscopic Entropy Related to Microscopic Quantum Effects?" and Dr. Charles Berney and Professor S. Yip spoke on "Probing Condensed Matter with Neutrons". Professor O. Deutsch offered a "Workshop on Methods for Linear Particle Transport Calculations" and organized a series of seminars entitled, "Post LOCA Heat Transfer" with Dr. Walter Kirchner from the Los Alamos Scientific Laboratory. Student-sponsored activities were organized by Messieurs Donald Dube, Joseph Sefcik, and Edward Fujita, including a discussion hour entitled, "Energy and Public Attitudes", a "Nuclear and Alternative Energy Film Festival", a seminar on "Modern Computer Codes in the Nuclear Industry", and a number of field trips to the Seabrook Nuclear Power site, the Northfield Pumped Storage Station, and the New England Power Exchange. Professor A. Henry and Professor R. Cartwright of the M.I.T. Philosophy Department offered the traditional afternoon of "Wine, Cheese, and Philosophy".

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 department 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 1977-78 academic year, twenty undergraduates were engaged in projects within the Department.

4.6 Descriptions of New and Revised Subjects

The academic program of the Department has continued to undergo revision and updating. Since the fall of 1977 eleven new subjects have been added to the curriculum. Seven of these (22.006, 22.021, 22.031, 22.033, 33.069, 22.092, 22.916) reflect the continued growth of our undergraduate program.

As described in Section 4.9, two of the new courses 22.092 and 22.92 are a result of the development of the Engineering Internship Program.

Additional courses added to the curriculum are Management in Engineering, Entrepreneurship and Seminar in Reactor Safety.

A. New Subjects

22.021: Nuclear Reactor Physics -- 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. Three lecture hours per week meeting concurrently with 22.211, plus a separate recitation; assignments and quizzes are different from those in 22.211.

22.031: 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 consideration in reactor design. Three lecture hours per week meet concurrently with 22.312, plus a separate recitation. (Primarily for Course XXII undergraduates; others admitted by permission of instructor).

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. Meets concurrently with subject 22.33, but assignments differ.

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. (Work knowledge of FORTRAN expected.)

22.069: Undergraduate Plasma Laboratory -- Basic engineering and scientific principles associated with experimental plasma physics. Investigation of vacuum pumping phenomena and guage operation, normal and superconducting magnetic field coils, microwave interactions with plasmas, laboratory plasma production including electrical breakdown phenomena Langmuir probe characteristics and spectroscopy.

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

22.314J: Structural Mechanics in Nuclear Power Technology -- Structural components in nuclear power plant systems: their functional purposes; mechanical, thermal, and nuclear operating conditions; mechanical-structural design requirements. Mechanics of continuous media are combined with models of material behavior to determine adequacy of component design. Effects which are considered include: mechanical loading, hydraulic forces, elevated temperatures, and neutron irradiation; normal operation, accident situations, and seismic effects. Lectures are given by several members of Institute faculty and by guest lecturers from nuclear power industry.

22.51: Radiation Interactions and Applications -- 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 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.

22.915: Seminar in Reactor Safety -- A survey of general consideration and methodology and safety analysis as applied to commercial and advanced reactor designs. Specific topics selected for review and discussion by the participating students. Invited speakers lecture on the status of current safety research.

22.916: Management in Engineering -- An introduction to the concepts of management of the engineering function, as found in a variety of industrial and non-industrial settings. Aim is to help the student 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. Topics: financial principles; management of innovation; engineering project planning, scheduling and control; human factors; career planning; contracts; patents; and technical strategy for firms. Taught, in part by the case method, which emphasizes student participation in discussion. (Intended for juniors, seniors, or graduate students; others should consult the instructor in charge.)

22.917: Entrepreneurship -- This class is an introduction to the various issues faced by technical innovators who are interested in becoming entrepreneurs. Lectures and discussions are held on concept evaluation, patents, licensing, contract negotiation, marketing, business planning, financing, accounting and small business management. Students are encouraged to use their own innovative ideas as the object of study topics.

22.92: Advanced Engineering Internship -- Provides credit for the third and fourth work assignments for students affiliated with the Engineering Internship Program. Students register for this subject twice. Students must complete both work assignments to receive the academic credit for this subject.

B. Subject with Major Revisions

22.314J: Structural Mechanics in Nuclear Power Technology -- Structural components in nuclear power plant systems: their functional purposes; mechanical, thermal, and nuclear operating conditions; mechanical-structural design requirements. Mechanics of continuous media are combined with models of material behavior to determine adequacy of component design. Effects which are considered include: mechanical loading, hydraulic forces, elevated temperatures, and neutron irradiation; normal operation, accident situations, and seismic effects. Lectures are given by several members of Institute faculty and by guest lecturers from nuclear power industry.

4.7 Undergraduate Program

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

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

22.006, 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).

22.003J, In Pursuit of Arms Control: Analysis of the Past and Choices for the Future, a review and analysis of nuclear and non-nuclear arms and efforts at arms control since World War II. Focus is on the interaction of technological factors, changing strategic concepts, intelligence estimates and political 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. Students learn to evaluate and to design alternatives to current government arms control and national security policy.

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

22.021, Nuclear Reactor Physics, 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. 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 meet concurrently with 22.312, plus a separate recitation.

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. 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 radiosotopes, radiations and lasers in research, radioactive pollutants and their demographic effects. Laboratory demonstrations of methods and instruments in radiation measurements are given at the MIT Reactor. The material is presented in an essentially descriptive manner, and is suitable for students interested in a general appreciation of the physical phenomena and their uses.

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

22.069, Undergraduate Plasma Laboratory, Basic engineering and scientific principles associated with experimental plasma physics. 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.

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

22.092, 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.)

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

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

22.916, Management in Engineering, An introduction to the concepts of management of the engineering function, as

found in a variety of industrial and non-industrial settings. Aim is to help the student 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. Topics: financial principles; management of innovation; engineering project planning, scheduling and control; human factors; career planning; contracts; patents; and technical strategy for firms. Taught in part by the case method, which emphasizes student participation in discussion. (Intended for juniors, seniors, or graduate students; others should consult the instructor in charge.)

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

4.8 Engineering Internship Program

The Engineering Internship Program has been adopted by most engineering departments as a new way for a student to obtain a strong combination of work and study experiences. The program is intended to lead to both a bachelor's and a 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. They completed their original work assignment during the summer of 1978.

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 re-designed 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 monochromator. 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. D.V. Berney with a doctoral student, David Johnson. 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 Nuclear Engineering Laboratories

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

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

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

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

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

5.5 Plasma Research Facilities

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

- (1) 30-cm linear Z pinch with holographic interferometer,
- (2) Advanced Thompson scattering experiment consisting of high power commercial CO₂ laser and 50-cm HCD,
- (3) 2 m linear 313ctron beam trapping solenoid for non-linear wave-plasma studies,
- (4) Gas target neutron source simulator consisting of hydrogen wind tunnel and 150 KV ion beam.

No large scale magnetic or inertial confinement facilities are used by the group although some collaboration with the National Magnet Laboratory Alcator group occurs from time to time.

5.6 Computing Facilities

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

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

6. DEPARTMENT PERSONNEL6.1 FacultyNorman C. Rasmussen

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

Manson Benedict

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

Gordon L. Brownell

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

Sow-Hsin Chen

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

Michael J. Driscoll

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

Thomas H. Dupree

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

Michael W. Golay

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

Elias P. Gyftopoulos

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

Otto K. Harling

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

Allan F. Henry

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

Irving Kaplan

Professor of Nuclear Engineering, 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

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

David D. Lanning

Professor of Nuclear Engineering
 B.S. '51 U. of Ore.; Ph.D. '63 (nuclear engineering) MIT
 Reactor operations; reactor engineering; reactor
 safety; reactor physics measurements.

Lawrence M. Lidsky

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

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.

Peter A. Politzer

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

David J. Rose

Professor of Nuclear Engineering
 B.A.Sc. '47 British Columbia; Ph.D. '50 (physics) MIT
 Energy and environmental policy; energy technology;
 controlled nuclear fusion.

Louis S. Scaturro

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

Dieter J. Sigmar

Adjunct Professor of Nuclear Engineering
 M.S. '60, Ph.D. '65, Tech. Univ. of Vienna
 Theory of fully ionized plasmas; controlled thermo-
 nuclear 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.

Lothar Wolf

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

Sidney Yip

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

6.2 Complete Listing of Personnel (as of September 1978)Professor

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

Associate Professor

M. J. Driscoll
M. W. Golay
P. A. Politzer
L. Wolf

Assistant Professor

M. S. Kazimi
L. S. Scaturro

Visiting Professor

O. K. Harling

Adjunct Professor

D. J. Sigmar

Instructor "G"

R. Ballinger
J. M. Noterdaeme

Administrative Officer

J. L. Cochran

Administrative Assistant

J. B. deVries
D. Dutton

Visiting Scientist

K. Iijima
S. Ranganathan

Senior Research Associate

C. V. Berney

Research Associate

B. W. Murray
H. B. Stewart

Research Affiliate

R. H. Ackerman
J. W. Hopps, Jr.
D. Hnatowich
S. Kulprathipanja
P. E. McGrath
S. Treves
W. E. Vesely

Clerical Staff

A. J. Bishko
R. A. Caso
C. Egan
K. Hicks
G. Jacobson
P. F. Kelly
M. B. Levine
C. A. Lydon
S. Mehta
L. P. Nelson
M. L. Southwick
D. J. Welsh

DSR Staff

R. I. Kramer
R. Morton

FALL 1978 Teaching Assistants

G. Alberthal
 M. Ashtary
 D. Coate
 K. Cogswell
 J. Combs
 P. Bayless
 J. Egan
 R. Hamza
 J. Herring
 C. Hoxie
 M. Manahan
 V. Manno
 G. Otten
 A. Pachtman
 J. Pasztor
 J. Rivera
 J. Sefcik
 M. Stiefel

FALL 1978 Research Assistants

A. Adegbulugbe	T. Suzuki
K. Araj	C. Thomas
J. Aspinall	M. Tillack
B. Atefi	K. Touqan
R. Ballinger	M. Tyson
R. Bennett	M. VanHaltern
F. Best	G. Was
T. Boutros-Ghali	C. Wong
L. Briggs	
P. Cavoulacos	
S. Chang	
J. Chao	
K-W. Chiu	
M. Corradini	
D. Ebeling-Koning	
W. Fisher	
P. Gierszewski	
W. Glantschnig	
E. S. Gordon	
T. Greene	
G. Greenman	
J. Hawley	
J. Hutchinson	
A. Jodidio	
D. Johnson	
H. Khan	
S. Kim	
J. Koclas	
K. Kreischer	
T. Kwok	
B. Labombard	
D. Lancaster	
A. Levin	
J. Loomis	
J. Maki	
R. Marlay	
M. McKinstry	
M. Modarres	
G. Nakayama	
N. Novich	
W. Parkinson	
S. Piet	
R. Potok	
K. Rubenstein	
I. Saragossi	
R. Sawdye	
A. Schor	
S. Shanfield	
K. Smith	
R. Smith	
K. SooHoo	

7. DEPARTMENTAL STATISTICSStatistical Summary

Academic Year Sept-June	<u>Sept. Registration</u>				<u>Degrees Granted</u>					No. of Professors	No. of Subjects
	Under- grad	Regular	Special	Total	B.S.	S.M.	Nuc. E.	ScD., PhD	Total		
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
Totals					13	726	100	286	1125		

8. STUDENTS

Some background information about the 170 full-time students registered in the Department in September 1977, 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.

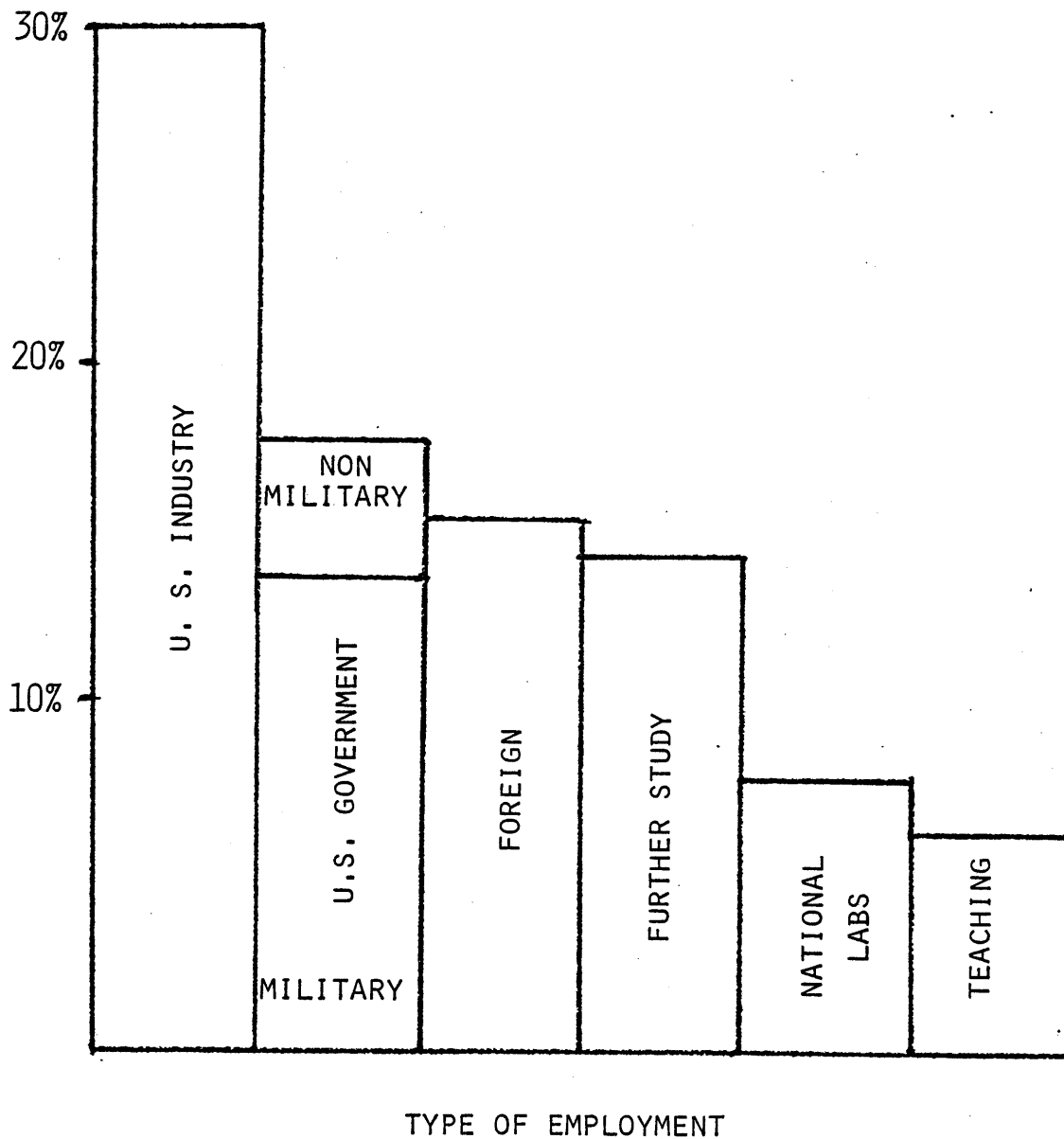
The distribution of schools from which our domestic students are drawn is very widespread. The number coming from MIT remains under 20%, as it has for many years. The foreign student population is relatively high, approximately 40%, and reflects the widespread recognition among foreign countries of their 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 1973/74 we had 24 research assistants, while in 1978/79 we now 59. 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 five 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.

FIGURE 8.1

DISTRIBUTION OF EMPLOYMENT OF GRADUATES (REPORTED*)



* EXCLUDES 108 (10.7%) STUDENTS NOT REPORTED

Table 8.1

Background of Graduate Students Registered
in Nuclear Engineering Department
(Spring 1978)

By Profession (162)

Chemical Eng. (4)
Civil Eng. (3)
Electrical Eng. (13)
Electronics (3)
Electrophysics (2)
Engineering (9)
Eng. Physics (9)
Fuels & Energy (1)
Materials (2)
Mathematics (4)
Marine Eng. (2)
Mechanical Eng. (16)
Meteorology (1)
Metallurgy (4)
Naval Science (1)
Nuclear Eng. (50)
Nuclear Physics (3)
Physics (33)
Radiation Physics (1)
Structures (1)

By College (89)
(U.S. cit. only)

Brooklyn Polytech. (1)
Carnegie Mellon (2)
CCNY (1)
Columbia (2)
Cornell (6)
Florida Atl. Univ. (1)
Florida State U. (1)
Geo. Wash. (1)
Ga. Inst. Tech. (3)
Harvard Univ. (1)

Harvey Mudd (1)
Iowa State (1)
Kansas State (1)
Lowell Tech (1)
Marquette (1)
MIT (19)
McNeese State (1)
New Jersey Inst. Tech. (1)
New York Univ. (1)
North Carolina S. Univ. (1)
Northeastern U. (2)
Oakland Univ. (1)
Oberlin College (1)
Ohio State Univ. (1)
Oregon State Univ. (1)
Penn. State (1)
Princeton (1)
RPI (3)
Rice (1)
Stanford (1)
Sweet Briar (1)
Texas A&M (1)
USMA (1)
USMMA (1)
USNA (3)
U. California (3)
U. Florida (2)
U. Lowell (3)
U. Michigan (6)
U. Tenn (2)
U. Virginia (1)
U. Wisc. (1)
Wash. Univ. (1)
Worcester Polytech. (2)
Yale (1)

By Country (162)

Algeria (2)
Argentina (2)
Belgium (2)
Brazil (4)
Canada (3)
Chile (1)
Egypt (2)
England (1)
Iran (26)
Israel (1)
Italy (1)
Japan (1)
Jordan (1)
Korea (3)
Libya (1)
Mexico (1)
Nigeria (1)
Pakistan (1)
R. China (9)
Saudi Arabia (5)
Spain (4)
United States (89)
Venezuela (1)

Table 8.2
Sources of Financial Support
(as of February 1978)

Research Assistantships (43)
 Teaching Assistantships (23)
 MIT Fellowships (1)
 NRC Fellowships (1)
 ERDA Traineeships (2)
 ERDA Fellowship (1)
 NIH Traineeships (3)
 NSF Fellowship (5)

Nigerian Scholarship (1)
 Saudi Arabian Govt. (2)
 Hertz Fellowship (1)
 Self-supporting (18)
 AEOI - Iran (15)
 Govt. of Iran (4)
 Canadian Scholarships (2)
 Westinghouse Lamme Scholarship (1)
 Air Force (1)
 Chinese Govt. Fellowships (3)
 Brazilian Fellowship (4)
 Govt. of Spain (1)
 Min. Eng. Council Fellow (1)
 Libya Govt. Fellowship (1)I
 TP Foundation/Spain (1)
 ROC Ministry of Education (1)
 Algerian Scholarship (1)
 U.S. Navy (2)
 Ida Green Fellowship (1)
 HST Fellowship (1)
 Biomedical Fellowship - MIT (1)
 Govt. of Chile (1)
 Govt. of Israel (1)
 Minorities Award (2)
 Rotary Foundary Fellowship (1)
 Belgium-American Education Foundation (1)
 Picker Scholarship (1)
 Mexican Govt. (1)
 Argentine Navy (1)
 Sherman Knapp Fellow (1)
 GE Fellowship (1)

Table 8.3

Activities of Nuclear Engineering Dept. Graduates -- July 1978

(Place of first employment -- information current as of July 1978)

U.S. Industry and Research (303) (30.0%)

Aerodyne Research Inc.	Hercules
Aerojet Nuclear	Hughes (4)
Air Research Mfg. Co.	Hybrid Systems
Allis Chalmers (2)	Hanford Eng. Dev. Lab.
American Electric Power	
Amer. Science and Eng.	IBM (2)
APDA (2)	Inst. for Defense Analysis
Assoc. Planning Res.	Internuclear Co.
Atomics Int. (10)	Isotopes, Inc.
Avco (6)	
	Jackson & Moreland (2)
Babcock & Wilcox (7)	Jet Propulsion Lab
Battelle Northwest (8)	
Bechtel (3)	
Bell Telephone Lab.	
Bendix	Lane Wells
Bettis (4)	A.D. Little (4)
Burns & Roe (2)	Lockheed
	Long Island Lighting Co.
California Oil	
Combustion Eng. (15)	Management & Tech. Cons.
Commonwealth Edison (13)	Martin-Marietta (2)
Computer Processing	Mass. General Hospital
Conn. Mutual Life Ins.	Maxson Elec.
Consolidated Edison	McKinsey & Co.
Consultant	MIT (research) (10)
Consumers Power	Mobil Oil
Cornell Univ. (research)	Monsanto
	MPR Associates
Detroit Power Co.	
Direct Energy Con. Lab.	Nat. Acad. of Eng.
Douglas Unite Nucl. (2)	New England Nuclear Corp.
Draper Lab	New England Power Service Co.
Duke Power & Light	New York law firm
Dynatech R/D Co.	North American Rockwell (2)
	Northeast Util. Service (3)
Ebasco (2)	Northern Research & Eng. (3)
Edgerton, Germ. & Grier	Nortronics
	Nuclear Fuel Service (2)
Georgia Power Co.	Nuclear Mater. & Equipment
General Atomic (2)	Nuclear Products
General Dynamics, Elec. Boat (7)	Nuclear Regulatory Commission (2)
General Electric (22)	Nuclear Utility Services (4)
Gulf General Atomic (18)	

Perkin-Elmer Corp.
 Philco
 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 (2)
 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)
 TRW Systems (2)

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

Vacuum Industries

Westinghouse (22)

Yale (research) (2)
 Yankee Atomic (10)

National Laboratories (73) (7.2%)

Argonne (13)
 Brookhaven (6)
 Knolls Atomic Power (17)
 Lawrence Livermore (2)
 Lawrence Radiation (5)
 Los Alamos (10)
 Oak Ridge (12)
 Sandia (4)
 Savannah River (4)

Further Study (144) (14.2%)

MIT (118)
 Other (26)

U.S. Government (176) (17.4%)

Atomic Energy Commission (22)
 Air Force (13)
 Army (74)
 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)
 NASA
 Naval Research Lab
 Navy (51)
 Peace Corps
 Picatinny Arsenal
 Dept. of Public Health

Teaching (53) (5.2%)

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

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 (2)
 Univ. of Wisconsin

Foreign (151) (14.9%)

Argentina
 Belgium (9)
 Brazil (15)
 Canada (11)
 Chile
 Columbia, S.A.
 England (2)
 France (17)
 Germany (2)
 Greece (6)
 India (13)
 Indonesia
 Iran (18)
 Israel (2)
 Italy (5)
 Japan (12)
 Malaysia
 Mexico
 Norway
 Pakistan (3)
 Philippines
 Poland
 Spain (11)
 Switzerland (6)
 Taiwan (4)
 Turkey (4)
 Venezuela (2)

NOT REPORTED (108) (10.7%)

TOTAL 1008*

*Records from early years are incomplete.

9. LIST OF THESES

The following theses were submitted to the Nuclear Engineering Department in September 1976:

G.C. Allen, Jr., "The Reactor Engineering of the MITR-II Construction and Startup", PhD Thesis.

P.W. Baum, "Incorporation of Irradiation Effects Into Creep-Fatigue Damage Criteria", SM Thesis.

N.A. Brooks, "Process Design Evaluation for Recovery of Uranium from Sea Water", SM Thesis.

N.M. Ceglio, "Zone Plate Coded Imaging of Laser Produced Plasmas", PhD Thesis.

C. Chiu, "Two-Dimensional Transport Coefficients for the PWR's Thermohydraulic Analysis", SM Thesis.

S. Fujimoto, "The Inclusion Effect on Bubble Migration in Uranium-Dioxide Fuel", NE Thesis.

M.J. Harper, "Hydrogen Storage in a Liquid Medium", SM Thesis.

J.C. Hsia, "Plasma Thomson Scattering at 10.6 Microns", PhD Thesis.

K.W. Huang, "Interrelationships Between LWR Fuel Rod Design and Fission Gas Swelling", NE Thesis.

J.M. Kelly, "Turbulent Interchange in Triangular Array Bare Rod Bundles", SM Thesis.

M. Maekawa, "A Method for Risk Analysis of Nuclear Reactor Accidents", PhD Thesis.

L.R. Pasquarelli, Jr., "Experimental Investigation of a Trapped-Electron Mode Saturation", SM Thesis.

R. Quintana-Alonso, "Depletion of Heterogeneous Subassemblies by a Block Calculation", SM Thesis.

The following theses were submitted to the Nuclear Engineering Department in February 1977:

H. Akbari, "Self-Consistent Initialization of Lattice Dynamics and Simulation Studies of Molecular System", SM Thesis.

- R. Chen, "Nuclear Reactor Rescheduling Study", SM Thesis.
- D. Cook, "A Calibrated Eight-Channel Neutral Atom Spectrometer", PhD Thesis.
- M.L. Corradini, "Studies in Fuel Coolant Interactions", SM Thesis.
- S.J. Feldman, "Residential Energy Consumption in the Greater Boston Area", SM Thesis.
- E.K. Fujita, "Numerical Verification of Control Rod Worth Techniques", NE Thesis.
- D.R. Giosetti, "Analysis of the Technological Differences Between Stationary and Maritime Nuclear Power Plants", SM Thesis.
- L. Guillebaud, "Vapor Diffusion in BWR Fuel Rod Bundles", NE/SM Thesis.
- E.C. Guyer, "An Engineering and Economic Evaluation of Some Mixed-Mode Waste Heat Rejection Systems", ScD Thesis.
- D.W. Hearing, "A Public Policy Analysis of Coal Utilization for Electric Power Generation in New England", EE-SM Thesis.
- S.C. Jones, "Carbon-11 Labeled Glucose for the Study of Brain Metabolism with Positron Radionuclide Imaging", PhD Thesis.
- J.M. Kelly, "Turbulent Interchange in Triangular Array Bare Rod Bundles", NE Thesis.
- W.F. Lenz, Jr., "Mixing Requirements for the Limiting Fuel Coolant Interactions in Liquid Metal Fast Breeder Reactors", NE/SM Thesis.
- F. Martin, "Experimental Study of Toroidal Plasmas with Non-Circular Cross-Section", PhD Thesis.
- P.C. Meagher, "Design of Central Irradiation Facilities for the MITR-II Research Reactor", SM Thesis.
- D. Morales, "Reactor Physics Calculation of BWR Fuel Bundles Containing Gadolinia", SM Thesis.
- A. Perez, "Core Reflector Boundary Conditions Accounting for Transport Theory in the Reflector", SM Thesis.

W. Saylor, "Plasma Position Control in a Tokamak Experimental Power Reactor", SM Thesis.

R.A. Shober, "Nonlinear Methods for Solving the Diffusion Equations", PhD Thesis.

J. Stetkar, "On the Design, Simulation and Policy Implications of Total Energy Systems", NE Thesis.

E.C. Vanterpool, "A Parametric Study of EBTR-48 Reactor Economics", SM Thesis.

C. Villaneuva-Moreno, "The Impact of Nuclear Fuel Cycle Economics in the Generation Expansion of the Power System of Mexico", NE Thesis.

G.S. Was, "A Materials Evaluation of a Gas-Cooled Solid-Breeding Fusion Reactor Blanket", SM Thesis.

The following theses were submitted to the Nuclear Engineering Department in June 1977:

B. Atefi, "Specific Inventory and Ore Usage Correlations for Pressurized Water Reactors", NE/SM Thesis.

A.C. Barroso, "A Three Dimensional Synthesis Code for Simulating Xenon Induced Oscillations", PhD Thesis.

W.A. Boyd, "Thermal-Hydraulic Analysis of Tight Lattice LWR's", SM Thesis.

L. Bromberg, "Theory of Low Pressure Thermionic Discharges Used for Positive Ion Extraction", PhD Thesis.

R.P. Bushore, "Synthetic Fuel Generation Capabilities of Nuclear Power Plants with Applications to Naval Ship Technology", SM Thesis.

H.C. Chan, "Anomalous Transport Theory of Alpha Particles in Fusion Plasma Due to Thermo-Nuclear Instabilities", Ph.D. Thesis.

J. Chan, "Comparative Evaluation of Cooling Tower Drift Eliminator Performance", Ph.D. Thesis.

R. Chen, "A Simple Model for Analysis of LWR Fuel Cycle Economics", SM Thesis.

Y.B. Chen, "Coolant Mixing in the LMFBR Outlet Plenum", PhD Thesis.

- R. Granetz, "A Theoretical Analysis of a Concentrating Solar Collector Designed for Air Conditioning", SM Thesis.
- S. Grill, "Methods of Switching from Point to Space-Dependent Kinetics in the Solution of the Time Dependent Diffusion Equation", PhD Thesis.
- M. Haji-Azim, "Alternative Isotopes for Lung Ventilation and Cerebral Blood Flow Measurements", SM Thesis.
- A. Herschcovitch, "Stabilization of a Plasma by Externally Induced Turbulence", ScD Thesis.
- T. Hollenberg, "Risk-Sharing in the Establishment of a Private Sector Uranium Enrichment Industry", SM Thesis.
- J.Y. Kim, "Fully Developed Mixed Convection Heat Transfer in the Finite Hexagonal Bundles", SM Thesis.
- G.P. Lasche, "A Study of the Diffusion of Tracer Impurities in the Versator Tokamak Plasma by Spectral Emissions in the Vacuum Ultraviolet Range", SM Thesis.
- D.P. Mahoney, "An Evaluation of a Nuclear Power Plant for a Large Surface Effect Ship", SM Thesis.
- R.E. Masterson, "Improved Multidimensional Numerical Methods for the Steady State and Transient Thermal-Hydraulic Analysis of Fuel and Pin Bundles and Nuclear Reactor Cores", PhD Thesis.
- M. Modarres, "A Study of the Possibilities of High-Level Radioactive Waste Disposal in Iran", NE/SM Thesis.
- M.S. Saïdi, "Measurement of the ^{37}S Contamination of the ^{49}Ca 3.10 MeV peak in 14 MeV Neutron Activation Analysis", SM Thesis.
- A.A. Salehi, "Resonance Region Neutronics of Unit Cells in Fast and Thermal Reactors", PhD Thesis.
- S.P. Schultz, "The Utilization of Fuel Integrity Prediction in Light Water Reactor Fuel Management", ScD Thesis.
- J. Shin, "Evaluation of Advanced Fast Reactor Blanket Designs", ScD Thesis.
- R.N. Sims, "A Coarse-Mesh Nodal Diffusion Method Based on Response Matrix Considerations", ScD Thesis.

- A.M. Sinaki, "Nuclear Waste Reprocessing and Disposal for Iran: An Assessment", SM Thesis.
- M. Todosow, "The Application of Finite Element Methods to Reactor Kinetics Problems", PhD Thesis.
- M.V. Moghaddam, "TLD vs FILM for Personnel and Environmental Dosimetry", SM Thesis.
- T. Tokunaga, "Important Structural Considerations in Design of Prestressed Concrete Reactor Vessels", SM Thesis.
- J.P. Yangos, "Stimulated Brillouin Scattering from a Laser-Produced Magnetoplasma", SM Thesis.
- M. Zaker, "Dose Rate Measurements in the MITR-II Facilities", SM Thesis.
- R.G. Zamenhof, "The Measurement of Body Elemental Composition by Radiative Capture Gamma Rays in Vivo Neutron Activation Analysis", PhD Thesis.

The following theses were submitted to the Nuclear Engineering Department in September 1977:

- M. Ashtary, "Migration of Radionuclides from Nuclear Waste Repository", SM Thesis.
- M. Baghail-Anaraki, "Effect of Nuclear Power Generation on Slow Speed Power System Dynamics", SM Thesis.
- R.G. Ballinger, "The Anisotropic Mechanical Behavior of Zircaloy-2", SM Thesis.
- F. Bamdad-Haghighi, "Natural Convection Analysis of MITR-II During Loss of Flow Accident", NE/SM Thesis.
- C.E. Barbehenn, "Neutronic Sensitivity Studies on MEKIN, an Accident Analysis Computer Code for Nuclear Reactors", NE/SM Thesis.
- J.G. Bartzis, "Hydrodynamic Behavior of a Bare Rod Bundle", PhD Thesis.
- K.L. Basehore, "Temperature Field Prediction Methods for an LMFBR Fuel Assembly", NE/SM Thesis.

- T.A. Bjornard, "Blowdown Heat Transfer in a Pressurized Water Reactor", PhD Thesis.
- M. Campbell, "Characterization of the Monkey Neutron Activation Analysis Facility at MIT", SM Thesis.
- F.R. Chang, "Technology Assessment of Fusion Systems", ScD Thesis.
- R.J. Chin, "DEPLESYN: A Three Dimensional, Discontinuous Synthesis, Diffusion-Depletion Code", PhD Thesis.
- M.M. Dashti, "Effect of Pre-Pressurization of Fuel Rods on Steady State and Transient Rupture Behavior", NE/SM Thesis.
- A. Eghlima, "Criteria for Selection of Power Reactors for a Developing Country", NE Thesis.
- F. Emami, "Steady-State Thermal-Hydraulic Sensitivity Study of LWR Core Modeling With COBRA IIIC/MIT", SM Thesis.
- M. Fakory, "Measurement and Analysis of Flow Wall Shear Stress in an Interior Subchannel Triangular Array Rods", NE Thesis.
- A.S. Hanson, "Fluid Mixing Studies in an Hexagonal 61-Pin, Wire-Wrapped Rod Bundle", PhD Thesis.
- R.C. Holland, "An Analysis of the Lennard-Jones Devonshire Cell Model: Equation of State Properties and Behavior in the Critical Region", SM Thesis.
- R. Karimi, "Two-Dimensional Structural Analysis of Reactor Fuel Element Claddings Due to Local Effects", NE/SM Thesis.
- K.E. Kreischer, "Parametric and Cost Analysis of a High Field Compact Tokamak Reactor", SM Thesis.
- J.Y. Liu, "Thermal-Hydraulic Analysis for PWR's by a One Pass Method", NE/SM Thesis.
- R. Malekzadeh, "Optimal Allocation of Nuclear Power Plants in Iran", SM Thesis.
- N. Meissami, "Cause of Pittings and Bone Image on Bone Lexan Samples", SM Thesis.

M.A. Moghimi, "Development of a Real Time Digital Correlator for a Neutron Time-of-Flight Analyser", SM Thesis.

A.N. Nobahar, "Computerized Thermal Analysis of PWR Power Plant Cycles", SM Thesis.

J. Olmos, "A Modular Approach to Fault Tree and Reliability Analysis", ScD Thesis.

R.I. Pettigrew, "The Development and Evaluation of ^{252}Cf Neutron Irradiation Facilities for Two Biomedical Applications Using Discrete Ordinates, Monte Carlo, and Experimental Methods", PhD Thesis.

T. Rodack, "Sensitivity Study of the Assembly Averaged Thermal-Hydraulic Models of the MEKIN Computer Code in Power Transients", NE/SM Thesis.

J. Willefert, "Comparative Analysis of the American and French Nuclear Power Plant Siting Policies with Respect to the Environmental Impact and Other Related Costs", SM Thesis.

B.A. Worley, "Spatial Homogenization of Diffusion Theory Parameters", PhD Thesis.

K.J. Laskey, "MHD Pressure Drop in a Flow Around a Corner in a Magnetic Field at High Hartman Number", SM Thesis.

B.M. Tucker, "Design of a MHD Liquid Metal Test Facility", NE/SM Thesis.

J.C. Hoy, "A Laser-Driven Pellet Accelerator for CTR Fuel Injection", SM Thesis.

F. Abtahi, "Out-of-Reactor Aspects of Thorium Utilization in Light Water Reactors", Ph.D. Thesis.

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

G. Andrade, "Load Following Operation of a Pressurized Water Nuclear Power Plant", NE Thesis.

C.T. Breuer, "Assessment of Coal for Utility Steam-Raising: Fluidized-Bed Combustion Compared to Currently Proven Technologies", PhD Thesis.

- C. Chiu, "Investigations in Coolant Mixing and Flow Split for LMFBR Wire Wrapped Assemblies", PhD Thesis.
- O. daSilva, "Fuel Element Performance Maps for Nuclear Reactor Operational Decisions", NE Thesis.
- E. Daxon, "Irradiation Damage Studies of AISI Type 316 Stainless Steel", SM Thesis.
- D. Dvore, "A Numerical Study of Nonuniformities in Disc MHD Generators", SM Thesis.
- M. Fardis, "An Accident and Seismic Containment Reliability Study Including Statistical Uncertainty", SM Thesis.
- K. Garel, "Fuel Cycle Optimization of Thorium and Uranium Fueled PWR Systems", PhD Thesis.
- S. Goldman, "Analysis of Alternative Community Energy Supply Schemes", SM Thesis.
- D. Kennedy, "Nonlinear Bremsstrahlung - An Absorption Process for Laser Radiation in a Plasma", SM Thesis.
- M. Krammen, "Calibration of the Cygro and LIFE Fuel Element Modeling Codes", NE/SM Thesis.
- G. Lucas, "Effects of Anisotropy and Irradiation on the Creep Behavior of Zircaloy-2", ScD Thesis.
- M. Macher, "Fast Reactor Blanket Benchmark Calculations", SM Thesis.
- W. Michell, "Significant Structural Design Considerations in Welded Components", SM Thesis.
- G. Orlov, "Self Shielding of Epithermal Neutrons by Resonances in Tantalum Wires", SM Thesis.
- J. Palmer, "An Assessment of Thermal Energy Storage and Waste Heat Dissipation with Total Energy Systems for MIT", SM Thesis.
- I. Papazoglou, "Markovian Reliability Analysis Under Uncertainty With An Application on the Shutdown System of the Clinch River Breeder Reactor", ScD Thesis.
- G. Pine, "Assessment of Integrated Urban Energy Options", PhD Thesis.

T. Sbarounis, "Treatment of the Spatial Shape of the Currents in the Response Matrix Method", PhD Thesis.

R. Sclove, "Scientists in the U.S. Nuclear Debate: An Inquiry Into the Structure, Evolution and Social Implications of a SocioTechnological Controversy", SM Thesis.

R. Smith, "Extending Core-Reflector Albedo-Type Boundary Conditions to Include Geometrically Simple Multiregion Reflectors", SM Thesis.

C.N. Wong, "A 3-D Slug-Flow Heat Transfer Analysis of Coupled Coolant Cells in Finite LMFBR Bundles", SM Thesis.

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

D.C. Aldrich, "Examination of Offsite Radiological Emergency Protective Measures for Nuclear Reactor Accidents Involving Core Melt", PhD Thesis.

H.P. Alesso, "Elementary Catastrophe Theory Modelling of an End Loaded Ring in a Rigid Cavity", NE/SM Thesis.

H. Aminfar, "Generation of Few Group Cross Sections for Thermal Reactors Using Fast Reactor Methods", NE/SM Thesis.

K. Armstead, "Empirical Approximations for Three Dimensional Neutron Flux Synthesis", SM Thesis.

C. Beard, Jr., "An Improved Long Range Fuel Management Program", SM Thesis.

M. Broussard, "Alternative Energy Systems: Application to the Extraction of Uranium from Seawater", SM Thesis.

D. Dube, "Analysis of Design Strategies for Mitigating the Consequences of Lithium Fire Within Containment of Controlled Thermonuclear Reactors", SM Thesis.

J. Fisher, "Finite Beta and Inertial Effects in a Toroidal Discharge", ScD Thesis.

A. Forbes, "Experimental Modelling Study of an Intense 14 MeV Gas Target Neutron Source for the Fusion Materials Program", PhD Thesis.

- D. Gould, "Economic Aspects of Tritium Separation from Water Via Laser Isotope Separation", NE/SM Thesis.
- M. Hadji-Mirzai, "Effects of Material and Microstructural Parameters on Void Nucleation in Irradiated Metals", SM Thesis.
- S. Keyvan, "The Application of Albedo Type Boundary Conditions to the Replacement of Reflectors", NE Thesis.
- T. Kwok, "Computer Molecular Dynamics Studies of Two Dimensional Grain Boundary Crystals", SM Thesis.
- D. Laning, "Experimental and Monte Carlo Studies of Patient Dose Received From Computerized Axial Tomography", SM Thesis.
- Y.Y. Liu, "A Mechanistic Study of Light Water Reactor Fuel Element Failures", ScD Thesis.
- T. Luniewski, "MITR-II Reactivity and Fuel Management Studies Including the Applicability of the SIMULATE Computer Code", SM Thesis.
- V. Manno, "Measurement of Heat and Momentum Eddy Diffusivities in Recirculating Flows", SM Thesis.
- M. Mehrabian, "Application of Numerical Methods in Steady-State and Transient Thermal Fuel Pin Modeling", SM Thesis.
- J. Noterdaeme, "Demountable Resistive Joint Design for High Current Superconductors", SM Thesis.
- R. Racana, "Analysis of Structures Operating at High Temperatures in a High Radiation Field", NE Thesis.
- A. Rosito, "Nuclear Merchant Ships for Argentina: An Analysis of Prospective Advantages and Economics", SM Thesis.
- M.S. Saiedfar, "Simulation of Oxide Dispersoid Stability in Irradiated Alloys", SM Thesis.
- M. Samek, "Probability of Control Rod Shear Occurring and Remaining Undetected by Incore Flux Measurements in PWR's", SM Thesis.
- I. Saragossi, "Effects of Environmental Protection and Public Safety Regulatory Practices Upon Light Water Reactor Economics", SM Thesis.

R. Sawdye, "Application of Probabilistic Consequence Analysis to the Assessment of Potential Radiological Hazards of Fusion Reactors", SM Thesis.

S.A. Seyyedi, "Theory of Void Nucleation on Dislocations", SM Thesis.

W. Strohmayer, "Approximate Representation of Thermal Neutron Spectra in Reactor Transients", SM Thesis.

M. Tyson, "Urban Energy Policy and Bureaucratic Politics in Boston", SM Thesis.