COO-3340-3

MIT RESEARCH REACTOR

MIT NUCLEAR REACTOR LABORATORY

REPORT OF EDUCATIONAL AND RESEARCH ACTIVITIES FOR ACADEMIC/FISCAL YEAR 1984-1985 WITH SELECTED DATA FROM PREVIOUS YEARS

REPORT NO. MITNRL-016

by

MIT Nuclear Reactor Laboratory Staff

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ABSTRACT

A report of research and educational activities which utilized the Massachusetts Institute of Technology five-megawatt nuclear research reactor (MITR) in the Nuclear Reactor Laboratory during the academic year 1984-1985 has been prepared for administrative use at MIT and for presentation to the US Department of Energy. The latter action is required by Contract No. DE-AC02-76-ER03340, under which DOE provides the uranium fuel and the heavy water for the neutron reflector.

Research projects at MIT which make significant use of the MITR are described, and principal participating personnel are named. Listings are provided of theses, reports, journal articles and conference papers resulting from these projects during MIT fiscal year 1985 (MIT fiscal and academic years roughly correspond). A comprehensive bibliography of all publications resulting from work at MITR is contained in Report No. MITNRL-013, "M.I.T. Response to USDOE Questionnaire on the Value of U.S. University Research and Training Reactors." Portions of MITNRL-013 of current interest are contained in this report. Previous reports with similar objectives to the current one are Report No. MITNE-91, "Research and Educational Activities at the MIT Research Reactor To and Including Fiscal Year 1967," and in MITNE-98, MITNE-119, COO-3340-1, and MITNRL-001, which are similar documents covering periods through fiscal year 1978.

In addition to the scientific and educational value derived from the many research activities and from the reactor modification project by the students who participated in them, training in several areas of nuclear technology is imparted through formal courses designed to make use of the reactor or its research projects. The courses are briefly described, and enrollment figures are given.

Detailed information concerning the research activities of the numerous other universities, hospitals and commercial firms which have used the MITR for irradiations has not been compiled here, but these organizations, the materials irradiated, and the publications of those institutions using the MITR under USDOE's Reactor Sharing Program are listed.

The reactor, its purpose, its organization and that of the Nuclear Reactor Laboratory, and a summary of operations are briefly described in order to provide a more complete understanding of the MITR program.

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1. INTRODUCTION

This report of MIT Research Reactor Utilization is prepared in compliance with the requirement of Contract No. DE-AC02-76-ER03340 between Massachusetts Institute of Technology and the US Department of Energy. It provides information for the academic year 1984-1985 as well as selected information for other years. Information concerning the contract is provided in Section 2.

In order to meet other objectives of the report, it incorporates brief summaries of information in a few areas not required by contract to be covered in the report. For example, Section 3 describes the purposes of the reactor, its availability to MIT and other users, its organization, a brief description of the reactor and related support facilities, and the functions of the MITR staff. A more detailed description of the reactor and its support facilities may be found in one of the appendices.

Some of the descriptive material presented in earlier reports is repeated here. For example, many of the research investigations are part of long-range projects, and a general explanation of such programs is essential to the cohesiveness of this report.

The Table of Contents provides a relatively detailed breakdown and, hence, a summary of information furnished in the report.

2. USDOE RESEARCH AND TRAINING CONTRACT

2.1 General

Round-the-clock operation of a 5 MW research and training reactor entails costs of several hundred thousands of dollars per year. In carrying out its mandate under the Atomic Energy Act of 1954 "to insure the continued conduct of research and development and training," it was the policy of the former US Atomic Energy Commission to provide to educational institutions certain assistance in return for their operation of research and training reactors. This policy has been continued by the US Energy Research and Development Administration (ERDA) under the Energy Reorganization Act of 1974 and by its successor, the US Department of Energy (DOE).

Pursuant to this policy, a series of contracts (most recently No. DE-AC02-76-ER03340) entitled "Research and Training Program and Loan of Certain Commission Materials in Connection Therewith," has set forth the nature and scope of the agreement between MIT and, originally, the AEC, then ERDA, and now DOE.

2.2. MIT Obligation

The University agrees to use its reactor in a program of education and training of students in nuclear science and engineering and to engage in research activities, using the reactor, such as studies of the structure of materials by neutron diffraction, neutron therapy experiments, exponential assembly studies, material irradiations, activation analysis, and studies of other nuclear processes. MIT further agrees to furnish the Commission with a current list of all published reports embodying the results of activities involving the facility.

MIT's utilization of the reactor for the above purposes is described in Sections 4.1-4.3, 5, 6, 7 and 9. Statistical information concerning publications and the required lists are provided in Section 8 and Appendices 10.3-10.8.

2.3 USDOE Obligation

In consideration of the performance of these activities by MIT, DOE has provided replacement fuel elements and reimbursement for return shipping of spent fuel; lent without use charge the uranium for the elements, the heavy water moderator, and an antimony-beryllium neutron source employed for the reactor startup; and waived charges for consumption and normal operational loss of uranium, neutron source, and heavy water during fabrication, use, and reprocessing.

Information on current and cumulative fuel consumption, heavy water utilization and spent fuel returns is provided in Sections 4.4-4.6.

3. THE MIT RESEARCH REACTOR

3.1 Organization

Administratively the MIT Research Reactor is part of the Nuclear Reactor Laboratory, one of many interdisciplinary laboratories at MIT. Until July 1, 1976 it had been part of the Nuclear Engineering Department, but the reorganization gave recognition to its multidisciplinary utilization and has enhanced its usefulness to the MIT community. The organization chart is shown in Fig. 3-1.

3.2 Purposes of the MIT Research Reactor

The MIT Research Reactor was built to serve the Institute's research and teaching requirements in the many fields encompassed by the general terms "nuclear science and technology." The reactor serves as a principal facility for strong programs of fundamental research in several of the basic physical and life sciences - such as solid state physics, metallurgy, geology, radiochemistry, and biology - and in numerous areas of the applied sciences and engineering disciplines - such as reactor physics, nuclear trace analysis, radiation effects, radiation therapy, closed-loop computer control of reactors, and radioisotope production. In addition to the educational benefits accruing to the students participating in the varied research projects, the reactor is utilized in several courses offered by the Departments of Nuclear Engineering, Physics, and Earth, Atomospheric and Planetary Sciences.

While the reactor is intended primarily to serve the needs of MIT, the Institute recognizes an obligation to help meet the requirements of other universities, of hospitals, and of industry, particularly in the local area. The reactor is available to other institutions whose educators and researchers also may wish to utilize reactor radiations in such fields of study as those enumerated above. Special facilities have been incorporated in the design of the reactor to enhance its value for medical research and therapy applications under the direction of specialists from the many renowned hospitals in the

M.I.T. NUCLEAR REACTOR LABORATORY ORGANIZATION CHART

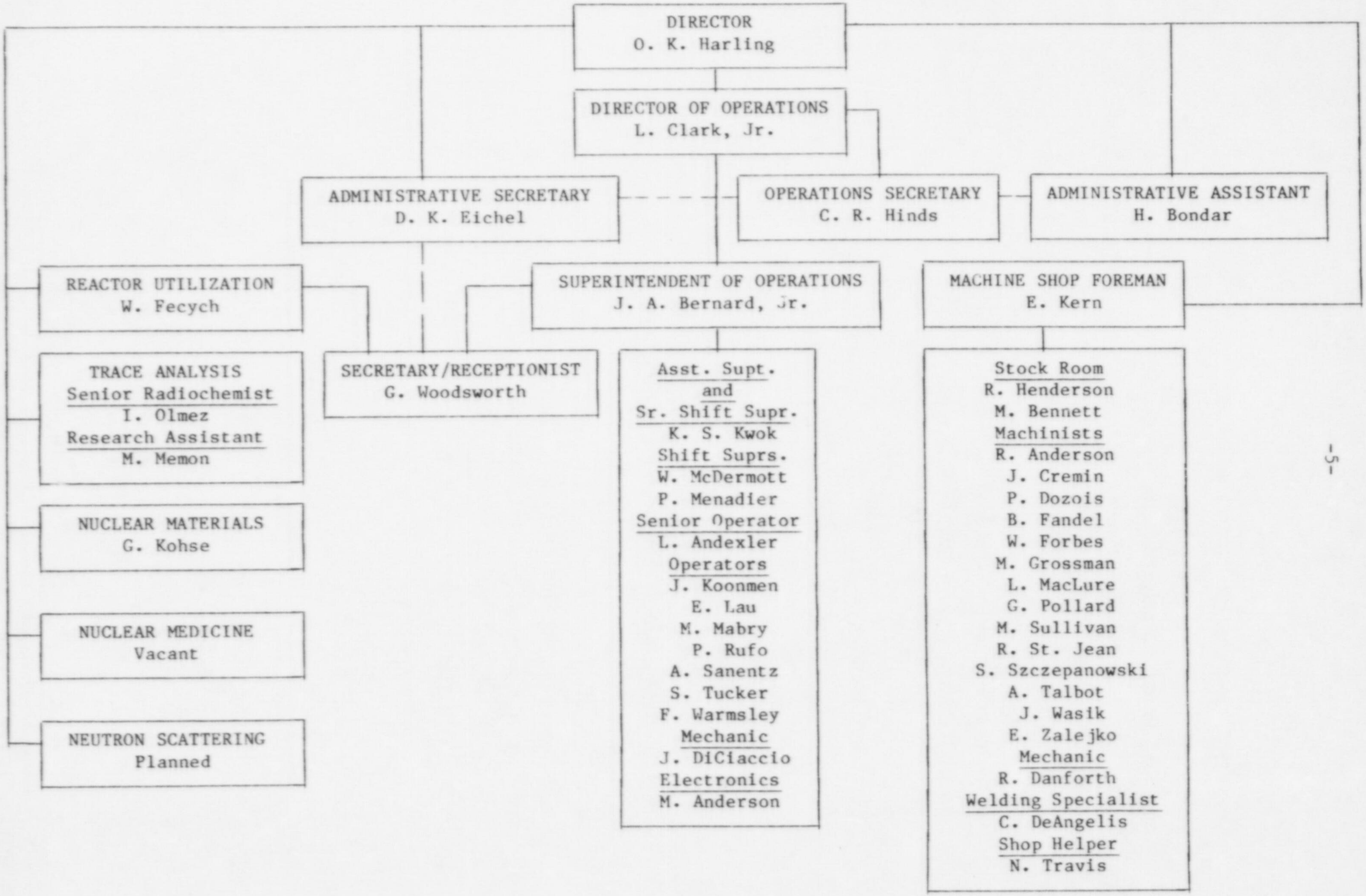

Fig. 3-1

area. MIT tries to meet the requirements of local industry for short-lived radioisotopes and other service irradiations.

In keeping with MIT policy, the construction and operation of the reactor can be justified only on the basis of its contributions to the educational objectives of the Institute. Research projects are undertaken not only for the results to be obtained but also for the educational benefits to be derived by students. In general, research problems must be sufficiently broad and basic so that they provide opportunities for thesis study by students; also, each must fall within the sphere of interest of some faculty or staff member desiring to supervise the project. The research described in this report is carried out primarily by student and faculty investigators; some laboratory staff members, however, in cooperation with reactor users, may participate in research projects as a service to them. In general, all personnel on the staffs of the Nuclear Reactor Laboratory or of the academic departments using the reactor are engaged in the conduct of research related to the Institute's education objectives.

In making radioisotopes and in performing other service irradiations for universities, hospitals, and industry, MIT does not desire to compete with commercial reactors for this work. However, where the half-lives of radioisotopes are short or where other factors dictate irradiations in the MITR, the Institute is happy to provide the required services. Tests or inspections are generally not made of irradiated specimens unless these are part of a larger research program (although such services can be provided by special arrangement).

All MIT research utilizing the reactor to date has been unclassified. This is highly desirable in order that maximum educational benefits may be enjoyed by the students without the limitations which result from security restrictions. In the occasional cases where classified projects have required service irradiations, it has been possible to perform these on an unclassified basis.

The MIT Research Reactor was designed so that a large number of experiments could be simultaneously accommodated in its experimental facilities. In total, there are over forty neutron irradiation and beam positions. This makes it feasible, in general, to accommodate more experiments than has been the case in the recent past, e.g., more neutron spectrometers, dosimetry studies, radiation damage investigations, loops, etc. The present broad and varied research and teaching programs could be increased in size significantly without undue crowding or inconvenience to the investigators.

3.3 Reactor Modification

The designer and original director of the MITR, Professor Theos J. Thompson, recognized that advances in reactor design technology by the late 1960's would permit the upgrading of the MITR-I to a more useful type of research reactor and, with the aid of the reactor staff and many students, he developed an improved concept which would nearly triple the beam port fluxes at the reactor face without any increase in reactor power and would enhance the in-core irradiation capabilities. The reactor was shut down in May 1974 to make the necessary changes, and the MITR-II, as the upgraded reactor is known, achieved criticality in August 1975. After several months of startup testing and a year of shakedown operation (mostly at 2.5 MW), the reactor resumed a routine 5 MW schedule on December 1, 1976.

The modification involved replacement of the heavy-water moderated and cooled core and its four-foot diameter tank. The associated shielding above the reactor and all of the primary piping had to be completely rebuilt. At the same time some of the instrumentation was improved, most of the original control and power wiring was replaced, and several other systems were upgraded.

3.4 Description of the MITR-II Reactor

The MITR-II is a tank-type reactor, having in fact two tanks: an inner one for the light water coolant-moderator and an outer one for the heavy water reflector. As may be seen in Figs. 10.1-1, 10.1-2 and 10.1-3 of Appendix 10.1, the fuel elements of fully-enriched (93%) uranium are positioned in a hexagonal core structure, 15" across, at the bottom of the core tank. Power is controlled by six shim blades and an automatic regulating rod. The two-foot thick graphite reflector and most other features of the MITR-I external to the core have been retained. The pressure in the system is practically atmospheric, and the temperature just slightly over 100°F. An exterior shield of dense concrete makes it possible for research workers and students to conduct experiments and training without radiation hazards.

Also shown in Fig. 10.1-1 are a number of the experimental facilities (see Table 10.1-1 of Appendix 10.1 for flux levels and other characteristics). There are a total of more than forty ports (horizontal and vertical) which penetrate the concrete shield and graphite reflector. In addition, vertical thimbles of special design permit insertion of samples into the core. The 5' x 5' thermal column conducts a stream of neutrons to special facilities (e.g., breeder blanket, cold neutron source, and positions for irradiation with fast or well-thermalized neutrons). Below the reactor is a shielded surgical room for the use of neutron beams in medical therapy, in biomedical research, and in other experiments requiring a minimum of gamma radiation and/or large volumes.

A more detailed description of the MITR-II may be found in Appendix 10.1.

3.5 Reactor-related Support Facilities

Effective utilization of the reactor requires an extensive range and variety of supporting facilities and equipment:

a) The reactor complex includes several well equipped shops (electronics, machine and mechanical).

b) The Nuclear Reactor Laboratory maintains several modern laboratories, including extensive facilites for radiochemistry and neutron activation analysis, and facilities for remote handling and testing of irradiated materials.

c) The facilities of the Nuclear Engineering Department (which occupies contiguous space) support both education and research in reactor-related fields and range from a nuclear measurements laboratory and reading room to a computer code library and a Tektronic 4051 microcomputer.

d) The most commonly used Institute facility is the computation center, but a wide range of other facilities is also available to researchers in reactor-related fields (science and engineering libraries, electron microscopes, accelerators, and others too numerous to mention in this summary).

Appendix 10.2 contains a listing of the major facilities and equipment to be found in each of the areas mentioned above.

3.6 Functions of the MITR Staff

The MITR staff has the dual responsibility for operation of the reactor in both an efficient and effective manner and also in a completely safe manner.

a) In carrying out the first responsibility for efficient and effective operation, the functions of the staff, in conjunction with other Nuclear Reactor Laboratory personnel include:

Operation of the reactor on a weekly schedule that is optimum for research and educational users, consistent with economic constraints.

Adjusting schedule to accommodate users as necessary and feasible.

Developing and providing detailed information concerning the reactor and its experimental facilities.

Assisting experimenters, both from MIT and elsewhere, in planning experiments for the most effective use of desired radiations, in evaluating safety questions and in preparing required applications.

Scheduling experiments and irradiations.

Advising experimenters on the availability of special equipment, laboratories and other facilities at the MITR-II, the Nuclear Reactor Laboratory and the Institute.

Providing, along with other staff of the Nuclear Reactor Laboratory, such administrative support as may be appropriate.

Advising on the need for Nuclear Regulatory Commission (NRC) licensing and providing, where appropriate, for utilization of existing source and special nuclear material licenses currently in effect at the MITR.

Providing for the accounting of nuclear materials, when required, under MIT's Accountability Station CCP.

Procuring the supplies, services and spare parts needed for reliable reactor operation; providing for an adequate fuel supply, its effecient use, and the storage and shipping of spent fuel.

Maintaining records of the above activities and reporting on most of them to USDOE under the terms of the contract described in Section 2.

Assisting other educational institutions in training and research uses of the MITR-II and reporting on such activities under the terms of the USDOE "reactor sharing" contract.

b) Staff functions related to safe operation are summarized below. All of them are subject to unannounced NRC inspections, which occur several times each year.

Developing a qualified staff and maintaining the required skills and knowledge through an approved requalification program. Members of the operating staff must hold NRC licenses.

Understanding and observing all the requirements of the Code of Federal Regulations, Titles 10 and 49, of the reactor license, and of other NRC licenses applicable to nuclear materials at the reactor and the Nuclear Reactor Laboratory.

Preparing written procedures, and adhering to them, for normal operation, abnormal and emergency conditions, for maintenance, for experiments and for other appropriate activities.

Reviewing new procedures, equipment and experiments and changes to existing procedures, equipment and experiments, and documenting such reviews.

Maintaining the reactor, its protective and process systems, and the containment in such condition as will assure safe and reliable operation.

Assuring the continuance of the above condition through a comprehensive program of tests and calibrations.

Providing a high level of quality in operation, maintenance, modification and use of the reactor, and also for radioactive material shipping, through an approved Quality Assurance Program.

Providing for the physical security of the reactor and associated nuclear materials through an approved security plan.

Working with MIT's Radiation Protection Office, the MIT Reactor Safeguards Committee, the Nuclear Regulatory Commission, and other cognizant agencies in achieving the above objectives.

Maintaining records of the above activities and reporting on them annually to USNRC.

4. RECORD OF REACTOR OPERATION

4.1 Historical Summary

July 1951	Nuclear Division, under direction of Professor Manson Benedict, established in MIT Chemical Engineering Department.
March to December 1955	Conceptual design of MIT Reactor completed by its first director, Professor Theos J. Thompson, and drawings sent out for bid.
May 7, 1956	Construction permit issued by US Atomic Energy Commission.
June 6, 1956	Ground broken on site at 138 Albany Street, Cambridge, Massachusetts.
June 9, 1958	Operating License R-37 issued by USAEC.
July 1, 1958	Department of Nuclear Engineering established, with Professor Manson Benedict its first head.
July 21, 1958	Initial criticality achieved at 7:03 p.m.
February 20, 1959	First operation at 1 MW.
July 20, 1959	Began three-shift operation.
July 12, 1961	Commenced operation at 2 MW.
November 1, 1965	Commenced operation at 5 MW.
March 1, 1967 to June 2, 1967	Operated at 2 MW due to leak in one of two main heat exchangers.
September 1967	MITR-II design studies initiated.
November 18, 1970	Application and Safety Analysis Report for MITR-II sent to USAEC.
April 9, 1973	Construction Permit CPRR-118 issued by USAEC; procurement of major components commenced.
May 24, 1974	MITR-I shut down for last time at 4:18 p.m.
July 23, 1975	Operation of MITR-II authorized by Amendment No. 10 to License R-37.
August 14, 1975	MITR-II achieved first criticality at 1:38 p.m.
December 8, 1975	Low power testing complete; power escalation commenced.

January 13, 1976	Operation at 2.5 MW (1 primary pump) commenced and three shift operation was resumed.
July 1, 1976	Reactor transferred from Nuclear Engineering Department to a new interdepartmental laboratory, the Nuclear Reactor Laboratory, under the MIT Vice President for Research.
December 1, 1976	Operation at 5 MW commenced.
December 1976	Routine operation at 5 MW for about 95 hours per week.

4.2 Operating Statistics

A summary of operations is given in Table 4-1, both for MITR-I and MITR-II.

Explanatory notes for Table 4-1:

1) Initial criticality MITR-I was on 7/21/58. Initial criticality MITR-II was on 8/14/75.

2) Includes 241 MWH of full power operation occurring during first year, 7/21/58-7/19/59, which consisted mostly of testing, calibration, and low power runs.

3) Power escalation commenced on 12/8/75 after completion of prerequisite subcritical and low power testing.

4)

1 MW	- 2/20/59 to 7/12/61
1.8 MW	- 7/12/61 to 11/17/61
1.95 MW	- 11/20/61 to 10/15/65
3.0 MW	- 10/18/65 to 10/22/65
4.0 MW	- 10/25/65 to 10/29/65
4.9 MW*	- 11/1/65 to 2/23/67
1.95 MW	- 3/1/67 to 6/2/67 (for heat exchanger repairs)
4.9 MW*	- 6/5/67 to 5/24/74 (shutdown date for modification)
2.5 MW	- 1/5/76 to 10/30/76
4.9 MW*	- 12/1/76 to 6/30/85

*May be less than 4.9 MW in hot summer weather.

5) Most reactor operator training is conducted during routine reactor startups and shutdowns or at full power and, hence, most of it is included on lines 2a, d, and e.

6) These classifications started 1/1/65; prior to that date these hours were included elsewhere or were not accounted for.

7) Usually Friday nights, Saturdays, Sundays, and major holidays.

TABLE 4-1

SUMMARY OF OPERATIONS

	MITR-I		MITR-II		
	15 Yr. Cum. 7/20/59 - 5/24/74	4 Yr. Aver. 7/1/70 - 5/24/74	9.6 Yr. Cum.[3] 12/8/75 - 6/30/85	4 Yr. Aver. 7/1/80 6/30/84	FY 1985 7/1/84- 6/30/85
1. Megawatt Hours:					
a. For period, MWH	250,324	23,969	186,326	21,315	19,037
b. Cumulative from initial criticality,[1] MWH	250,565[2]		436,891		
2. Hours of Reactor Operation:					
a. At full power[4]	71,823	5,046	41,309	4,544	4,487
b. Subcritical and critical (less than full power) for operator training[5]	204[6]	24	157	2	10
c. Same - for teaching, experimental and other purposes	1,458	40	1,706	63	103
d. Approaching full power (including startup checks)	2,995[6]	235	2,236	155	90
e. Completing shutdown	2,103[6]	236	2,195	216	182
Subtotal 2a - 2e	78,583	5,581	47,603	4,980	4,872
3. Hours for Reactor Maintenance and Other:					
a. Refueling	668[6]	77	662	33	19
b. Maintenance and changing experiments	8,131[6]	563	6,533	642	619
c. Not in use, no maintenance[7]	42,720[6]	2,545	29,034	3,124	3,226
Subtotal 3a - 3c	51,519	3,185	36,229	3,799	3,864
Total Hours in Period	130,102	8,766	83,832	8,779	8,736
4. Hours/Week at Full Power - Average	93.0	96.8	82.8	87.0	86.3
5. Samples Irradiated	18,795	566	28,236	4,887	2,627
6. U-235 Burnup, Grams	13,204	1,255	9,937	1,137	1,014

NOTES: See previous page.

4.3 Current Operating Schedule

The normal operating schedule calls for raising power to 5 MW on Monday, usually in the late morning or during the afternoon, after completion of mechanical and electronic startup checklists, experiment changes, and preventive maintenance. The reactor normally shuts down for the weekend around 6 p.m. on Friday, giving 90-100 hours at full power during a typical week.

The reactor usually runs through mid-week minor holidays, but it may start up on Tuesday when a holiday is observed on Monday. Holidays and other shutdowns contributed to reducing the MITR-II full power hours to an average of 86.3 hours/week, as shown on Table 4-1.

4.4 Fuel Utilization

The MITR-II core structure can hold a maximum of 27 fuel elements. Normally several positions are occupied by irradiation facilities, by in-pile experiments, or by solid aluminum dummy elements (to reduce reactivity). At the end of FY 1985 there were 24 fuel elements in the core.

Under the fuel management program for the MITR-II, the fuel elements (the two ends of which are identical) are inverted at least once during their lifetimes in the core for the purpose of maximizing the burnup. This has averaged about 42% with a peak fission density of 1.8 x 10^{21} fissions/cm^3 in the fuel meat. Based on studies at the Advanced Test Reactor in Idaho, it may be possible to increase the peak limit by 20-30%. Elements are changed a few at a time and average about four years in the core.

In 1974, 44 elements were fabricated as the first batch of fuel for the MITR-II. During 1980-81 another 25 were made, followed by an additional 16 in 1982 (four of which remain in storage off-site). Six more are scheduled for 1986. About six on the average will be required every year thereafter, based on the present operating schedule.

Table 4-2 shows the fuel receipts from AEC/ERDA/DOE, burnup and returns, by MIT fiscal year (July 1 through June 30). A total of 243 elements of the MTR-type were used in the MITR-I.

TABLE 4-2

U-235 RECEIPTS, BURNUP AND RETURNS

Date of Transfer (Fiscal Year)	Receipts Kgs. U-235	Form	Burnup Kgs. U-235	Returns to AEC/ERDA/DOE Kgs. U-235
1958	5.00	Metal (26 elements)	0	0.03[1]
1959	1.00	Metal (13 elements)	0.01	0
1960	0		0.23	1.61[2]
1961	2.90	18 elements	0.24	0
1962	1.05	8 elements	0.50	0
1963	5.65	35 elements	0.50	0
1964	0		0.49	0
1965	0		0.53	0
1966	5.43	36 elements	1.03	0
1967	1.43	9 elements	1.04	5.44[3]
1968	3.18	20 elements	1.25	0
1969	3.51	21 elements (333 plates)	1.22	5.97[3]
1970	4.18	25 elements (400 plates)	1.29	0
1971	4.57	27 elements (438 plates)	1.29	0
1972	0		1.26	5.32[3]
1973	2.11	12 elements (203 plates)	1.27	0
1974	19.58	44 elements (MITR-II)	1.06	0
1975	0		0	0
1976	0		0.12	7.57[4]
1977	0		0.89	0
1978	0		1.21	0
1979	0		1.05	0
1980	2.03	4 elements	1.11	0.35[5]
1981	4.05	8 elements	1.15	0
1982	4.56	9 elements	1.10	0
1983	2.03	4 elements	1.13	0
1984	4.56	9 elements	1.17	0.51[6]
1985	1.52	3 elements	1.01	0
Totals to 6/30/85	78.34	331 elements	23.15	26.80
1986 estimate	3.06	6 elements	1.12	6.27[7]
1987 estimate	6.12	12 elements	1.12	0
1988 estimate	0		1.12	0
1989 estimate	6.12	12 elements	1.12	6.27[7]
1990 estimate	0		1.12	0
	93.64	361 elements	28.75	39.34
Less:	-1.61	Returned, cold scrap[2]		
	-0.03	Transferred, not fuel[1]		
	92.00	Total fuel received by 1990		

1. Transferred as cold U-235 from MITR License R-37 to MIT License SNM-171. (This was received in the form of calibration rods, etc., not fuel elements, in 1958).
2. Returned to AEC as recoverable cold scrap in 1960.
3. Returned to AEC as 56 spent fuel elements, 28 elements per shipment.
4. Returned to ERDA as 75 spent fuel elements, in three shipments.
5. Returned to DOE as special unirradiated elements.
6. Returned to DOE as one damaged fuel element (unirradiated).
7. Return to DOE as 24 spent fuel elements (MITR-II).

4.5 Heavy Water Utilization

The MITR-I was cooled and moderated by heavy water and required an inventory of 10,400 pounds of D_2O. Sampling losses, minor leaks and evaporation into the helium cover gas resulted in an annual consumption of about 100 pounds per year.

Tritium formed by the neutron irradiation of the heavy water built up to a concentration of 2.5 Ci/liter in the MITR-I. Since this created a radiation exposure risk upon breeching of the primary system or its helium cover-gas system during maintenance or otherwise, it was decided to request a supply of low-tritium heavy water, granted by ERDA, with which to fill the MITR-II reflector tank. In June 1977, 14,072 pounds of D_2O from the MITR-I were returned to ERDA.

In the MITR-II only the reflector tank is filled with heavy water, and the inventory is just over 5,000 pounds. It is not necessary to open this system, as was the case with the MITR-I for each refueling, and less leakage at valves and pump seals occurs, so that losses have been less than for the MITR-I. Deuterization of ion columns, sampling, and small leaks in the heavy water and helium systems have resulted in losses averaging 44 pounds per year.

4.6 Spent Fuel Shipments

As indicated in Table 4-2 and its footnotes, nine shipments of MITR-I fuel have been made with 24.30 Kg. U-235 in 243 elements. Twenty-nine MITR-II elements have now accumulated in the spent fuel storage tank, and so additional shipments of spent fuel can be made as soon as a suitable approved shipping container can be made available by DOE.

5. MIT RESEARCH USE

5.1 Faculty and Student Participation

The principal users of the reactor are MIT faculty and students involved in research of types that require a reactor, neutrons or other reactor radiations. The nature of the research conducted by the more frequent users is given in the following subsections.

Since the MITR-II began relatively routine operation in 1976 (first at 2.5 MW and then at 5 MW starting on December 1, 1976), the reactor was used by four MIT departments and laboratories in FY76, by ten such groups a year later in FY77, and by sixteen in FY85. The following Table 5-1 lists the FY85 users as well as previous groups, 33 in total since the MITR began operation in 1958.

Statistics on the number of faculty, students and other personnel involved in research related to the reactor have been maintained for the principal MIT groups using the reactor. In the past these have been the Departments of Nuclear Engineering, Mechanical Engineering, Physics, Chemistry, Chemical Engineering, Earth, Atmospheric and Planetary Sciences, Nutrition and Food Sciences, and Materials Science and Engineering. Effective July 1, 1976 the administrative control of the reactor was transferred from the Department of Nuclear Engineering to a new interdepartmental Nuclear Reactor Laboratory (NRL). The Director and other personnel of the NRL now constitute another group among the principal users and, starting with FY76, were included in the tabulation of the number of individuals doing research involving the reactor. Table 5-2 lists the number of research users of MITR-II for the last three years, including 1985.

5.2 Description of Research and Sources of Support

Brief descriptions of the research projects undertaken by the major reactor users during FY85 are provided below. Major technical highlights developed by these projects are provided in Section 8. Listings of theses, journal articles, conference papers and reports emanating from these projects are given in Appendices 10.3-10.8.

TABLE 5-1

MIT DEPARTMENT AND INTERDEPARTMENTAL LABORATORIES
THAT HAVE USED THE MIT REACTOR

	1984-1985 (FY85)
A. Department[1] and Laboratories[2] within Departments	
1. Aeronautics and Astronautics	
2. Instrumentation Laboratory (to 1973)	*
3. Chemical Engineering	*
4. Chemistry	
5. Civil Engineering	
6. Hydrodynamics Laboratory	
7. Water Quality Laboratory	
8. Earth, Atmospheric and Planetary Sciences	*
9. Electrical Engineering	*
10. Insulation Research Laboratory	
11. Electronic Systems Laboratory	
12. Materials Science and Engineering	*
13. Mechanical Engineering	*
14. Surface Laboratory	
15. Materials Processing Division	
16. Meteorology	
17. Naval Architecture and Marine Engineering	
18. Nuclear Engineering	*
19. Nuclear Engineering Laboratories	*
20. Nutrition and Food Science	*
21. Physics	*
22. Radioactivity Center	
23. Biology	*

TABLE 5-1 (continued)

MIT DEPARTMENTS AND INTERDEPARTMENTAL LABORATORIES THAT HAVE USED THE MIT REACTOR

	1984-1985 (FY85)
B. Centers and Interdepartmental Laboratories	
1. Center for Advanced Engineering Studies	
2. Center for Materials Science and Engineering	
3. Lincoln Laboratory	
4. Laboratory for Nuclear Science	
5. National Magnet Laboratory	*
6. Nuclear Reactor Laboratory[3]	*
7. Radiological Safety Office	*
8. Research Laboratory for Electronics	
9. Energy Laboratory	*
10. Plasma Fusion Center	*

NOTES:
1. Used for teaching and/or research by department faculty or students not associated with a particular laboratory.
2. Used for research by laboratory personnel.
3. Since 7/1/76.

TABLE 5-2

Number of Individuals Participating in Research Involving the Reactor
(during school years 1982-83, 1983-84, and 1984-85)

Department	Faculty & Research Staff			Students			Engineering Assistants			Technicians			Others			Total		
	83	84	85	83	84	85	83	84	85	83	84	85	83	84	85	83	84	85
Nuclear Reactor Laboratory	10	8	6[1]	6	8	6[1]	3	3	4[2]	12	10	11[2]	14	14	14[2]	45	43	41
Nuclear Engineering	8	7	5	8	7	5					1					16	15	10
Physics	4	4	4	1	5	2	1									6	9	6
Earth & Planetary Sciences	8	6	5	6	6	7										14	12	12
Materials Science & Engineering	6	6	5	5	2	6										11	8	11
Chemical Engineering	2	1	1	2	2	2										4	1	1
Applied Biological Sciences	2	2	2	4	1	1										6	3	2
Other MIT	6	6	5	1	1											7	7	5
MIT Subtotal	46	40	33	33	32	29	4	3	4	12	11	11	14	14	14	109	98	88
Collaborating with MIT Researchers	43	29	27													43	29	27
Reactor Sharing Program (research only; academic users not included)	27	14	18	6	24	16										33	38	34
Non-MIT Research Subtotal	70	43	45	6	24	16										76	67	61
Total Research Involvement	116	83	78	39	56	45	4	3	4	12	11	11	14	14	14	185	165	149

(1) Includes faculty, staff and students of unlisted departments involved in joint projects with NRL.

(2) These three categories are mainly reactor operations and support staff.

During the past year the Nuclear Reactor Laboratory (NRL) engaged in joint activities with nine academic departments and interdepartmental laboratories. These joint research or teaching and training activities cover a wide spectrum in the life and physical sciences and in engineering, including neutron scattering studies of condensed matter, nuclear materials research and development, radiochemistry and trace analysis applied to health effects of coal use, nutrition studies, earth and planetary sciences, nuclear medicine, reactor engineering, computer control of reactors, and training in reactor operations.

5.2.1 Neutron Physics

Professor Clifford G. Shull and his Physics Department group, including several visiting faculty from the Technical University of Vienna, Stonehill College, New York University, and Hampshire College, have continued their studies on the fundamental wave properties of thermal neutrons and the diffraction physics of neutrons in crystals. Present-day interest in the possible existence of magnetic monopoles (isolated magnetic charges) has led the group to consider the question of magnetic neutrality of the neutron or, equivalently, the degree of magnetic balance between the magnetic poles of the known magnetic dipole moment. An experiment has been designed and carried out which has led to an upper limit of 10^{-17} for the fractional unbalance of the separated poles, which represents about six orders of magnitude increase in sensitivity over that available from previous observations. In this experiment, the anomalously low effective mass of diffracting neutrons in a crystal is exploited in searching for trajectory deflections with an applied homogeneous magnetic field. Studies have continued on the coherence characteristics of neutrons while traversing a two-crystal interferometer system. The action of phase-retarding edges and refracting prisms on neutrons passing through a limiting slit placed inside the interferometer has been studied. These observations are compared with calculations of wave-mechanical effects and lead to fundamental conclusions concerning the coherence characteristics of the neutron wave packets. Theoretical studies have continued on the possible existence of a neutron-spin Pendellösung resonance effect in crystals in which the Larmor spin precession length is matched to the Pendellösung length in the crystal. An experiment to test this effect is being designed. Support for this research is provided by the National Science Foundation (NSF) and the US Department of Energy.

5.2.2 Nuclear Materials Research and Development

A major alloy development project for fusion reactor first wall materials was continued for the seventh year with USDOE support. This research is directed by Professor Nicholas J. Grant, of the Department of Materials Science and Engineering, and Professor Otto K. Harling, director of the NRL. Professor Linn W. Hobbs, of the Department of Materials Science and Engineering, also participated in the project. Senior research staff included Drs. Janez Megusar and Gordon Kohse. One graduate student completed his Ph.D. dissertation, and several others are currently doing their research on this project. More than 50 journal articles and formal reports have been completed to date as a result of project activities. A major thrust of this research effort has been the exploration of the use of innovative alloy processing techniques, such as rapid solidification from the melt, for the purpose of developing primary first wall alloys for fusion reactor first wall applications. The development of improved first wall alloys is on the critical path toward economical fusion power. The MIT approach provides a means to manipulate alloy microstructure and microchemistry in order to beneficiate irradiation performance. Alloy design, alloy production, irradiation testing, and postirradiation characterization are the major parts of this interdisciplinary project. Important results from the program included a model for irradiation performance of Ti and C containing austenitic stainless steels and successful testing of highly irradiated ($\approx$40 dpa) miniature alloy specimens using a miniature tensile test developed at the NRL. Emphasis in this project has shifted from austenitic stainless steels to ferritic steels and high performance copper alloys. The ferritic materials are inherently more resistant to radiation-induced void swelling but are susceptible to hydrogen embrittlement and exhibit a ductile-to-brittle transformation which after irradiation can shift to the normal operating temperature range. Major emphasis is being placed on improving the ductile-to-brittle transformation temperature by alloy design and processing. Characterization of materials from a major irradiation experiment on high performance copper alloys is proceeding on schedule. This experiment is expected to provide, for the first time, information on the irradiation performance of copper alloys at service temperatures for high neutron doses. Significant progress was also achieved with support from the Electric Power Research Institute in the development of a new miniature specimen test for the determination of the ductile-to-brittle transition temperature. Graduate students involved in all phases of alloy design, production, and testing obtained unique research experience in materials research with irradiated specimens.

5.2.3 Radiochemistry and Trace Analysis

Professor Frederick A. Frey and research collaborators utilize the MITR-II for neutron activation analysis of geologic materials. The activation analysis laboratory operated by Professor Frey and Dr. Pillalamarri Ila was utilized by ten graduate students doing thesis research in the Department of Earth, Atmospheric and Planetary Sciences and by visiting scientists from foreign countries and other New England universities. During the past year MIT-based research has used geochemical studies to understand how volcanoes evolve and to define the compositions of the materials melted to form lavas in various geologic environments. A complementary geochemical study has focused on mantle-rocks which formed at depths below the earth's crust. The results can be used directly to understand processes occurring at 50-100 km depth, a region where partial melts segregate from their source materials.

In the same department, Professor M. Gene Simmons, Dr. Louis J. Caruso, and students have used particle track etch and other techniques to study the location and distribution of uranium with respect to mineral grain boundaries, microcracks, and clay components. Recent results, based in part on improved resolution (on the order of microns), indicate that popular models and theories must be modified or discarded, e.g., uranium once ascribed to grain boundaries has been shown to be located in sealed microcracks, and mineral hosts for uranium have been misidentified. These findings bear on our understanding of the origin, deposition, and migration of uranium in the earth's crust and our plans for selecting and engineering repository sites for radioactive waste. Support for work in Geology and Geochemistry was provided principally by the National Science Foundation, although significant support was also obtained from a variety of other sponsors.

NRL's capability for supporting research that relies on the neutron activation technique of trace analysis has been significantly enhanced by the recent addition of Dr. Ilhan Olmez, an experienced radiochemist, to the Laboratory staff. He replaced Dr. Morteza Janghorbani, who last year resigned from his position at NRL to accept a faculty appointment at Boston University's School of Medicine. Dr. Olmez has been actively engaged in a number of environmental research projects that use neutron activation analysis, and he brings this expertise to NRL. He and Mr. William Fecych are modifying the technique as applied to analyses of fly ash in order to improve on the technical support for the coal combustion research of Professor Adel F. Sarofim in Chemical Engineering. Meanwhile Dr. Janghorbani and his radiochemistry group at Boston University are continuing their activities in the area of stable isotope applications in human studies and are using the MIT Reactor to activate samples and NRL counting equipment to analyze them. In earlier research at MIT they developed methodology for metabolic studies of MIT young adults in the areas of zinc, selenium, and copper nutrition. Much of the work is based on recently developed concepts of biologically labeled foods and has been carried out for the first time at MIT. In addition to their metabolic studies, carried out jointly with Professor Vernon R. Young of the Department of Nutrition and Food Science and the MIT Clinical Research Center, they have continued to develop collaborative programs in areas for which stable isotopic methods are the sole practical approach: studies with neonates, mineral metabolism in relation to human pregnancy, and many human metabolic disorders. They have ongoing programs with researchers at such other institutions as Wayne State University (zinc marginal deficiency in man and homeostasis of zinc-copper in Wilson's disease) and Yale University (mineral nutrition of neonates). Additional projects that are being developed include the use of lanthanides as non-absorbable markers, initiation of selenium metabolic studies in infants, and use of rubidium and bromine as markers in body composition study. Support for these varied research efforts was obtained from the National Institutes for Health (NIH), USDOE and MIT.

In collaboration with Professor Alexander Varshavsky and Dr. Robert M. Snapka, Biology Department, neutron radiography has been combined in a unique manner with chromatograph evaluation of amino acid systems. In initial studies assay sensitivity was increased by an order of magnitude. Work during the past year has resulted in further substantial gains in sensitivity while at the same time this new technique of post-separation activation eliminates the considerable uncertainties and errors which can result from the direct use of high concentrations of radioactive tracers in biochemical experiments. This work was supported by MIT and USDOE.

5.2.4 Computer Control of Reactors

Professor David D. Lanning, Nuclear Engineering Department, and Dr. John A. Bernard continued studies on the closed-loop, digital control of nuclear reactors during both steady-state and transient operation. A general set of control principles, based on reactivity constraints and intended for nonlinear conditions, has been deduced and experimentally demonstrated on the MIT Reactor. This approach is unique in that it is based on the general equations of reactor dynamics rather than measurements of specific response characteristics. This work, which is supported by the National Science Foundation, resulted in six publications and three major accomplishments during the past year. The first accomplishment was that the US Nuclear Regulatory Commission approved an amendment to the MIT Reactor's license that permits the automatic control of the reactor's shim blades. (Previously, such permission existed only for the fine control regulating rod.) Closed-loop control experiments can now be performed without à priori restrictions on the associated reactivity. The issuance of this license culminated an 18-month effort in which safety evaluations were prepared. The significance of this amendment is that 1) no other research reactor in the United States has such a broad approval for closed-loop control and 2) a precedent has been established for our approach regarding closed-loop control. This gives the reactivity constraint concept an enormous lead over competing ideas in the United States. The project's second major accomplishment during the past year was the successful completion of closed-loop control experiments using actuators with differential worths that were a factor of five greater than those previously tested. The third accomplishment was the first use of 'fuzzy' logic in the closed-loop control of reactor power. This work may lead to controllers based on cognitive models of the human decision process.

A collaborative effort with the Charles Stark Draper Laboratory in the areas of signal validation and fault detection remains ongoing. This research resulted in two S.B. theses during the past year. Real-time demonstrations of this technology were conducted during the 1985 Annual Meeting of the American Nuclear Society.

5.2.5 Coolant Corrosion and Dose Reduction Studies

Professor Michael J. Driscoll of the Nuclear Engineering Department and Professor Otto K. Harling of the Nuclear Reactor Laboratory initiated a study concerning the use of research reactor in-pile loops for coolant corrosion and dose reduction in light water power reactors (LWR's). A compact and inexpensive loop to simulate a pressurized water reactor was designed as part of a student thesis. Substantial progress was made toward the definition of a comprehensive research program for dose and corrosion reduction in LWR's and a conceptual design for a compact loop to simulate boiling water reactor conditions was completed. Support for this work was provided by the Institute of Nuclear Power Operations through a student fellowship and by MIT. Further support from the nuclear utilities is expected and major support for a full-blown research and testing program is being sought from EPRI, USDOE and the nuclear industry.

5.2.6 Nuclear Medicine

Professor Gordon L. Brownell, Nuclear Engineering Department, continues a program of basic study leading toward the successful application of boron neutron capture therapy. Working with Dr. John Kirsch, track etch autoradiography has been developed to determine the boron distribution in tissue samples. Resolutions approaching the theoretical limit of about 0.5 μm for present techniques have been achieved and make it possible to determine boron distributions at the cellular level. Under study is the feasibility of using electron microscopy and image processing, which could further improve resolution by orders of magnitude. The group participated in the Second International Symposium on Boron Neutron Capture Therapy held in Tokyo in October 1985. Support for this work was received from NIH.

Medical imaging using reactor produced isotopes is assuming increased importance in biomedical research. Studies of F-18 production, supported by the Massachusetts General Hospital and MIT, at the MIT reactor have indicated that this isotope can be produced in adequate quantities.

5.2.7 Undergraduate Research Opportunities Program

The Undergraduate Research Opportunities Program (UROP) provides MIT undergraduates the opportunity to participate with faculty and staff members in a wide range of research activities both on and off campus. Students may participate in ongoing research or find a faculty sponsor for a self-originated project. The program is supervised by coordinators in each Institute department and laboratory. Students involved in reactor-related projects have come from the Department of Nuclear Engineering, Civil Engineering, and Physics and have participated in such areas as:

trace element concentrations in environmental materials by neutron activation analysis

neutron spatial and energy distributions by foil activation in the Blanket Test Facility

neutron physics measurements on a triple-axis spectrometer

heat transfer characteristics of gamma heated materials in the MITR
studies of trace element distributions by particle track etch techniques

trace element behavior in aquaculture systems and essential trace element dynamics of animal models

nuclear materials research

5.2.8 Other MIT Research Use

Use of the MITR by the other MIT departments and laboratories listed in Section 5.1 generally consists of material irradiations for studies of irradiation effects, production of radioactive tracers, neutron activation analysis and similar projects. Since some of these constitute comparatively minor utilization of the reactor, no attempt is made to obtain information concerning the number of personnel involved (usually at least a student and a faculty supervisor), the source of support or the titles of theses and papers which may ultimately be generated.

6. MIT EDUCATIONAL USE

6.1 Department of Nuclear Engineering

The reactor is now used in five courses of instruction offered each year by the Department of Nuclear Engineering. The catalog descriptions follow:

22.09 Introductory Nuclear Measurements Laboratory

Basic principles of interaction of nuclear radiation with matter. Statistical methods of data analysis; introduction to electronics in nuclear instrumentation, counting experiments using Geiger-Muller counter, gas filled proportional counter, scintillation counter, and semiconductor detectors. A term project emphasizes applications to experimental neutron physics, radiation physics, health physics, and reactor technology. Meets with 22.29, but assignments differ.

22.29 Nuclear Measurements Laboratory (A)

Basic principles of interaction of nuclear radiations with matter. Principles and methods for detection and energy determination of gamma rays, neutrons and charged particles. Experiments on gas-filled, scintillation, and semiconductor detectors; nuclear electronics such as pulse amplifiers, multichannel analyzers, and coincidence techniques; applications to neutron activation analysis. X-ray fluorescence analysis, neutron diffraction, and radiation dosimetry. Meets with 22.09, but assignments differ.

22.39 Nuclear Reactor Operations and Safety (A)

Principles of operating nuclear reactor systems in a safe and effective manner. Emphasizes light water reactor systems with transient response studies including degraded core recognition and mitigation. Consequence analysis and risk assessment. Lessons from past accident experience. NRC licensing and regulations. Demonstrations: operation of the MIT Research Reactor, use of a PWR concept simulator. Optional laboratory section involves a project at the Nuclear Reactor Laboratory.

22.55J Biological and Medical Applications of Radiation and Radioisotopes (A)

Principles of radiation production and interactions. Radiation dosimetry emphasizing 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. Requires a comprehensive term paper and presentation.

22.58 Principles and Practices of Radiation Measurement and Protection

This "new" course has now been taught successfully three times. It is a combination of lecture, demonstrations and laboratory exercises which make heavy use of the MITR. It covers the theory and practice of radiation detection and measurement. The control and management of radiation exposure with applicable standards. Real experience in radiation use, measurement, and control is provided at the MITR, power reactors and several accelerators. Also covers preparation of isotopes, shielding, analysis and design of radiation protection systems and procedures. Designed to provide a good introduction to most aspects of radiation measurement and protection at the graduate level.

6.2 Department of Physics

The Department of Physics offers an undergraduate course that uses the Nuclear Reactor Laboratory. See the course description below:

8.13 Experimental Atomic Physics I
8.14 Experimental Atomic Physics II

About six fundamental laboratory experiments carried out each term, covering most aspects of modern physics relating to names such as Rutherford, Franck-Hertz, Hall, Ramsauer, Doppler, Fraunhofer, Faraday, Mössbauer, Compton, Stern-Gerlach. Stresses basic experimental techniques and data analyses, and written and oral presentation of experiment results. Second term requires knowledge of quantum mechanics at the 8.05 level.

6.3 Department of Earth, Atmospheric and Planetary Sciences

Neutron activation analysis is taught in an undergraduate laboratory subject offered by the Department of Earth, Atmospheric and Planetary Sciences.

12.066 Analysis of Geological Materials

Determines the chemical composition of geologic materials. Analytical techniques include X-ray fluorescence, neutron activation, atomic absorption, mass spectrometry, electron microprobe, experimental petrology, Mössbauer, and other absorption spectral methods. Laboratory projects utilize these techniques to solve specific geologic problems. Limited to 12.

Table 6.1 provides data on enrollments in the above and other courses.

6.4 Undergraduate Seminars

Undergraduate seminars, which meet during the regular term, are designed to provide students an opportunity for close association with a faculty member in smaller and less formal groups and to provide freedom in planning and executing a selected program. The MIT Reactor was first involved in 1970-71, when the Department of Nuclear Engineering first offered such a seminar. Its current catalog description is as follows:

22.001 Seminar in Nuclear Engineering

Surveys the range of topics covered by the Nuclear Engineering Department. Introductory discussion of the basic phenomena of fission and fusion power and related aspects of reactor design. The many applications of Nuclear Engineering for research in biology, earth sciences, medicine, and physics discussed by guest lecturers from the appropriate discipline. A demonstration of the MIT Reactor as a research tool is given.

6.5 Independent Activities Period (IAP)

A month-long intersession period between the fall and spring terms provides opportunities for special activities involving the reactor. During January 1985 the Nuclear Reactor Laboratory sponsored a variety

TABLE 6-1

Enrollment in MIT Courses Using the Reactor

Subject No.	Level	Title	First Utilization	24 Years	Academic Year 81-82	82-83	83-84	84-85	28 Years
Nuclear Engineering Department									
22.001	U	Undergraduate Seminar in Nuclear Engineering	1970-71	217	34	19	9	11	290
22.04	U	Radiation Effects and Uses	1981-82	-	7	4	1	(a)	12
22.09	U	Introductory Nuclear Measurements Laboratory	1977-78	33	6	8	1	3	51
22.29	G	Nuclear Measurements Laboratory	1957-58	444	6	16	12	14	492
22.39	G	Nuclear Reactor Operations and Safety	1958-59	281	17	14	0	19	331
22.55J	G	Biological and Medical Applications of Radiation and Radioisotopes-I	1975-76	56	5	0	5	13	79
22.56J	G	Biological and Medical Applications of Radiation and Radioisotopes-II	1976-77	26	0	7	9	(a)	42
22.58	G	Health Physics II	1982-83	-	-	1	5	6	12
Physics Department									
8.13 & 8.14	U	Experimental Atomic Physics	1982-83	-	-	8	25	40	73
Earth and Planetary Sciences Department									
12.066	U	Analysis of Geological Materials	1970-71	69	5	7	8	(a)	89
Mechanical Engineering Department									
2.80S	S	Man-Machine Interfacing in Nuclear Power and Industrial Process Control	1979-80	55	55	30	(a)	12	152
2.672	U	Project Laboratory	1979-80	107	43	52	70	67	339
Institute-Wide									
IAP	U &G	Independent Activities Period (mini-courses)	1971-72	141	88	268	82	12	591
Discontinued or replaced (5 courses)				148					148
			TOTALS	1577	266	434	227	197	2701

NOTE: (a) Not offered

of demonstrations and lectures involving the MITR. These included demonstrations of neutron activation analysis of fly ash from coal combustion and neutron radiography.

6.6 Operator Training

Two MIT undergraduates completed the reactor operator training course during the period, received licenses from the Nuclear Regulatory Commission, and since then have been working about half time as operators. One previously licensed operator passed the Senior Operator examination and received that license.

7. EDUCATIONAL, RESEARCH AND MEDICAL USE BY OTHERS

Since the beginning of operation, a total of 149 educational, research, medical, and commercial organizations (in addition to MIT) have utilized the reactor. A breakdown of this utilization is provided by Table 7-1.

In accordance with the policy set forth in Section 3.2, the Institute has always encouraged use of the reactor by local organizations. The nature and extent of such use is given in the following subsections.

7.1 Use by Educational Institutions and Research Centers

During FY 1983, FY 1984 and FY 1985 seven, five and eight, respectively, educational institutions and research centers used the MITR on a paid basis. Table 7-2 lists the organizations and the materials irradiated. Except for the technical information necessarily furnished in connection with the irradiation applications, we have not found it feasible generally to follow up on the research findings resulting from such utilization. The general nature of the research, however, is known to involve neutron activation analysis of geological and environmental samples, radiobiology studies by the particle track etch technique, and studies of radiation damage to electronic components.

7.2 Reactor Sharing Program

The US Department of Energy's Reactor Sharing Program makes feasible the conduct of reactor-related education and research by providing funds for such purposes where research contracts, grants, or other types of financial support are not available. Under this program a university owning a reactor may be reimbursed for the costs of making the reactor available to other educational institutions. Originally sponsored by the US Atomic Energy Commission, the program was continued by the Energy Research and Development Administration and subsequently by the Department of Energy.

Since the MITR became a participant in FY 1972, students from 43 departments at 32 educational institutions (as many as four different departments from some of them) have received training there, utilized it in research, and/or participated in tours and lectures. During the past

TABLE 7-1

SUMMARY OF EDUCATIONAL, MEDICAL AND RESEARCH USE BY OTHERS

	1959 -82	83	84	85	1959[1] -85
Educational and Research Institutions on Paid Basis	43	7	5	8	48
Educational Institutions in Reactor Sharing Program	27	21	14	21	43
Hospitals	9	4	4	4	9
Private Industry and Government Contractors	44	3	4	6	49
TOTAL ORGANIZATIONS	123	35	27	39	149

NOTE: 1. Columns do not add since many organizations are tabulated in more than one column.

TABLE 7-2

MITR USE ON A PAID BASIS BY OTHER EDUCATIONAL INSTITUTIONS AND RESEARCH CENTERS

	FY 1983	FY 1984	FY 1985
1. Boston College Chestnut Hill, Mass.	Rock samples for NAA	Rock samples for NAA	Rock samples for NAA
2. Boston University Boston, Mass.			Activation of stable isotope specimens for NAA
3. C.S. Draper Laboratory Cambridge, Mass.	Fast neutron irradiation of electronic components	Fast neutron irradiation of electronic components	Fast neutron irradiation of electronic components
4. University of Maine Orono, Me.			Radiation effects on solar cells
5. University of Massachusetts Amherst, Mass.	Rock samples for NAA		
6. National Bureau of Standards Gaithersburg, Md.			Activation of bio-medical specimens for NAA
7. Sandia National Laboratory Albuquerque, N. Mex.		Fatigue cracking of stainless steel under irradiation	
8. US Army Materials and Mechanics Research Center Watertown, Mass.			Activation of semi-conductor materials for NAA
9. University of Utah Salt Lake City, Utah	Trace Pu assay in biological specimens by particle track etch	Trace Pu assay in biological specimens by particle track etch	Trace Pu assay in biological specimens by particle track etch
10. Vanderbilt University Nashville, Tenn.	Rock samples for NAA		
11. Washington University School of Medicine St. Louis, Mo.	Radiation stability of estrogen (17α-CSE_2)		
12. Woods Hole Oceanographic Institute Woods Hole, Mass.	Activation of sea water specimens for NAA	Activation of sea water specimens for NAA	Activation of sea water specimens for NAA

three fiscal years (1983, 1984 and 1985) there have been 21, 14 and 21 such users, respectively. Table 7-3 lists the participants for those years, and as of this writing there is an increasing demand, especially for neutron activation analysis services.

7.3 Use by Hospitals

The local medical community benefits from use of the reactor (1) through research collaboration with MIT faculty and staff, (2) through purchase of radiopharmaceuticals made by local firms from radioisotopes produced in the MIT Reactor, and (3) through direct procurement of reactor services from the Nuclear Reactor Laboratory. Activities in the first category are described in Sections 5.2.3, 5.2.6 and 8.2, while the production of radioisotopes for radiopharmaceutical houses has been listed under commercial use, Section 7.4, even though a hospital is the ultimate user.

Hospitals in category (3) above are listed in Table 7-4. Principally they have called on the reactor in recent years for the activation of gold seeds used for cancer implants, chlorine-38 for pulmonary studies and dysprosium-165 for radiation synovectomies.

7.4 Use by Private Industry and Government Contractors

Since the reactor began operation it has been used by 49 industrial organizations, three, four and six during the most recent three fiscal years, FY 1983, FY 1984 and FY 1985, respectively. The companies and reasons for utilization are given in Table 7-5.

7.5 Visitors

Over 45,000 people have signed the MITR visitor registration book, and the current rate is about 1,500 per year. For FY 1985, tours for schools and other organized groups have been tabulated in Table 7-6, where there were five or more individuals on the tour. Smaller groups and individuals, such as potential applicants to MIT, visiting faculty, prospective reactor users, service and maintenance personnel, etc., make up the balance.

TABLE 7-3

MITR USE BY EDUCATIONAL INSTITUTIONS
UNDER USDOE REACTOR SHARING PROGRAM

	FY 1983	FY 1984	FY 1985
1. Bates College Lewiston, Maine	Fission track dating by particle track etch		Analysis of paintings by neutron radiography
2. Bentley College Waltham, Mass.	Lecture and tour for nuclear engineering students		
3. Boston College Chestnut Hill, Mass.	Activation of rock samples for NAA	Activation of rock samples for NAA	Activation of rock samples for NAA
4. Boston University a) School of Public Health Boston, Mass.	Lecture, tour and demonstrations for environmental health course		
b) School of Medicine Boston, Mass.			Activation of biomedical specimens for NAA using stable isotopes
5. Brandeis University Waltham, Mass.	Lecture and tour for neutron diffraction course		
6. Clark University Worcester, Mass.	Production of Mossbauer sources for Dy-161 relaxation studies	Production of Mossbauer sources for Dy-161 relaxation studies	
7. Gould Academy Bethel, Maine			Lectures and tour for in depth study of nuclear energy
8. Harvard College Physics Department Cambridge, Mass.		Assay of U in urine by particle track etch	Studies of donor atom, P, in amorphous hydrogenated silicon

TABLE 7-3 (continued)

9. Harvard-Smithsonian Astrophysical Observatory Cambridge, Mass.	Fission track dating of Antarctic specimens		Fission track dating of Antarctic specimens
10. Harvard University Medical School at Massachusetts General Hospital Boston, Mass.			
a) Physics Research Lab.	Production of F-18 for labeling brain metabolite (2 FDG)	Activation of Sr and Cu for calibration of PET scanner	
b) Pulmonary Unit	Production of Cl-38 for pulmonary studies	Production of Cl-38 for pulmonary studies	Production of Cl-38 for pulmonary studies
11. Harvard University Medical School at New England Deaconess Hospital Boston, Mass.		Lecture and tour for nuclear medicine students	Lecture and tour for nuclear medicine students
12. Massachusetts High School Science Teachers Numerous towns and cities			Lectures, tour and demonstrations on research reactors and their use - 17 teachers from 7 schools (new program)
13. Middlebury College Middlebury, Vt.	Activation of rock samples for NAA	Activation of rock samples for NAA	Activation of rock samples for NAA
14. Mt. Ida Junior College Newton, Mass.	Lecture and tour		
15. Northeastern University Boston, Massachusetts			
a) Chemistry Department		Mossbauer sources for study of Au-197 compounds	Mossbauer sources for study of Au-197 compounds

TABLE 7-3 (continued)

b) Mechanical Engineering Department	Tour and experiments for Nuclear Engineering course	Tour and experiments for Nuclear Engineering course	Tour and experiments for Nuclear Engineering course
c) Metallurgy Department	Assay of trace U in Si by partical track etch	Assay of trace U in Si by partical track etch	
d) Physics Department	Activation of Er-168	Tour and neutron energy spectrum measurements for Physics course	Tour and neutron energy spectrum measurements for Physics course
16. Purdue University Lafayette, Ind.	Labeling of food with stable isotopes for metabolic studies of Se and Zn		
17. Rensselaer Polytechnic Institute Troy, N.Y.			NAA of mouse organs
18. So. Maine Vocational Technical Institute South Portland, Maine			Tour for faculty and students
19. Teachers College Tanzania			Lecture and tour (6 faculty)
20. University of Maine Orono, Maine			Effects of radiation on surface acoustic wave devices
21. University of Massachusetts Boston, Mass.	Tour, NAA and other experiments for Physics course		Tour, NAA and other experiments for Physics course
22. Washington University St. Louis, Mo.	Radiation stability of estrogen (17 α - CEB_2)		

TABLE 7-3 (continued)

23. Wayne State University Detroit, Mich.	Study of Zn metabolism using stable isotopes and NAA	Study of Zn metabolism using stable isotopes and NAA	Study of Zn metabolism using stable isotopes and NAA
24. Wellesley College Wellesley, Mass.			
a) Biology Department	Study of boron deficiency in agricultural products by particle track etch		
b) Geology Department	Study of U distribution in granite by particle track etch	Study of U distribution in granite by particle track etch	
25. Worcester Polytechnic Institute Worcester, Mass.			Lecture on reactor design and tour
26. Yale University School of Medicine New Haven, Conn.	Study of Ca bioavailability in preterm infants using stable isotopes and NAA	Study of Ca bioavailability in preterm infants using stable isotopes and NAA	Study of Ca bioavailability in preterm infants using stable isotopes and NAA

TABLE 7-4

MITR USE BY HOSPITALS

	FY 1983	FY 1984	FY 1985
1. Beth Israel Hospital Boston, Mass.	Au-198 seeds	Au-198 seeds	Au-198 seeds
2. Brigham and Women's Hospital Boston, Mass.	Au-198 seeds and Dy-165	Au-198 seeds and Dy-165	Au-198 seeds and Dy-165
3. Massachusetts General Hospital Boston, Mass.	Cl-38	Cl-38	Cl-38
4. New England Deaconess Hospital Boston, Mass.	Au-198 seeds	Au-198 seeds	Au-198 seeds

TABLE 7-5

MITR USE BY PRIVATE INDUSTRY

	FY 1983	FY 1984	FY 1985
1. Boston Edison Co. Boston, Mass.		Reactor operator training	
2. Electric Power Research Institute Palo Alto, Calif.			NAA of coal fly ash
3. Gamma Diagnostics Laboratory, Inc. Attleboro Fall, Mass.			Dy-165 for radiation synovectomy
4. General Electric Co. Schenectady, N.Y.			Fast neutron irradiation of silicon
5. G.T.E. Products Corp. Sylvania Lighting Center Danvers, Mass.		NAA analyses of arc lighting materials	NAA analyses of arc lighting materials
6. International Copper Research Associates, Inc. New York, N.Y.	Irradiation effects on Cu alloy		
7. New England Nuclear, Inc. Boston, Mass.	P-32	P-32	P-32
8. Radiation Monitoring Devices, Inc. Watertown, Mass.	Evaluation of radiation detectors	Evaluation of radiation detectors	Evaluation of radiation detectors

TABLE 7-6

Reactor Tours - School Year 1984-85

1. Tours for groups of five or more:

Organization	Visits	Number of Visitors
American Nuclear Society members	1	16
Full Circle High School, Somerville, Massachusetts	1	5
Gould Academy, Bethel, Maine	1	69
Independent Testing Laboratory, New Jersey	2	11
Margaret Fuller Houser Computer Camp	1	17
Massachusetts High School Science Teachers	2	17
Massachusetts High School Teachers' Workshop on the Peaceful Uses of Atomic Energy	1	12
MIT orientation tours	15	159
National Science Teachers Association	1	11
Northeastern University	7	71
Phoenix School, Cambridge, Massachusetts	1	25
Rindge and Latin School, Cambridge, Massachusetts	1	6
Umana Technical High School, Cambridge, Massachusetts	1	9
University of Massachusetts, Boston, Massachusetts	4	34
Worcester Polytechnic Institute, Worcester, Massachusetts	1	9
Above listed tours	40	471

2. Visitors in groups of four or less — 405

3. Service, maintenance and miscellaneous — 336

Total Registration, School Year 1984-85 — 1212

8. PUBLICATIONS

8.1 Tabulation of Publications

Since the inception of the MIT Research Reactor, there have been 1580 theses completed and papers published that describe research activities supported by the MITR or that in some cases concern the reactor itself. About one-third of the publications have been student theses.

In FY 1985, at MIT, five theses (3 Ph.D. and 2 M.S.) were completed; 19 journal articles, 12 technical presentations and seven formal reports were published. Non-MIT educational and research institutions accounted for an additional nine publications, for a fiscal year total of 52. This number is somewhat down from the previous year. However, FY 1986 will show a marked increase in such output, e.g., publications completed, in press and submitted already total at mid-year 22 theses, 32 journal articles, 18 presentations and four reports, for a total of 76.

As mentioned in Section 2.2, MIT's contractual obligation with DOE requires that the Institute furnish a current list of all published reports embodying the results of activities involving the facility. Appendices 10.3-10.8 furnish the list of publications for fiscal year 1985 and also for FY79-FY84, a period for which listings have not been previously compiled in an annual report. The listings include title, authors, publication date and the affiliation of the authors, e.g., Physics Department, MIT. Together with previous reports this constitutes a complete bibliography of theses, journal articles, presentations and reports concerning research related to the MITR and concerning the reactor itself up until June 30, 1985.

The 1580 known publications (total output of the MITR) are tabulated in the following Table 8.1, which breaks them down according to the departments and laboratories making major use of the reactor. For those making only minor use, the publications (if known, which too often is not the case) are included in the Nuclear Reactor Laboratory totals. In all cases, the figures are derived from the listings in Appendices

TABLE 8-1

Tabulation of Theses, Journal Articles, Presentations and Reports Related to the MIT Research Reactor

Academic Year	Nuclear Reactor Laboratory[1]				Nuclear Engineering[2]				Physics				Earth and Planetary Sciences				Non-MIT Institutions				Totals[3]			
	T	J	P[4]	R	T	J	P	R	T	J	P	R	T	J	P	R	T	J	P	R	T	J	P	R
1954-55 thru 1977-78	10	4		6	276	233		65	48	53		23	28	92		12	Not tabulated prior to 1979-80				407	459		134
1978-79	5	4		7	10	2		4	3	1				15	14		1	3	3		14	24	17	8
1979-80	3	10	4	11	6	2	3	6	1	3	1		1	7	3	2		2			9	22	9	14
1980-81	6	24	3	8	4	4	2	1		2				2	5	1		3	5		6	32	15	10
1981-82	6	18	11	5	10	5	2	2	3	2	1		2	5	9			9	4		16	37	27	7
1982-83	7	19	9	11	8	6	2	3		4	1		2	4	7	1	7	14	12	2	23	45	30	16
1983-84	6	35	19	3	8	5	12	5	3	11	8	1	3	9	9		6	12	5		22	68	48	9
1984-85	3	11	11	6	1	3	6			3		1	2	5	1		1		8		6	19	20	7
31 years	46	125	57	57	323	260	27	86	58	79	11	25	38	139	48	16	15	43	37	2	503	706	166	205
	285				696				173				241				97				1580			

NOTES: T - Theses; J - Journal Articles; P - Presentations[4]; R - Reports

(1) The Nuclear Reactor Laboratory was established July 1, 1976. Includes publications of several other departments not listed separately (e.g., Materials Science and Engineering, Chemical Engineering, Applied Biological Sciences, etc.)

(2) Where applicable (i.e., theses and publications authored by department faculty), the figures are included in the individual department data as well as under the Nuclear Reactor Laboratory. The duplication is not included in the overall totals, which, therefore, are less than the sums of the department data.

(3) Includes 45 theses, 72 papers and 20 reports by the Department of Chemistry, and 9 theses, 9 papers and 9 reports by the Department of Materials Science and Engineering, 1957-1975 (total 164 publications).

(4) Prior to 1978-79, presentations were lumped with journal articles, tabulated separately since then.

10.3-10.8. In so far as they are now known and in order to present further information concerning present activities, theses in progress or completed after June 30, 1985, and articles, presentations and reports published after that date or now in press are listed in the appropriate appendix but not included in Table 8.1. They will be included in future tabulations for the year completed or published.

Table 8.1 is designed to show the research activity and support in the several groups shown. Consequently, although the Nuclear Reactor Laboratgory does not grant degrees, the first column under NRL shows the numbers of theses completed each year, these being theses written by students supervised by NRL staff or by students supported by NRL. Where the student is registered in a department for which publication data is likewise shown in Table 8-1 (principally this involves students in the Department of Nuclear Engineering), the thesis is tabulated both under NRL and the appropriate department. Where NRL staff coauthor a paper, presentation or report with faculty or students from another department, that document likewise is tabulated under both. This practice was adopted with the establishment of NRL on July 1, 1976. In order to avoid distortion of the overall picture, however, such theses and papers are counted only once in the "Totals" column.

Because of the above procedure, the "Totals" column figures are slightly less than the sum of the figures under each department [see Note (2) of the Table]. For a second reason, the 31-year subtotals and the overall totals do not add up, namely, the grand totals contain 164 publications of the Departments of Chemistry and of Materials Science and Engineering during the FY55-FY78 period, and these departments are no longer tabulated separately [Note (3) of the Table].

8.2 Major Technical Highlights

Major technical achievements, of greater import than "another good paper in a good journal," constitute technical highlights. Some particularly interesting research results which are judged to be technical highlights are listed below for 1985.

Neutron Physics

• It has been found that neutrons passing through a diffracting crystal display an "effective mass" which is not only anomalously low (five orders of magnitude smaller than normal) but is also of both algebraic signs. This was demonstrated by applying a magnetic force to the neutrons and measuring the resultant large deflection.

Zeilinger, A., C.G. Shull, M.A. Horne and S.A. Werner, "Measurement of the Effective Mass Enchancement of the Deflection of Neutrons in Perfect Crystals," Proc. of XIII Int'l Congress of Crystallography, Hamburg, 1984: Acta Crystallographica, A40, p. 345 (1984).

• The very low effective mass of neutrons in crystals is being used to set new limits on the magnetic neutrality of neutrons.

Shull, C.G., et al., "Magnetic Neutrality of the Neutron," presented at Int'l Conf. on Neutron Scattering, Santa Fe, August 1985, publication in preparation.

• Extensive studies of neutron interferometer systems have been carried out to determine their operational and coherency characteristics. This has led to the development of new types of two-crystal systems which offer advantage over the usual three-crystal assembly for some applications.

Shull, C.G., "Neutron Interferometry System Types and Features," Int'l Conf. on Neutron Scattering, Santa Fe, August 1985, publication in preparation.

• Rotational motion of a two-crystal neutron interferometer has been shown to introduce an inertial Coriolis force on the neutrons which produces a phase modification of the neutron wave function. Accurate measurements of this effect have been found in excellent agreement with theoretical prediction.

Atwood, D.K., M.A. Horne, C.G. Shull and J. Arthur, "Neutron Phase Shift in a Rotating Two-Crystal Interferometer," Phys. Rev. Letters, Vol. 52, p. 1673 (1984).

Nuclear Materials

• A unique miniature mechanical property test has been developed, at the MIT Reactor, for use on irradiated materials. Specimens as small as 3mm diameter by 0.25mm thick can be used to obtain strength and ductility information. An important feature of this test is the use of finite element analysis to extract mechanical properties.

Harling, O.K., and G. Kohse, "Miniaturization of Specimens for Mechanical Testing," invited paper presented at Workshop on the Relation Between Mechanical Properties and Microstructure under Fusion Irradiation Conditions, Ebeltoft, Denmark, June 27-July 2, 1985 (in press).

Harling, O.K., M. Lee, D.-S. Sohn, G. Kohse and C.W. Lau, "The Miniaturized Disk Bend Test," ASTM Symposium on the Use of Nonstandard Subsized Specimens for Irradiation Testing, ASTM Special Technical Publication 888 (in press).

• The MIT Reactor facility has been essential in the development and execution of several major nuclear materials projects. Major emphasis has been placed on the use of rapid solidification processing to create unique alloy microstructures for the fusion reactor application.

Imeson, D., M. Lee, J.B. Vander Sande, N.J. Grant and O.K. Harling, "Irradiation Response in Titanium Modified Austenitic Stainless Steels Prepared by Rapid Solidification Processing, Part I: Microstructural Response to Neutron Irradiation," J. Nucl. Mater., Vol. 122 & 123, pp. 266-271 (1984).

Imeson, D., C.H. Tong, C.A. Parker, J.B. Vander Sande, N.J. Grant and O.K. Harling, "Irradiation Response in Titanium Modified Austenitic Stainless Steels Prepared by Rapid Solidification Processing, Part III: A Model for the Effect of Titanium Addition," J. Nucl. Mater., Vol. 122 & 123, pp. 278-283 (1984).

Tong, C.H., D. Imeson, J. Megusar, J.B. Vander Sande, N.J. Grant and O.K. Harling, "Irradiation Response in Titanium Modified Austenitic Stainless Steels Prepared by Rapid Solidification Processing, Part II: Dual Ion Irradiations," J. Nucl. Mater., Vol. 122 & 123, pp. 272-277 (1984).

Nuclear Medicine

• First study of the effects of BNCT on intercranial implanted tumors in beagle puppies injected with boron. In those dogs where the implanted tumor remained interstitially and intercranially, tumor destruction was successful by BNCT.

Brownell, G.L., J.E. Kirsch, J.C. Murphy, M. Ashtari, W.C. Schoene, C. Rumbaugh, G.R. Wellum, "Neutron Capture Therapy Treatment of Transplanted Intracranial Tumors in the Neonate Beagle at the MITR-II," in: Use and Development of Low and Medium Flux Research Reactors, Atomkernenergie-Kerntechnik, Vol. 44, Suppl., p. 573 (1984).

• First quantitative dose determination on a micro and macro scale for the B-10 (n,α) reaction in tissue.

Kirsch, J.E., "Neutron-Induced Track Etch Autoradiography: Studies in Track Detection and Neutron Capture Therapy," Ph.D. Thesis, Nuclear Engineering Department, MIT (June 1984).

Nuclear Engineering

• **Computer Control of Reactors**

Development and experimental demonstration of a set of general principles for the closed-loop, digital control of reactor power. The approach uses reactivity constraints for the on-line evaluation of the safety of any proposed control action.

Enumeration and definition of the specific concepts required for the closed-loop control of reactor power. Examples include the 'sufficient' and 'absolute' reactivity constraints.

First demonstration of decision analysis techniques for the closed-loop (steady-state) control of reactor power.

First demonstration of the use of 'fuzzy' logic in the closed-loop (transient and steady-state) control of reactor power.

Development and first experimental demonstration of closed-loop, transient controller based on a cognitive model of the human decision process.

Bernard, J.A., and D.D. Lanning, "Reactivity Constraints and the Automatic Control of Reactor Power," Trans. Am. Nucl. Soc., Vol. 47, pp. 394-396 (November 1984).

Bernard, J.A., D.D. Lanning and A. Ray, "Experimental Evaluation of Reactivity Constraints for the Closed-Loop Control of Reactor Power," NRC-EPRI Symposium on New Technologies in Nuclear Power Plant Instrumentation and Control, Washington, DC, published by Instrument Society of America (November 1984).

Bernard, J.A., D.D. Lanning and A. Ray, "Use of Reactivity Constraints for the Automatic Control of Reactor Power," IEEE Trans. Nucl. Sci., Vol. NS-32, No. 1, pp. 1036-1040 (February 1985).

Bernard, J.A., K.S. Kwok and D.D. Lanning, "Experimental Evaluation of 'Fuzzy' Logic in Closed-Loop Reactor Control," Trans. Am. Nucl. Soc., Vol. 49, pp. 392-393 (June 1985).

Bernard, J.A., A. Ray, K.S. Kwok and D.D. Lanning, "Design and Experimental Evaluation of a 'Fuzzy' System for the Control of Reactor Power," Am. Cont. Conf., Boston, MA, Vol. 3, pp. 1466-1474 (June 1985).

Bernard, J.A., and D.D. Lanning, "Experimental Evaluation of the Reactivity Constraint Approach for the Closed-Loop Control of Reactor Power Over a Range of Differential Reactivities," 1985 Int'l Conf. on Computer Applications for Nuclear Power Plant Operation and Control, Pasco, WA (September 1985).

- **Radioactive Waste Storage**

U in clays - Clay minerals, because of their sorption properties have been assumed to be suitable materials for secondary and higher order barriers to the migration of radioisotopes from rad-waste repositories in the event of a breach in the primary barrier. Examination of the location of U in clay rich regions of several granites has shown that the uranium is not located in clay minerals but in grains (1 to 2 microns, or smaller, in size) of several non-clay minerals. This finding suggests that the retention times for radioisotopes in clays may not be the most important factor in designing engineered backfill and in selecting repository site in crystalline rocks.

Simmons, G., and L.J. Caruso, "Characteristics of Granites as Host Media for Radioactive Waste Repositories," Mater. Res. Soc. Sympo., Stockholm (September 1985).

Oceanography

• Novel methods were developed for determination of picomolar concentrations of twelve rare earth elements (REE) in seawater by neutron activation analysis. These methods and isotope dilution mass spectrometry are the only analytical techniques with adequate sensitivity for determination of REE distributions in the open ocean environment.

DeBaar, H.J.W., "Neutron Activation Analysis of Rare Earth Elements in Seawater," in: Proc. Int'l Sympo. on the Use and Development of Low and Medium Flux Research Reactors, MIT, Cambridge, MA, Suppl. to Atomkernenergie-Kerntechnik, Vol. 44, pp. 702-709 (1984).

Earth Sciences

• At the earth's surface there are rare occurrences of rocks which originated at deep levels (30-300 km) within the earth. Such samples provide direct information about the inaccessible interior of the earth. We were the first to obtain extensive trace element data for such samples, and to interpret these data in terms of melt-solid segregation processes occurring at depth within the earth.

Roden, M.F., F.A. Frey and D.M. Francis, "An example on consequent metasomatism in peridotite inclusions from Nunivak Island, Alaska, J. Petrol., Vol. 25, pp. 546-577 (1984).

Roden M., S.R. Hart, F.A. Frey and W.G. Melson, "Ree and Sr, Nd and Pb Isotopic Geochemistry of St. Paul's Rocks, the Metamorphic and Metasomatic Development of an Alkali Basalt Mantle Source," Contrib. Mineral. Petrol., Vol. 85, pp. 376-390 (1984).

• It is well known that the trace element and radiogenic isotopic characteristics of lavas forming oceanic islands are very different from those of the lavas forming ocean floor away from islands. This is interpreted as reflecting compositional heterogeneity within the earth's mantle, but the size, distribution, and cause of these heterogeneities are not understood. In order to resolve this problem, we have studied lavas from Iceland and various Hawaiian islands. The Hawaiian islands are particularly interesting because of the linear trend they form on the surface of the Pacific Plate. Our results show that at each island there are systematic geochemical variations as a function of age, and such data enabled us to formulate quantitative models for oceanic lavas involving mixing of components from the deep and shallow oceanic mantle. Our data and models have stimulated several other approaches to the problem, and have been responsible for a major increase in the understanding of how oceanic island volcanoes form and evolve.

Frey, F.A., and M.F. Roden, "The Mantle Source for the Hawaiian Islands, Constraints from the Lavas and Ultramafic Inclusions, in Mantle Metasomatism," M. Menzies and C. Hawkesworth, eds., Academic Press (in press).

Roden, M.F., F.A. Frey and D.A. Clague, "Geochemistry of Tholeiitic and Alkalic Lavas from the Koolau Range, Oahu, Hawaii, Implications for Hawaiian Volcanism," Earth Planet. Sci. Letts., Vol. 69, pp. 141-158 (1984).

Chen, C.-Y., and F.A. Frey, "Trace Element and Isotope Geochemistry of Lavas from Haleakala Volcano, East Maui, Implications for the Origin of Hawaiian Basalts," J. Geophys. Res., No. 90, B110, pp. 8743-8768 (1985).

Lauphere, M., and F.A. Frey, "Geochemical Evolution of Kohala Volcano, Hawaii," Contrib. Mineral. Petrol. (in press).

• U and microcracks - It is commonly believed in the geological community that U occurs on grain boundaries in rocks. We have shown that in at least 98% of the cases in which the location of U would be ascribed to grain boundaries, the U is located in sealed microcracks. This finding changes completely models of the origin of such uranium.

Simmons, G., and L. Caruso, "Uranium Migration and Microcracks in Sherman Granite, Wyoming," Contrib. Mineral. Petrol. (in press).

• Migration of U and rare earths (RE's) in granites - The precise mapping of the location of U and associated rare earths has allowed us to show that the RE's have been mobile in many granites. One of the basic assumptions of a very large amount of work in geochemistry is that the RE's are immobile. We have shown that this assumption is not valid on a local scale. Its validity on a scale larger than perhaps a meter has now been placed in question.

Caruso, L., and G. Simmons, "Uranium and Microcracks in 1000-meter Core, Redstone, New Hampshire," Contrib. Mineral. Petrol., Vol. 90, pp. 1-17 (1985).

• Age of U Mineralization - The Sherman granite of Wyoming and Colorado is 1.35 billion years old (determined by others). We have shown that the U in that rock was redistributed about 1.35 billion years ago and has not migrated since. The redistribution occurred in open microcracks which beame sealed and have not been reopened for a period of time about one-fourth the age of the earth.

Simmons, G., and L. Caruso, "Uranium Migration and Microcracks in Sherman Granite, Wyoming," Contrib. Mineral. Petrol. (in press).

• In order to understand the origin and evolution of silicate melts formed in the earth's interior, it is necessary to understand the partitioning of elements between coexisting melts and mineral phases. We have analyzed minerals formed at high pressures and inferred trace element partition coefficients between such minerals and melt.

Irving, A.J., and F.A. Frey, "Trace Element Abundances in Megacrysts and Their Host Basalts, Constraints on Partition Coefficients and Megacryst Genesis," Geochemica Cosmochimica Acta, Vol. 48, pp. 1201-1221 (1984).

Molecular Biology/Analytical Chemistry

• One of the important recent applications of neutron activation analysis is the use of neutron irradiation to radioactively label biopolymers, such as RNA, DNA and proteins, after their separation by a variety of biochemical procedures. The approach ("indirect labeling") involves binding of highly activable metal ions, such as Mn^{2+} or Eu^{3+} to separated biopolymers followed by a neutron irradiation. Extremely high sensitivities and the ability to deal with nonradioactive polymers until the very last step of the procedure are among the unique advantages of this new method.

Kwok, K.S., R.M. Snapka, J.A. Bernard, O.K. Harling and A. Varsharsky, "Detection of Unlabeled, Separated, Biological Molecules via Neutron Activation," Trans. Am. Nucl. Soc. (in press) and paper in preparation.

9. REACTOR UTILIZATION

9.1 Experiment and Sample Hours

This section provides data indicating the substantial and diverse use of the MIT Research Reactor. It supports the statement that research reactors can be utilized for many different purposes simultaneously.

Table 9-1 restates for fiscal years 1983, 1984 and 1985 the hours of reactor operation given in Table 4-1 (sum of items 2a, b and c). It also provides the hours of utilization, broken down into five separate categories. It shows that the number of sample capsules being irradiated plus experiments being conducted simultaneously averaged nearly twenty. Increasing activity in the area of neutron activation analysis should increase utilization hours in FY 1986.

9.2 Industrial Utilization

The industrial users listed in Table 7-5 accounted for the hours tabulated in item 2(e). In the most recent year this amounted to 14% of total utilization hours, but the withdrawal of the major commercial user shortly before the end of the fiscal year is expected to reduce this category substantially during FY 1986.

TABLE 9-1

Reactor Utilization

	FY 1983	FY 1984	FY 1985	Projected FY 1986
1. Hours of operation (Table 4-1)	4,488	4,852	4,600	4,600
2. Experiment and sample hours				
a) Use by MIT	43,560	42,402	64,050	70,000
b) Use by other universities and non-profit institutions on a paid basis.	4,476	1,890	8,922	9,000
c) Use by hospitals on a paid basis.	1,212	534	528	1,000
d) Use by (b) and (c)* with USDOE Reactor Sharing support.	8,334	10,032	3,444	10,000
e) Industrial use	14,688	16,008	12,972	5,000
Total Hours of Use	72,270	70,886	89,916	95,000

Note: *Support for teaching hospitals, usually for research.

APPENDIX 10.1

DESCRIPTION OF THE MIT RESEARCH REACTOR

The research reactor, MITR-I, which ran for 16 years from July 1958 until May 1974, was a heavy-water cooled and moderated reactor, fueled with fully enriched uranium and operating at a power level of 5 MW. It has now been converted to a light-water cooled and moderated design, which uses heavy water as an inner reflector and the previously existing graphite as an outer reflector. The purpose of the change was to increase the beam port fluxes by a factor of two-and-one-half to three, and the quality of well-thermalized beams by another factor of three, by use of a compact undermoderated core, even though the power level remains the same at 5 MW.

Feasibility studies for this design were initiated by Professor T.J. Thompson in fiscal years 1967 and 1968 and were continued and implemented under Professor D.D. Lanning. The MITR-I was shut down for the last time on May 24, 1974, and MITR-II went critical on August 14, 1975.

The MITR-I and its early utilization have been described in some detail in several publications (References 1-15 in Appendix 10.9).

This section is devoted to a description of the MITR-II and its beam port and irradiation facilities. The associated supporting and related facilities are of vital interest to many reactor users and are described in Appendix 10.2

10.1.1 The Modified MIT Reactor, MITR-II

The principal change involved in the modification from MITR-I to MITR-II, as mentioned earlier, was the adoption of a light-water cooled and moderated design. The MITR-I fuel, core tank, control rods and drives, and most of the upper shielding were removed and replaced by the system described below. While this represents a fundamental change, the major portion of the reactor facility remained unaffected (Figs. 10.1-1 and 10.1-2).

The fuel continues to be fully enriched (93%) uranium contained in relatively thin, aluminum-clad plates; 15 plates are assembled into a fuel element. In order to achieve the higher fuel loading required by the new design, the fuel meat in the plates is a compacted intermetallic mixture of uranium-aluminide (UAl_x) and aluminum powders instead of the uranium-aluminum alloy previously used in the MITR-I. The UAl_x fuel has been used by DOE's Advanced Test Reactor in Idaho and in other research reactors. The fuel meat is 0.030 inch thick instead of 0.020 inch, as in MTR-type fuel. The plates are flat and have longitudinal grooves cut in the surfaces, providing a finned effect which nearly doubles the heat transfer capability. By assembling the plates into an element having a rhomboidal cross section, it is possible to obtain a core which is hexagonal in shape: the core thus approaches a circular geometry, which would be optimum for this design but which would result in a relatively higher cost for fuel element fabrication.

The core consists of up to 27 elements housed in an aluminum structure, Fig. 10.1-3. It measures 15 inches between the hexagonal faces, and the height of the core (fuel meat) is 22-3/8 inches; as indicated below, the effective height of the core can be reduced by about 50% by the installation of fixed absorbers in the upper half. The aluminum core housing fits into a cylindrical pocket at the bottom of the aluminum core tank. A core tank shroud directs light-water coolant downward in a thin annular flow pattern just outside the core housing (indicated the [illegible] coolant entrance channels" in Fig. 10.1-3) and then upward through [illegible] elements, into the core tank, and then out to the pumps and heat exchangers. A feature of this design is the location of the inlet and outlet connections near mid-height on the core tank so that the core will not suffer a loss of coolant due to a pipe break; analysis shows that the tank itself will remain intact after any conceivable earthquake.

Slots in the six walls of the core housing contain six shim blades, Fig. 10.1-3, consisting of 1.1% boron in stainless steel. They are

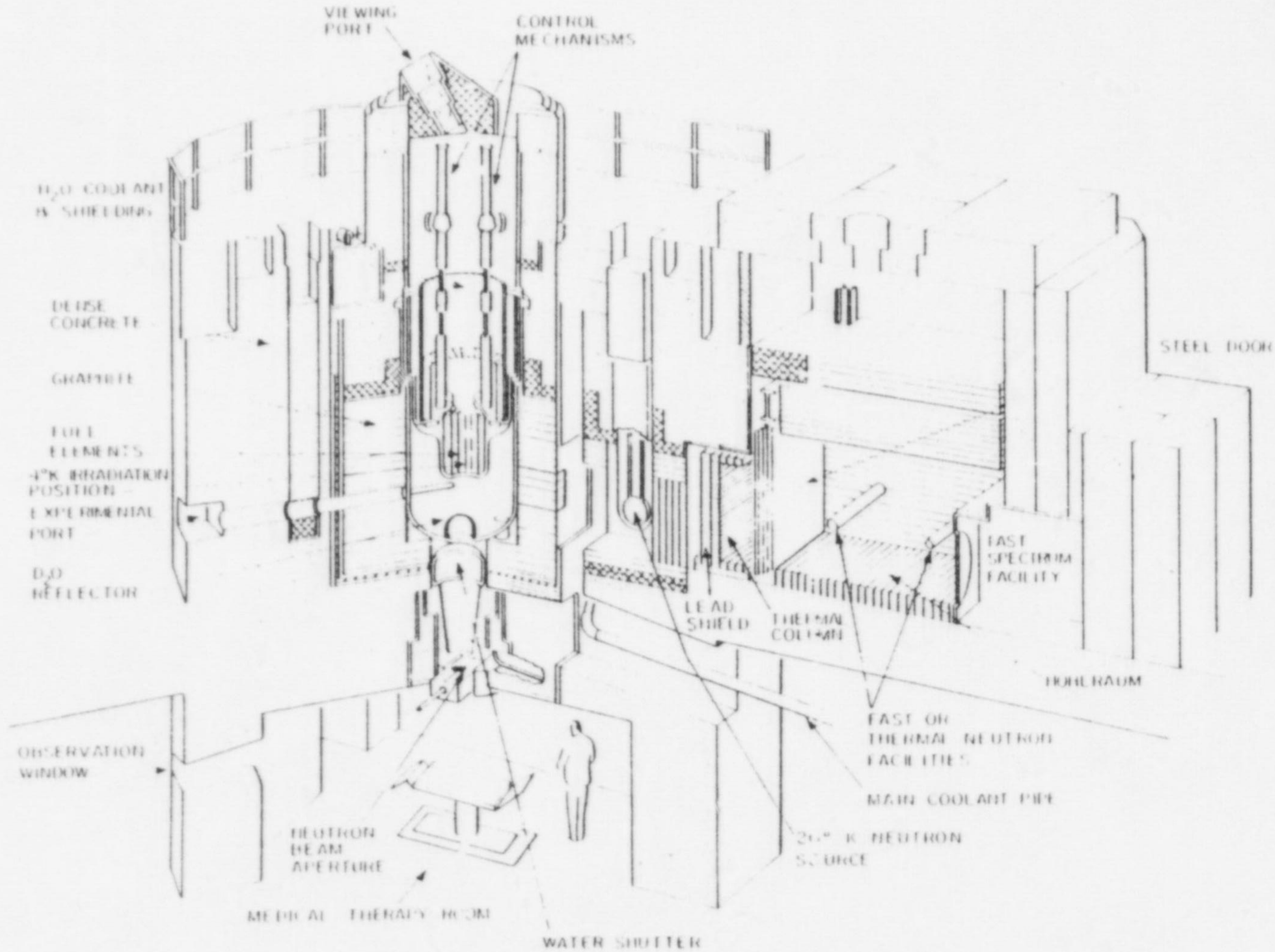

Fig. 10.1-1

VIEW OF M.I.T. RESEARCH REACTOR, MITR-II, SHOWING MAJOR COMPONENTS AND EXPERIMENTAL FACILITIES

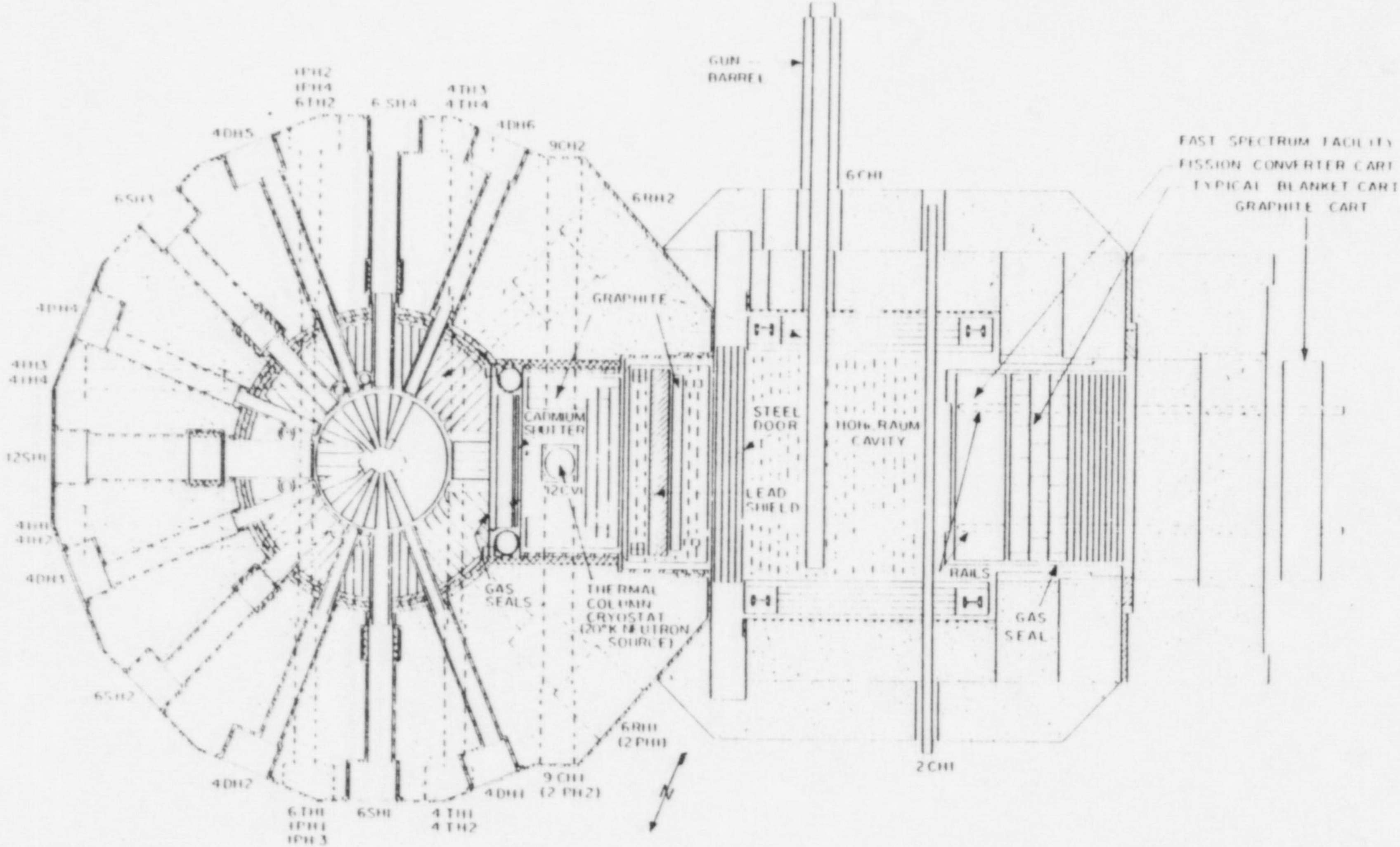

Fig. 10.1-2

HORIZONTAL SECTION THROUGH REACTOR, THERMAL COLUMN AND FAST SPECTRUM FACILITY

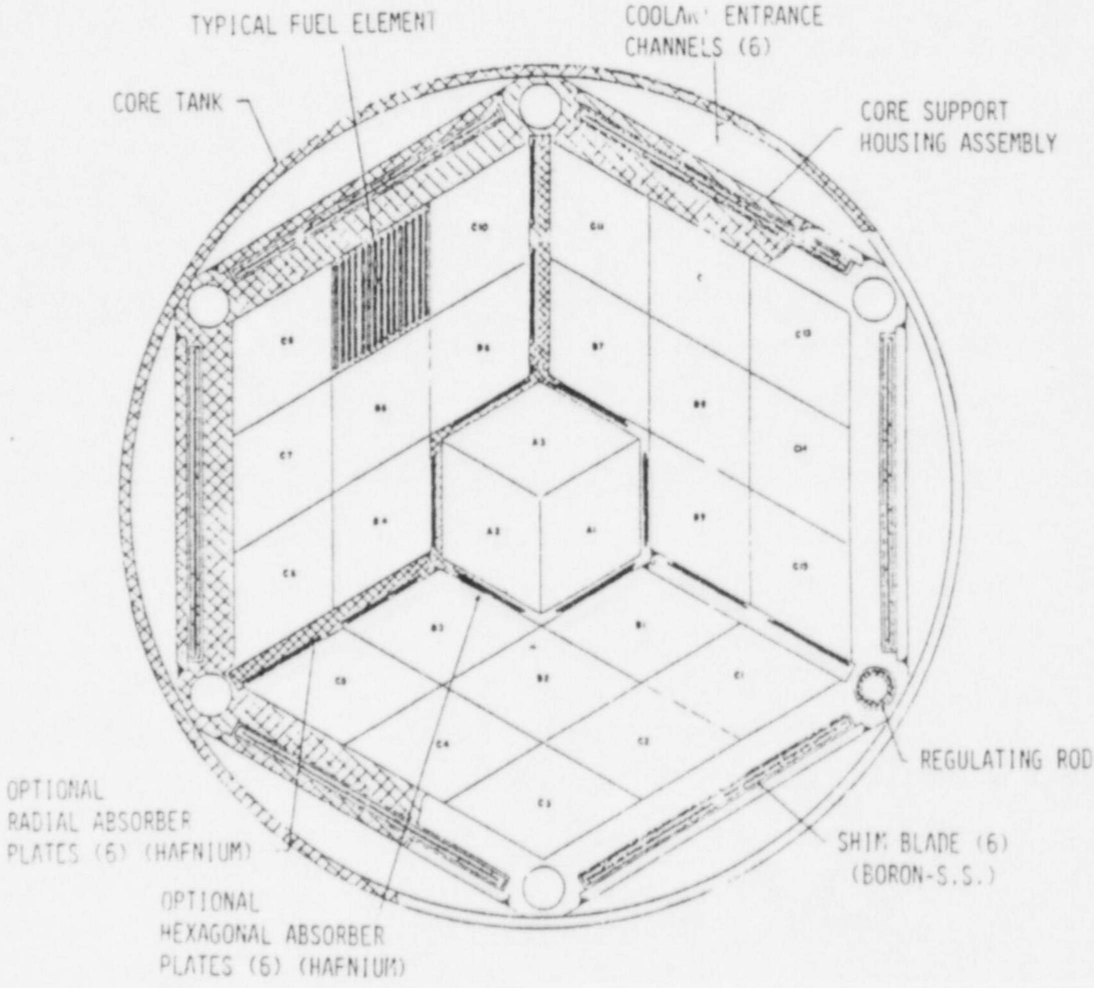

Fig. 10.1-3

CORE SECTION - MITR-II

coupled electromagnetically to drive mechanisms near the top of the core tank which provide for slowly raising the blades during startup of the reactor and for compensating changes in blade height during other reactivity changes. The blades may be rapidly dropped to the shutdown position by cutting off the electric current to the magnets, or they may be inserted more slowly under motor control. A regulating rod, made of cadmium clad in aluminum, at one corner of the hexagon provides for small reactivity changes and may be placed on automatic control during constant power operation.

The objective of the above design is to enchance the thermal neutron flux for the radial beam ports and to maximize the power density and, hence, the fast neutron flux in the core. The former is accomplished by surrounding the bottom and sides of the light-water core with a heavy water reflector. This is contained in a four-foot diameter reflector tank, also aluminum, which fits within the cavity of the graphite reflector in essentially the same manner as the original core tank did. In the MITR-I, the beam ports looked at the D_2O at the outer surface of the core tank, where the flux was approximately 2×10^{13} n/cm^2-sec. In the MITR-II, the flux at this point is little changed, but re-entrant thimbles in the new reflector tank are aligned with the existing beam ports and terminate under the core in a flux of about 8×10^{13} n/cm^2-sec. Neutron currents in the beam ports are calculated to increase by a factor of two-and-one-half to three, taking into account the greater port length and geometry factors. A further advantage is a greatly improved thermal to fast neutron ratio. Better neutron thermalization has produced an essentially Maxwellian distribution with a characteristic temperature of 304°K compared to 404°K previously. The available thermal flux at subthermal energies, e.g., $\lambda = 4$ Å, has been increased by almost an order of magnitude. Also, a reduced gamma background is achieved, since the ports no longer look directly at the fuel. Maximizing the fast in-core flux is accomplished by making the core relatively small in comparison with the MITR-I and by undermoderating. The core, therefore, provides a very useful region for irradiation damage testing.

In addition to the variable neutron absorption provided by the shim blades, the upper part of the core may be heavily poisoned by the semi-permanent installation of hafnium partitions between the four fuel compartments, Fig. 10.1-3, i.e., a hexagonal absorber surrounding the three central fuel elements and radial absorbers separating the three outer zones, which each house eight elements. The effect of this heavy neutron absorption in the upper part of the core is to further enhance the neutron flux in the cup-shaped region below and surrounding the lower half of the core and to increase further the flux in the active part of the core. The length of facilities available in-core for irradiations is necessarily reduced by this option.

It was necessary to modify only moderately the upper biological shielding in order to accommodate the 12-foot deep core tank. The top lid may be rotated to facilitate viewing and some fuel handling, and it may be removed as necessary for maintenance in the tank and for fuel changes in the core.

Plans for fuel management call not only for movement of elements from one position to another within the core but also for inverting them after approaching the limit of burnup on the lower end, in order to achieve optimum utilization of all the fuel.

An annular fuel storage rack is placed against the tank wall above the core and provides 29 cadmium-lined positions for the storage of partially used fuel elements and also of fully used elements awaiting transfer to the spent fuel storage tank.

The critical mass for the operating MITR-II is about 10.2 Kg U-235, more than for the MITR-I, because of the light water design and high degree of undermoderation. The heavy water inventory for the reflector tank is about 5000 pounds. The operating pressures and temperatures remain essentially the same as in the MITR-I, i.e., nearly atmospheric and close to 100°F.

There were no changes to the thermal shield or to the biological shield other than noted above. The process system pumps, heat exchanges, storage tanks, gas cover systems, cooling towers, and instrumentation remain relatively unchanged except for the addition of one more fluid system for the reflector. This did, however, require major piping alterations. The electronic safety and control systems and the radiation monitoring systems are essentially the same except for a few additions required by the new design; some improvements in redundancy have been incorporated, and much of the old wiring has been replaced. The containment and ventilation systems are unchanged, although eqiupment has been added for the controlled relief of accidental building overpressure.

Further details of the design, licensing, renovation work, and measurement and verification of the MITR-II operating characteristics are provided in References 17-33 of Appendix 10.9.

The shutdown afforded an opportunity to inspect internal regions. No undue corrosion or other deterioration was noted, although radiation levels in some areas were higher than anticipated, principally as the result of activity induced in some of the graphite impurities.

10.1.2 Beam Port, Irradiation and Other Reactor Facilities

Utilization of the reactor by many experimenters simultaneously is possible because of its numerous beam ports, thermal column, medical room, irradiation and other facilities. The principal ones are shown in Figs. 10.1-1 and 10.1-2. They are also listed in Table 10.1-1, along with details regarding size, flux levels, and special features. Further information pertaining to the development and characteristics of some of the more specialized facilities is given in References 34-40.

TABLE 10.1-1

CHARACTERISTICS OF EXPERIMENTAL FACILITIES

IRRADIATION FACILITIES

Facility	No Available	Size	Approximate Thermal Flux at 5 MW n/cm^2-sec	Special Features
Horizontal Beam Ports 4" 6" 12"	 6 4 1	 4½" i.d. 6 5/8" i.d. 12 11/16" i.d.	at reentrant thimble source in D_2O 8×10^{13}	All ports have readily available the following services: 1. Demineralized cooling water 2. 110V AC 3. Access to basement 4. Access to reactor top 5. Inert gas system 6. Off gas system 7. Waste drain. In addition the 6" and 12" ports have shutters useful for changing experiments
Horizontal Thru Ports 6" 4"	 1 1	 6 5/8" i.d. 4½" i.d.	6×10^{12} at point closest to tank	
In-Core Vertical Thimbles	1 2 1	1 1/8" 1¾" i.d. 2.7" x 2.0"	fast $\sim 10^{14}$ slow 1-3 x 10^{13}	Space is available for additional in-core irradiations. (Also gammas 10^8-10^9 r/hr.) Access to experiments from top of reactor.
Thermal Column Thermal Neutron Facilities	1 2 1 1	5' x 5' 9" x 9" 12" x 12" 6' x 6'	10^9-10^{12} 6×10^{11} 6×10^{11} 10^9 at entrance	Cadmium and steel shutters Pneumatic rabbit, 1.6" i.d. x 3" l. Cold neutron source available 10' x 10' x 3' irradiation room available
Fast Neutron Facilities in Hohlraum	1 1 1	5' x 5' 4" i.d. x 4' long 1 1/8" i.d. x 4' long	6×10^8 6×10^8 6×10^8	Fast reactor spectrum Fission spectrum Fission spectrum
Pneumatic Tubes Graphite Reflector	4	Sample space 1" i.d. x 2 3/8" long	6×10^{12}	"In" to "out" travel time is 0.5 secs., pneumatic operation, cooled, Cd ratio = 220
D_2O Reflector	1	1½" i.d. x 6" long	3-6 x 10^{13}	Pneumatic operation, gas cooled, Cd ratio = 15-33
Thermal Column	1	1 5/8" i.d. x 3" long	6-9 x 10^{11}	Manual operation, Cd ratio $>$ 250
Vertical Thimbles in Graphite Reflector	4	3½" i.d.	$\sim 4 \times 10^{12}$	Manual operation, 2 are cooled, Cd ratio = 220, suited for medium and long-term irradiations
Medical Therapy Facility	1	6" diam. port	10^{10}	Opens into operating room beneath reactor; variable energy spectrum
Gamma Facility	Many	Flexible	10^4-10^5 r./hr.	Spent fuel storage

*Note: Some of these facilities have sample changers to permit insertion and removal of samples during reactor operation at full power. They use standard aluminum or titanium cans as outside containers.

APPENDIX 10.2

SUPPORT FACILITIES AND EQUIPMENT

The MIT Research Reactor is supported by a broad range of facilities and equipment within (1) the Nuclear Reactor Laboratory, (2) the contiguous Department of Nuclear Engineering spaces, and (3) other Institute laboratories and research centers.

10.2.1 Nuclear Reactor Laboratory

NRL facilities, totaling about 43,000 square feet, include a trace analysis laboratory, a low-level radioactivity counting area, a drafting room, low and intermediate level hot cells equipped for mechanical testing of radioactive specimens and several well-equipped shops (electronic, machine, mechanical, and welding).

The trace analysis laboratory, which is located in the building complex adjacent to the reactor, is equipped to perform both instrumental and radiochemical neutron activation analysis on samples of materials irradiated in the reactor. A pneumatic rabbit system permits insertion and removal of samples either within the reactor containment building or in the adjacent laboratory. In the latter case, transit times are about ten seconds. For studies involving still shorter half-lives, there is a chemistry hood in the reactor basement room where two of the rabbit stations are located.

Several complete radiochemical laboratories, equipped with ventilation hoods and other services are available. The major counting equipment used for trace analysis research consists of high-resolution gamma spectroscopy systems, including multichannel analyzers and Ge(Li) and Si detectors, X-Y plotter, automatic sample changer, and associated equipment. In addition to the digital output, a magnetic tape permits data reduction with any of several computer programs (SPECTRA-III and others) on the Institute's mainframe computer. Other equipment includes a horizontal flow clean hood (Clean Rooms, Inc.), a freeze drier, and all the usual radiochemistry apparatus.

The electronics shop is equipped with a wide range of test equipment, such as oscilloscopes, multichannel analyzer, picoammeters, signal generators and so forth. The shop services not only the reactor, but also the research projects and academic teaching laboratories.

Finally, the mechanical group possesses the capabilities and equipment for installing and servicing, for the reactor and associated experiments, the required control and process systems, with their related pneumatic, hydraulic and other mechanical devices (pumps, blowers, valves, seals, piping, tubing, conduit, etc.).

The above shop activites are supported by a tool crib and by a stockroom which maintains a large inventory of alumninum, stainless steel, and many other supplies, much of which is certified stock.

Within the reactor restricted area are two vaults, appropriately equipped for security purposes, for the storage of nuclear materials. One is for reactor fuel and the second, maintained in cooperation with the Department of Nuclear Engineering, is for any nuclear materials utilized in research or training projects. Appropriate Nuclear Regulatory Commission licenses are held, and procedures for material control are established under Accountability Station CCP.

10.2.2 Department of Nuclear Engineering

The Department of Nuclear Engineering complex adjacent to NRL contains a number of facilities useful to the conduct of reactor-oriented research and education. One is a reading room well furnished with reference books, manuals, pertinent journals, and theses by Nuclear Engineering students.

The Department maintains a library of the more widely used reactor design and analysis computer codes and employs a computer assistant to aid with their utilization. It has its own minicomputers and terminals for access to the MIT mainframe computer.

The Department has a well-equipped reactor physics laboratory with two subcritical natural uranium reactors, one moderated by water and the other by graphite. The latter consists of an eight-foot cube containing 25 tons of high-purity nuclear graphite and 2,500 kg of natural uranium furnished by the USDOE under an educational loan. Neutrons for the subcritical exponential pile are supplied by a number of plutonium-beryllium sources also loaned by DOE. While not large enough to support a self-sustaining nuclear chain reaction, these subcritical reactors make possible a variety of experiments on reactor lattices. There is also a sigma pile of graphite. Other facilities of the Department include laboratories for instruction in nuclear instrumentation and in plasma physics, several radiochemistry laboratories, a nuclear chemical engineering laboratory, and a 14 MeV Cockcroft-Walton neutron source.

10.2.3 Related Institute Facilities

Many of the research facilities at MIT are of an interdepartmental character. As a result, researchers and students from the various departments have access to a wide range of research services and facilities outside of NRL and their own departments.

In the MIT Information Processing Center, the facilities include an IBM 4381-1 with the virtual memory operating system for batch processing and for time-sharing purposes. Access to the time-sharing system is via consoles scattered around the Institute. A network of several VAX main frames and micro VAX's are also available on the MIT campus for research and teaching uses.

Research activities in nuclear science and technology are closely related to the long-standing programs of basic research in atomic and nuclear science which have brought distinction to the Institute for more than four decades. Since 1946 most of this research has been carried out through the interdepartmental Laboratory for Nuclear Science; the facilities include a number of Van de Graaff generators and the MIT cyclotron. The Laboratory currently operates the Bates Linear Accelerator in Middleton, Massachusetts, a high intensity facility for 800-MeV electrons.

Where studies of materials are an aspect of research at NRL, the laboratories of MIT's Center for Materials Science and Engineering are of substantial use. The Center maintains facilities for NMR, EPR, optical spectroscopy, scanning electron and electron microscopy, Auger spectroscopy, electron microprobe, ion microprobe, and laboratories for crystal growing and characterization.

The principal equipment in the low-level radioactivity counting area is a two-inch, well-type, NaI crystal with multichannel pulse height analyzer for gamma-spectroscopy.

The low-level hot cell is situated in the reactor basement where the two-inch high flux rabbit station and two of the one-inch stations are located. These exit into the hot cell, which also contains a transfer station, so that rabbits may be inserted into the reactor from the trace analysis laboratory and vice versa. The cell is equipped with an AMF Atomics Master-Slave Manipulator and other remote handling tools for relatively simple handling activities.

The intermediate level hot cells, installed on the main reactor floor (southeast side), can be used for materials having radioactivity levels in excess of 100 curies. Remote manipulators (Central Research Laboratories, Inc., Model 8) permit such activities as inspections, mechanical testing, repackaging of radioisotopes, etc. A 10 kips computer-controlled hydraulic testing machine with an environmental chamber for vacuum or inert gas environments and a fast digital data recording system is installed in one of the hot cells. A high resolution optical comparator with remote readouts is located in another cell.

The several shops at the NRL make possible the complete fabrication, installation, instrumentation and servicing of reactor components and experiments. All commonly used machine tools are available in the shop.

In addition to the shop foreman, there are 18 machinists, mechanics, welders and a stock clerk. The shop provides services not only to NRL, but also to many other laboratories and research centers around the Institute. A separate hot machine shop is used for all work on radioactive components from the reactor and experiments, and is equipped with a milling machine, lathe, drill press, grinder, and necessary hand tools.

The weld shop has metal arc and TIG welders plus oxy-acetylene and plasma arc cutting capabilities (including under-water for the latter). Electrical power outlets for welding and cutting are provided both in the shop and in the reactor building.

MIT's research in electronics and such related fields as microwave physics, radioastronomy and applied plasma physics is conducted in the interdepartmental Research Laboratory for Electronics. In the Francis Bitter National Magnet Laboratory several large fusion devices have been designed, constructed and put into very successful operation.

MIT is also affiliated with Associated Universities, Inc., in operating the Brookhaven Laboratory, whose extensive facilities are available to staff and students.

APPENDIX 10.3

PUBLICATIONS OF THE NUCLEAR REACTOR LABORATORY (FY79-FY85)

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APPENDIX 10.4

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APPENDIX 10.5

DEPARTMENT OF PHYSICS (FY79-FY85)

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APPENDIX 10.6

DEPARTMENT OF EARTH, ATMOSPHERIC AND PLANETARY SCIENCES (FY79-FY85)

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APPENDIX 10.7

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APPENDIX 10.9

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