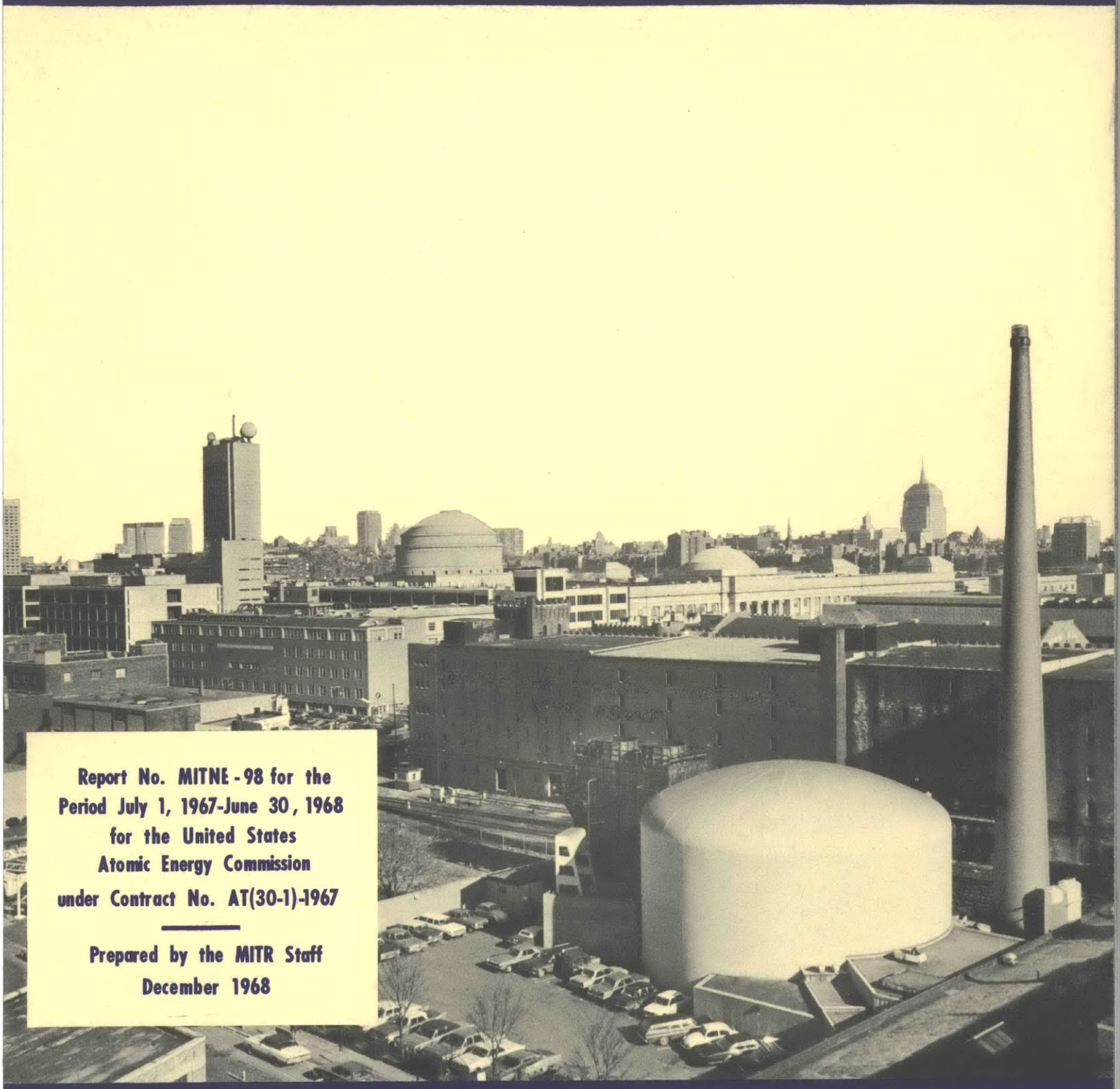
RESEARCH AND EDUCATIONAL ACTIVITIES at the MIT RESEARCH REACTOR

fiscal year 1968



Report No. MITNE-98 for the
Period July 1, 1967-June 30, 1968
for the United States
Atomic Energy Commission
under Contract No. AT(30-1)-1967

Prepared by the MITR Staff

December 1968

MASSACHUSETTS INSTITUTE OF TECHNOLOGY • DEPARTMENT OF NUCLEAR ENGINEERING
Cambridge, Massachusetts 02139

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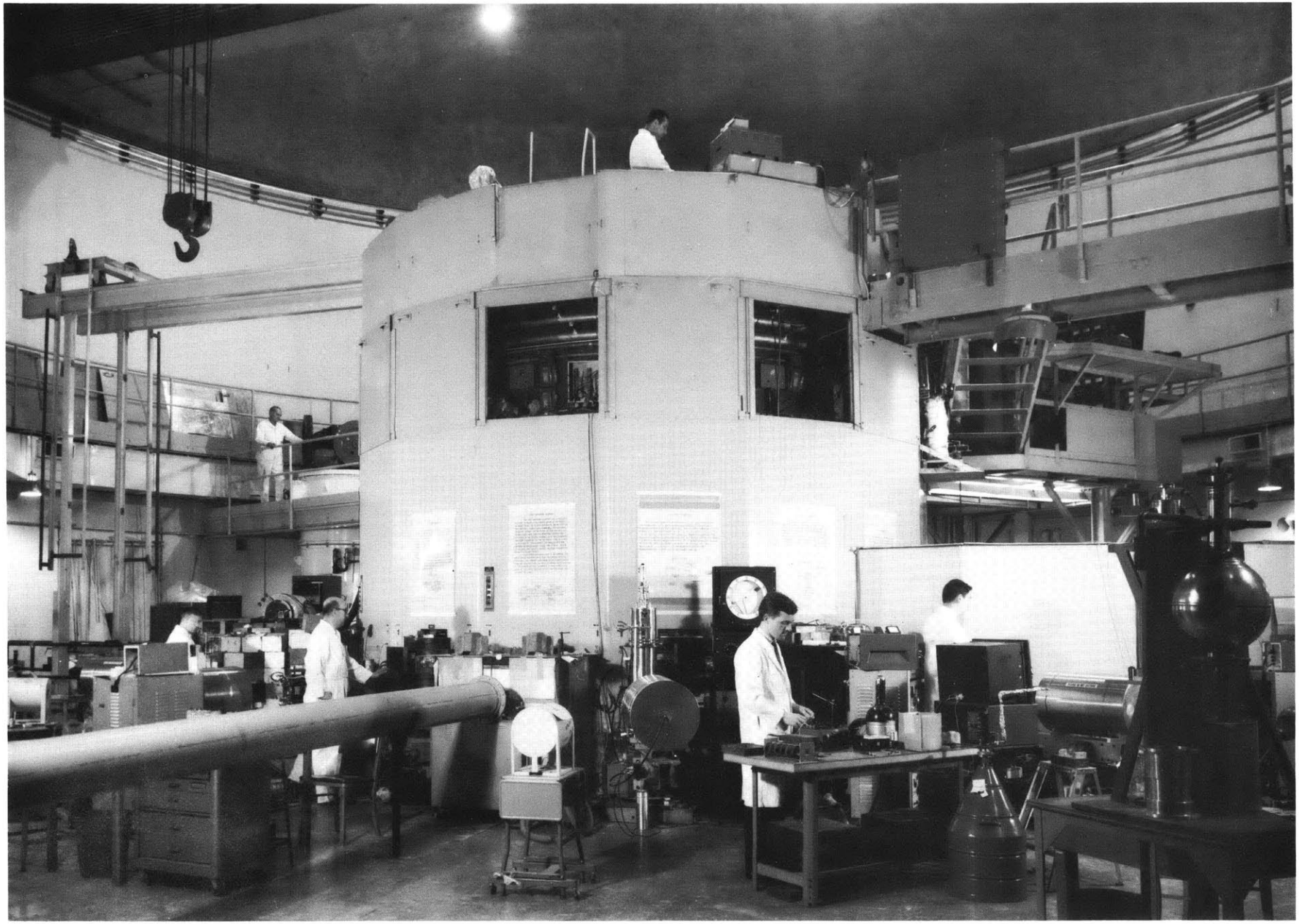

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I. ABSTRACT

A report of research and educational activities which utilized the Massachusetts Institute of Technology, five-megawatt, heavy water, research reactor during fiscal year 1968 has been prepared for administrative use at MIT and for presentation to the U.S. Atomic Energy Commission. The latter action is required by Contract AT(30-1)-1967 under which the AEC provides the fully-enriched uranium-235 fuel and the heavy-water moderator-coolant for the reactor.

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 fiscal year 1968. A comprehensive bibliography of earlier publications was contained in Report No. MITNE-91 "Research and Educational Activities at the MIT Research Reactor To and Including Fiscal Year 1967". That report lists essentially all documents of these types which are concerned with the design, operation, or research use of the MITR from the time its construction was first contemplated at the Institute until June 30, 1967.

In addition to the educational value derived from the many research activities 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 attendance figures are given.

Detailed information concerning the research activities of the numerous other universities, hospitals, and commercial companies which have used the MITR for irradiations is not available, but these organizations and also the materials irradiated are listed.

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

II. INTRODUCTION

The Massachusetts Institute of Technology Research Reactor first went critical in July, 1958. The MITR, therefore, completed essentially ten years of successful operation by the close of fiscal year 1968, i.e., by June 30, 1968.

The reactor was constructed, following an MIT design, by the nuclear division of ACF Industries, Inc., later transferred to Allis-Chalmers Manufacturing Company. Ground was broken on June 6, 1956, and the first criticality was achieved July 21, 1958. After a year of low power tests and calibration, the reactor began a routine three-shift schedule at a power level of 1 MW on July 20, 1959, and since that time its operation has been almost continuous with the exception of week-end shutdowns for maintenance and for changing fuel and experiments. In July 1961 the power was raised to 2 MW, and in November 1965 to 5 MW, the power level for which the reactor was designed.

The purpose of this document is to summarize the research and training activities which utilized the reactor during the last year of the decade of operation, i.e., fiscal year 1968. Also, under the terms of Contract AT(30-1)-1967 between the U.S. Atomic Energy Commission and M.I.T., the Institute agrees to furnish the AEC with a current list of published reports of activities which involve the reactor. Such reports for fiscal year 1968 are listed herein, Appendices A-E, for the purpose of fulfilling the requirements of that contract. In addition, in order to meet other objectives of the report, it contains a description of the reactor, the reasons for its existence, its capabilities, availability to non-MIT experimentalists, and a summary of the 1967-68 operating record.

A similar report, MITNE-91, "Research and Educational Activities at the MIT Research Reactor To and Including Fiscal Year 1967", was published last year. Since it was the first such report, it

covered the first nine years of MITR operation through June 30, 1967. It contained a complete bibliography of theses, reports, journal articles, and conference papers (in excess of 600) concerning research related to the MITR to that date. The current report brings the bibliography up to date.

Some of the descriptive material presented in MITNE-91 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. Likewise, the reactor itself is again described in some detail both in order that the information will be readily available to those who may be interested but also in order to facilitate the presentation of information concerning the modifications and improvements made during the past year and planned for the current year. Some additional material is also included in the interest of completeness.

In order to provide background for an understanding of the nature and scope of the activities described and the publications enumerated, the purposes and utilization policies of the MIT Research Reactor are first briefly outlined in Section III. The MITR itself is then described in Section IV, its capabilities and characteristics explained, and the supporting facilities summarized. In Section V, the operating and administrative organizations are described. Section VI provides a summary of reactor operating information. Services provided by the AEC in the form of financial reimbursement for fuel fabrication, loans of uranium and heavy water, and other assistance under the above contract are summarized in Section VII, "USAEC Research and Training Contract".

Section VIII is devoted primarily to descriptions of MIT research activities which have utilized the reactor during fiscal year 1968. All major projects, whether conducted by the Department of Nuclear Engineering or by other departments or laboratories, are included. In addition to these, a substantial number of irradiations were made for research purposes by various staff members or groups within MIT; but since it has not been feasible to gather information

from all of these sources concerning theses, papers and project descriptions, the departments and laboratories have simply been listed (Table VIII-1).

Most of the descriptions of research are concerned with long-term projects, and much of the work is continuing into the current year. Whenever available, the titles of theses in progress and of papers submitted for future publication have been included in the lists. They will appear again in future reports covering the year in which completed.

In keeping with M.I.T. 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. The research described in this report is carried out almost entirely by student investigators, under the direction of supervising faculty members, and indeed the reports and journal publications, as well as the theses, almost invariably are authored in large part by students. Because all research programs provide training in one aspect or another of nuclear science or technology and because they serve also to teach research methods in general, it is impossible to classify most reactor use as either research or as educational. Both objectives are simultaneously achieved in the great majority of cases.

However, some use of the reactor is purely for educational purposes. It is employed for the production of radioisotopes, as a source of neutron beams, or for other purposes in a number of academic subjects which are offered by the Department of Nuclear Engineering and by other departments. These are described in Section IX.

The MIT Reactor is available to organizations outside MIT for the purpose of making radioisotopes, for carrying out other types of service irradiations, and for a variety of education and training purposes. Section X provides data concerning the numbers of hospitals, other universities, and commercial firms for which irradiations have been conducted. Such groups are not required to provide descriptions of the intended uses for the irradiated materials nor lists of publications

which may ultimately result from these uses; however, the substances irradiated are listed in Appendices G, H, and I. Section X also describes the appreciable educational and training benefits which have accrued to academic, professional, military, and other organizations outside MIT. Statistics and lists of organizations making substantial use of the reactor for such purposes (five people or more) are provided in that section and in Appendices J and K.

III. OBJECTIVES OF THE M.I.T. RESEARCH REACTOR

The M.I.T. 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 sciences--such as solid state physics, metallurgy, radiochemistry, and geology--and in numerous areas of the applied sciences and engineering disciplines--such as reactor physics, neutron activation analysis, radiation effects, radiation shielding, and heat transfer. 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 Chemistry.

While the reactor is intended primarily to serve the needs of M.I.T., 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 researchers may wish to utilize reactor radiations in any of a wide variety of applications in the physical and life sciences and in engineering. 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 hospitals in the area. M.I.T. tries to meet the requirements of local industry for short-lived radioisotopes and other service irradiations.

As mentioned earlier, research projects are undertaken not only for the results to be obtained but also for the education benefits to be derived by students. Research problems must be sufficiently broad and basic so that they provide opportunities for thesis projects by students; also, they must fall within the sphere of interest of some Faculty member desiring to supervise the research. In general, there

are no personnel on the staffs of either the reactor or of the Department of Nuclear Engineering who are engaged in the conduct of research unrelated to the Institute's educational objectives. Likewise, tests or inspections are generally not made of irradiated specimens unless these are part of a larger research program.

In making radioisotopes and in performing other service irradiations for universities, hospitals, and industry, M.I.T. 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. As mentioned above in connection with research, services are usually limited to making the irradiations.

All M.I.T. 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 unclassifed basis.

The M.I.T. Research Reactor was designed so that a large number of experiments could be simultaneously accommodated in its experimental facilities. In total, there are over 70 neutron irradiation and beam positions. While it would not be practical to use all of these continuously or all at one time, it would be very feasible to accommodate more experiments than has been the case in the 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 considerably without undue crowding or inconvenience to the investigators. From an economic viewpoint, utilization costs would be almost inversely proportional to the volume of work.

IV. DESCRIPTION OF THE M.I.T. RESEARCH REACTOR

The M.I.T. Nuclear Reactor is heavy-water cooled and moderated and is designed to operate at powers up to 5 MW. The design of this reactor originated at M.I.T. and is delineated in some detail in previous publications (Ref. 1-13, Appendix L). The reactor, a cutaway section of which is shown in Fig. IV-1, utilizes an inventory of 10,000 pounds of heavy water and an operating critical mass of approximately 3,200 gm of fully enriched uranium. Fuel elements are of the MTR plate type with certain variations dependent upon the experiments in the reactor. The reactor operates at atmospheric pressure and at a coolant temperature just slightly above 100°F.

This type of reactor was selected by M.I.T. because of its inherent safety and its ability to accomplish well the missions of research and education for which it was built. As shown in the cross-section view of Fig. IV-2, there are nineteen primary fuel positions in the reactor core. In addition, there are eleven positions shown at the edge of the tank. These are utilized for three separate purposes. First of all, these positions enable the operations staff of the reactor to add fuel as required to maintain sufficient operating reactivity without having to make extensive fuel changes or to utilize elements having excessively large U-235 loadings. Second, by placing the fuel elements in the outermost position, the spectrum available at various ports can be changed quite noticeably. For instance, there are two of these eleven positions located at the front of the 12" port (12SH1) in such a manner that the neutron chopper, located just outside this port, can look at the spectrum which one might see near the edge of the core or at the spectrum which one might see through the approximately 20-cm heavy-water reflector at the outside of the primary core. Port 4DH6 can be used for shielding investigations often involving fast neutron attenuation. In order to augment the fast neutron flux, a fuel

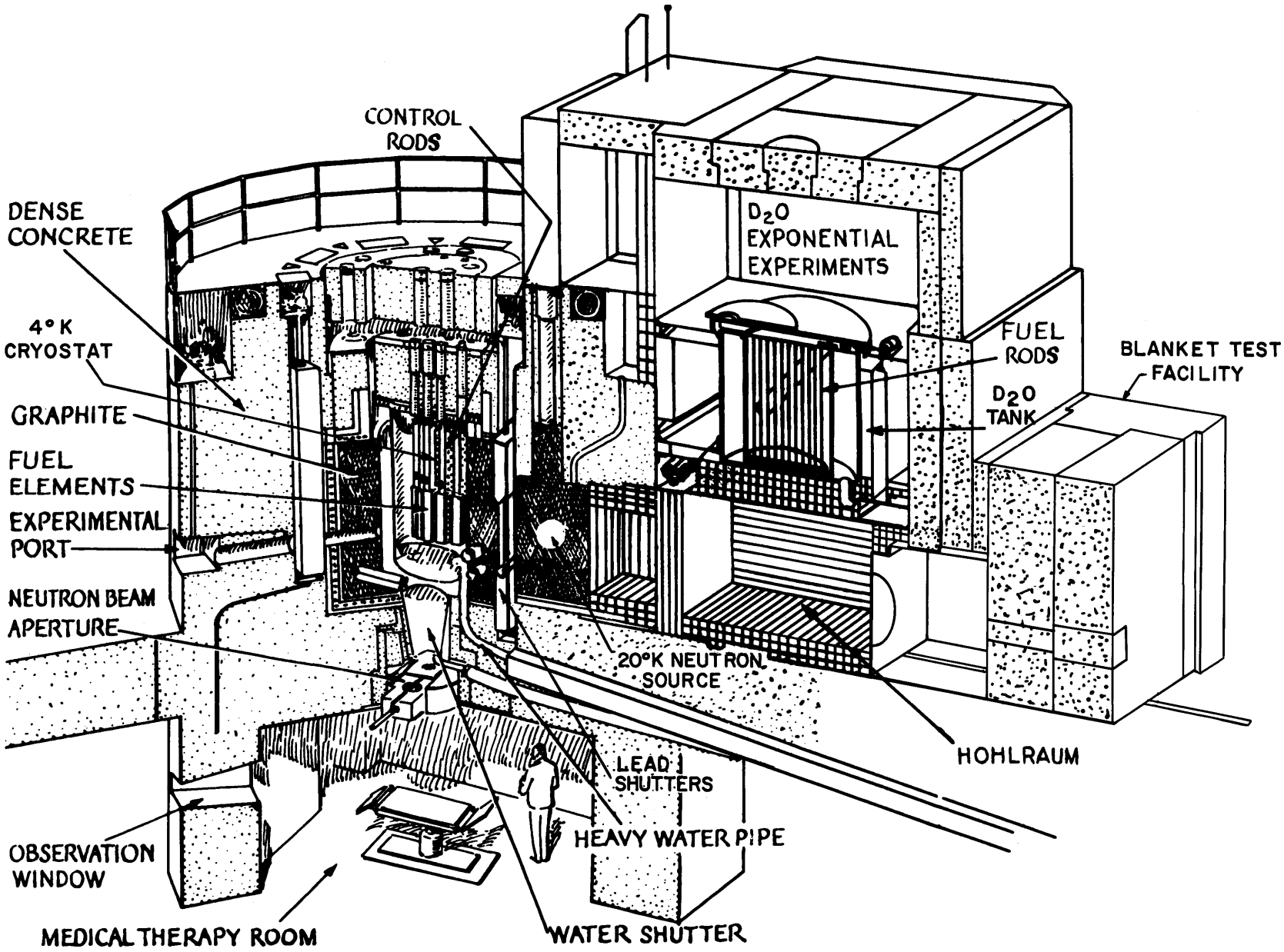

FIG. IV-1 VIEW OF M.I.T. RESEARCH REACTOR SHOWING MAJOR COMPONENTS AND EXPERIMENTAL FACILITIES

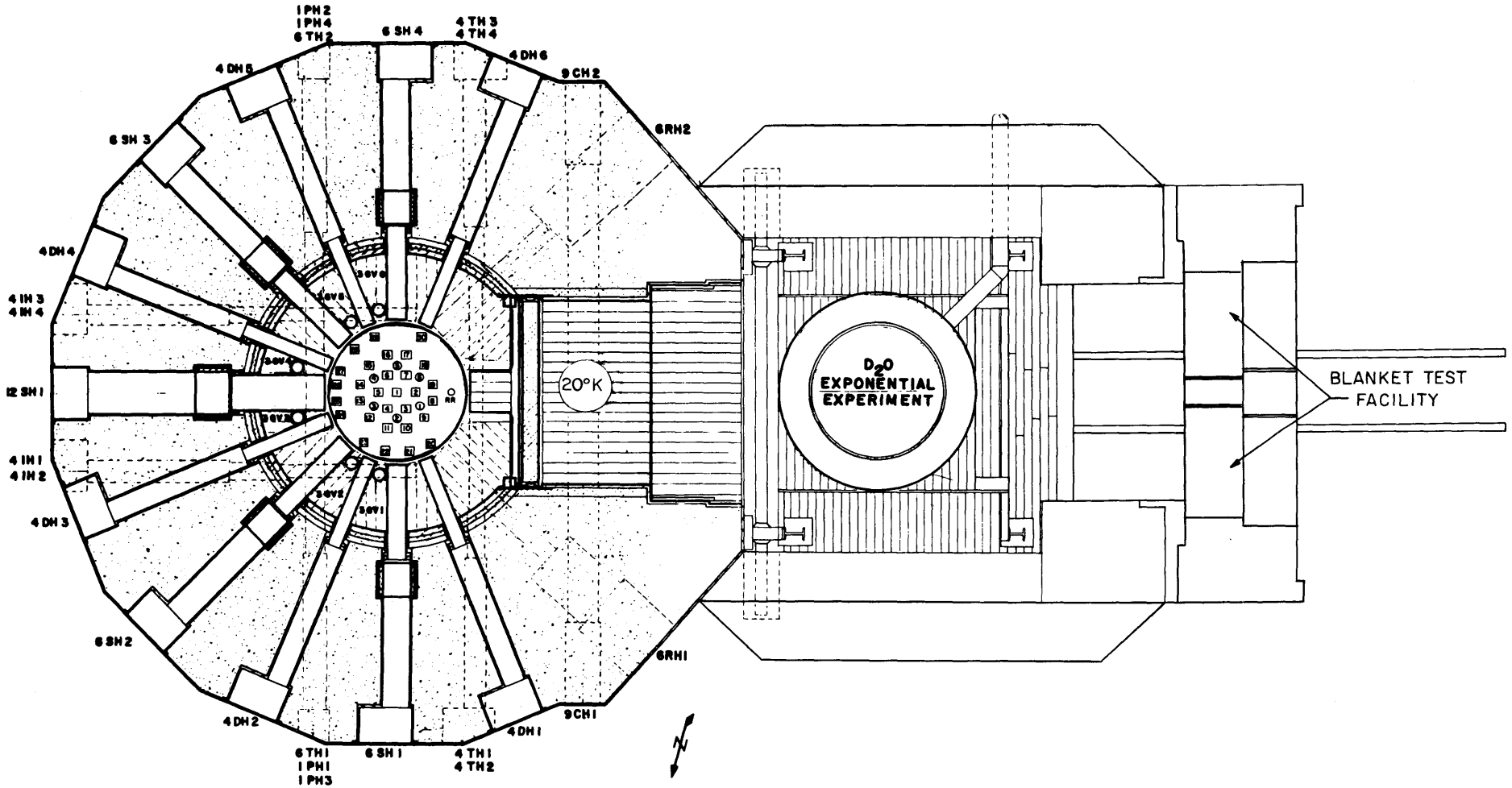

FIG. IV-2 HORIZONTAL SECTION THROUGH REACTOR AND EXPONENTIAL EXPERIMENT

element is generally placed in front of this position. Ports 4DH2, 6SH2, 4DH3, 4DH4, and 4DH5 are normally used for neutron spectrometers. Since, in this case, it is desirable to have as low a dE/E spectrum as possible and as high a thermal flux as possible, fuel elements are not usually placed in positions in front of these ports. The third use of these eleven flexible fuel element positions is to insert samples within the heavy-water reflector at the edge of the core. When the reactor operates at high powers, there is an increase in the graphite zone temperature and, hence, a tendency for low-melting samples to liquefy there. Since a sample inserted into the heavy-water reflector is normally cooled to a temperature of about 120°F, while at the same time the flux is more than a factor of two higher than that in the edge of the graphite zone, it is often advantageous to insert samples into the region of the D_2O reflector itself.

It can be seen from Fig. IV-2 that the principal ports at the reactor consist of a single 12" port with shutters, four 6" ports with shutters, and six 4"ports. The 4" ports can be shuttered by making use of the port boxes which are at the outer extremities of the shielding. In addition to these, there are two other radial ports which contain special rotary sample changing systems. There are four "through ports" extending completely through the reactor from one side to the other. One of these is a 6" port tangent to the core tank (6TH1-2 of Fig. IV-2), which can be used for viewing capture gamma rays or for providing neutron beams essentially free of the fast neutrons and gammas which come direct from the core in radial ports. Immediately below this port are four small pneumatic sample changer tubes (1PH1, 2, 3 and 4 of Fig. IV-2). One of these sends irradiated samples via a transfer station and a 300' delivery tube to the Radiochemistry Laboratories in an adjacent building, so that short-lived isotopes may be received for use six seconds after leaving the high flux zone of the reactor.[14]

There are two 4" through ports (4TH1, 2, 3, and 4 of Fig. IV-2), one above the other on the other side of the core tank. These ports are utilized for a combination of control instrumentation and for

experimental use in a manner similar to the 6" through ports. The fourth through port is 9" square, and it is located in the front portion of the thermal column. The thermal column itself serves as a source of neutrons for the D_2O exponential experiment shown on the right-hand side of the drawing.

It is possible to remove and insert samples from any fuel position within the reactor; and, in addition, there are six holes to the graphite region accessible from above. Four more instrument ports (4IH1, 2, 3, and 4 of Fig. IV-2) are utilized for reactor instrumentation. There is also a vertical port in the graphite thermal column which looks directly down to the same point which can be seen through the two side through ports of the thermal column. Thus, at this one point, it is possible to see the same sample from above, from either side, or from the front of the thermal column. It is planned to install a cold neutron source (described below in this section) at this point in the near future.

Beneath the reactor is the medical therapy facility. The facility itself consists of an operating room, complete with operating table and a shutter system. The latter consists of a variable water shield, a movable lead section, and a movable boral sheet, and these enable a beam to be extracted from the reactor in a downward direction onto the patient.

In conjunction with the reactor, there is also a 23'-deep tank, used for storing spent fuel, in which gamma experiments can be carried out. Irradiation by charged particles is also possible by means of appropriate nuclear reactions such as (n, p), (n, α), or (n, f). In all, there are over 70 separate positions in which various types of experiments can be carried out.

One of the most interesting facets of this reactor is the fact that it is the first one to be designed, built, and operated with a tank as small as 120 cm in diameter surrounded, in turn, by a graphite reflector. As pointed out previously, this diminishes the inventory of heavy water by a factor of almost two over that of a CP-5 type reactor.

Thermal neutron fluxes close to 10^{14} n/cm^2-sec are available in some of the irradiation positions, and fast fluxes in excess of this figure can be obtained inside those fuel elements equipped with irradiation thimbles. Specific flux levels and special features are listed in Table IV-1.

Reactor experimental facilities are continually being improved for the benefit of users. During fiscal year 1968, the Ball Sample Changer, which had been used very little in comparison with other sample irradiation positions, was removed from through port 4TH1-3. It was replaced by a permanent facility at the north end of the port which is being employed for high-resolution gamma-ray spectroscopy in the measurement of neutron-capture gamma rays and in prompt activation analysis. Test materials placed in either of two shielded positions in the facility are exposed to a current of well-thermalized neutrons issuing from the port. One position is designed to accept reactor fuel rods (including partially burned rods) so that their composition may be studied non-destructively by interpreting the characteristic gamma rays emitted as neutrons bombard the rod. A triple-coincidence pair spectrometer, using a lithium-drifted germanium detector to obtain high resolution, measures the gamma spectrum from either position. It is also possible to insert a sample into the high flux region deep within the port and look at the gamma ray spectrum from outside.

A surplus helium compressor and refrigeration plant has been made available on loan by the AEC. A major portion of the installation was completed during the year. The necessary AEC regulatory approvals have recently been obtained, and the equipment should be ready for use during the current fiscal year.

The helium plant will refrigerate two cryogenic chambers in the MITR. One of these is a materials irradiation thimble located within a fuel element in the core. The fast flux in the thimble (for neutron energies above 0.5 MeV) is about 1.5×10^{13} neutrons/cm^2-sec in the central fuel element position, and consideration is being given to increasing the fuel loading around the cryostat to raise the

Facility	No. Available	Size	Estimated Thermal Flux at 5MW n/cm^2-sec	Special Features
Horizontal Beam Ports 4" 6" 12"	 6 4 1	 $4\frac{1}{2}$" i.d. $6\frac{5}{8}$" i.d. $12\frac{11}{16}$" i.d.	 at tank wall 2×10^{13}	All ports have readily available the following services: 1. Demineralized cooling water 2. 110 V 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
Rotary Horizontal Ports 6"	 2	 $6\frac{5}{8}$" i.d.	 at tank wall, 2×10^{13}	
Horizontal Thru Ports 6" 4"	 1 1	 $6\frac{5}{8}$" i.d. $4\frac{1}{2}$" i.d.	 2×10^{13} at point closest to tank	
Vertical Thimbles Graphite $3\frac{1}{2}$" * In-tank 1" (in reflector) * In-tank 1" (in core) *	 6 up to 10 up to 3	 $3\frac{5}{16}$" i.d. - up to 12" long 1" i.d. - up to 24" long same size	 $1 - 3 \times 10^{13}$ 5×10^{13} 8×10^{13}	Exposure to fast neutrons is possible in in-tank thimbles (also gammas up to 8×10^{8} r./hr.)
Thermal Column	1	Holes up to 14" × 14" extend into thermal column. Larger holes can be made if needed	$10^{9} - 10^{12}$	The thermal column has lead and steel shutters
Pneumatic Rabbit Tubes	4	Space for sample 1" dia. × $2\frac{3}{8}$" long	2×10^{13}	"In" to "out" travel time is 0.5 sec.
Medical Therapy Facility	1	---	Thermal 2×10^{10} Fast 2×10^{7}	Opens into operating room beneath reactor
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 cans as outside containers ($\frac{13}{16}$" i.d. × $1\frac{1}{4}$" or $2\frac{1}{4}$" long).

TABLE IV-1 CHARACTERISTICS OF IRRADIATION FACILITIES

fast flux by about 50 percent. This cryostat will provide for irradiation of solid samples at any controlled temperature between reactor ambient (325°K) and 4.2°K and will permit samples to be kept in liquid helium while they are stored for radioactive decay and transferred to other laboratories at M.I.T. The incore cryostat has a working space of one-inch diameter by six inches long, and the refrigeration capacity at 4.2°K is designed to be sufficient to cool about 80 grams of nonfissionable material (samples plus instrumentation). When irradiations at some higher temperature are carried out, the refrigeration capacity is greater--for example, at 20°K the plant capacity is sufficient to cool roughly 1.5 kilograms of nonfissionable material in the cryostat. This would allow, for example, using a heavy jig for irradiation of stressed samples; alternatively, lesser amounts of materials doped with U-235 could be irradiated to induce fission fragment damage. Funds for some of the equipment required by the system are being provided by the National Science Foundation.

The second cryostat chamber will be located in the reactor thermal column to provide a refrigerated moderator assembly. The cold moderator serves to absorb energy from the already highly thermalized neutrons, slowing them to very low speeds. Beams of these "cold" neutrons can be obtained at any one of four ports extending from the thermal column. Curved copper tubes may be inserted into these ports to serve as internal reflection guides which "pipe" the neutrons to experimental assemblies at the face of the reactor. The basic cryostat shielding and the support system was constructed during 1968. The first cryostat test chamber has been designed and was under fabrication during the latter part of 1968. Calculations are being made for a second design, and parts are on order. Experimental work leading to these two facilities had been undertaken in previous years.

An important addition designed during the past year and currently being installed is a facility to permit expanded research in the area of fast breeder reactor physics. It consists, basically, of a large fission plate (approximately 20 sq. ft.) and appropriate

diluents which partially degrade the fission neutron energy spectrum into one typical of that emanating from a fast reactor core. This converter assembly is being installed in an irradiation cave located at the end of the thermal column (Figures IV-1 and IV-2). The assembly will feed neutrons into an adjacent blanket test assembly or into other materials. By appropriate arrangement of components, it will be possible to obtain a wide range of neutron spectral energy distributions from very high near the converter to relatively low deep in a moderator, in which to conduct experiments. The converter fission power of 50 watts is much higher than that of typical fast critical assemblies, and thus the facility should be able to serve very effectively in many applications.

Another modification to the reactor during the past year was the installation of a facility, 2CH1, which permits exposure of small test samples to neutron fluxes having primarily a fission energy spectrum. This facility consists of an aluminum tube extending across the thermal column hohlraum into which may be inserted an annulus made of slightly enriched UO_2 fuel rods. These convert the thermal flux to one with a fission spectrum for irradiation of materials which can fit into a cylindrical hole about 1-1/8" in diameter by 4'long. In order to accommodate larger specimens, a similar facility, 6CH1, with an inside diameter of 4" has been planned (and has been installed since the end of the fiscal year.)

The reactor is supported by well-equipped machine and electronics shops, a low-level radioactivity counting room, a radiation protection laboratory, a drafting room, and a reading room stocked with nuclear engineering texts, references and journals. A four-station, time-sharing electronic calculator was installed during the previous year.

Within the Department of Nuclear Engineering are many other facilities useful to the conduct of reactor-oriented research and education. 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 AEC under an educational loan. Neutrons for the subcritical exponential are supplied by a number of plutonium-beryllium sources also loaned by the AEC. 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 a laboratory for instruction in plasma physics, a hot cell for handling materials made radioactive by the reactor, and a nuclear chemical engineering laboratory for investigating extraction of uranium, separation of fission products, and isotope separation.

Many of the research facilities at M.I.T. are of an interdepartmental character. As a result, Nuclear Engineering students have access to a wide range of research services and facilities outside of the Department.

The facilities of the M.I.T. Computation Center, including use of an IBM 360/67 computer, are available for use by students and staff in Nuclear Engineering. Further, the M.I.T. time-sharing system permits users to have remote access to the computer from various locations on campus, including a console in the Nuclear Engineering Department. In addition, some students may become interested in Project MAC, which is investigating the scope and application of time-shared computers. Also, numerous special purpose computers are available for data processing.

Research activities in nuclear engineering 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 three decades. Since 1946, most of this research has been carried out through the interdepartmental Laboratory for Nuclear Science; the facilities here include a number of Van de Graaff generators and the M.I.T. cyclotron. The Laboratory is building a high-intensity

linear accelerator for 400-MeV electrons, to be in operation in 1969. The Laboratory and Harvard University operate jointly the 6-BeV Cambridge Electron Accelerator on the Harvard campus.

M.I.T.'s research in electronics and such related fields as microwave physics, radioastronomy and applied plasma physics is conducted in the interdepartmental Research Laboratory of Electronics. Students and staff of the Nuclear Engineering Department engaged in research on plasmas and controlled fusion do so under the auspices of the Research Laboratory of Electronics and use its excellent facilities.

One of the two stations of the Engineering Practice School operated by the Chemical Engineering Department is located at the Oak Ridge National Laboratory. Students here work in small groups directed by M.I.T. Faculty on technical problems or research topics which have arisen in connection with the laboratory's programs. Nuclear Engineering students are permitted to use attendance at the Oak Ridge Practice School for one term to satisfy the thesis requirement for the Master of Science degree.

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

V. ORGANIZATION

Administratively, the M.I.T. Research Reactor is part of the Department of Nuclear Engineering, one of several departments in the School of Engineering at M.I.T. The Reactor Director is Dr. T. J. Thompson, Professor of Nuclear Engineering, who reports to the Department Head, Professor Manson Benedict.

The normal complement for the reactor staff and the names of the individuals serving in the various positions on June 30, 1968, are given in Table V-1. A number of the 35 individuals listed devote fractions of their time to other activities, such as teaching or research projects related to the reactor, so that the equivalent full-time complement for the reactor is approximately 26 people. Reactor Operator Licenses are held by 17 of the above, and nine of these are Senior Operator Licenses.

In order to insure organizational independence for the health physics group assigned to the reactor and associated research projects and teaching laboratories, the radiation protection personnel report directly to the M.I.T. Medical Department's Occupational Medical Service. Consequently, these individuals are not listed as part of the reactor staff, but they should nevertheless be recognized as playing an important role in helping to maintain a completely safe environment for reactor personnel, experimentalists, and the general public. Also important to our program are the Building Custodians, who are shown separately because they are administratively part of the Physical Plant Department at M.I.T. These groups are listed in Tables V-2 and V-3.

The several research projects at M.I.T. which utilized the reactor in a major way during fiscal year 1968 are listed in Table V-4. The names of personnel associated with these projects are given in those portions of Section VIII containing the descriptions of the research performed by the projects. It would be impracticable

TABLE V-1

REACTOR STAFF

(June 30, 1968)

Director	T. J. Thompson
Associate Director and Business Manager	Lincoln Clark, Jr.
Assistant Director for Engineering and Design	Edward J. Barnett
Assistant Director for Operations	James W. Gosnell
Operations Superintendent	David F. Frech
Electronics Supervisor	David A. Gwinn
Assistant Superintendent	Kenneth D. Collins
Senior Shift Supervisor	Lawrence T. Papay
Shift Supervisors	William E. McDermott Paul T. Manadier
Shift Supervisor in Training	Alfred Torri
Reactor Operators	Leonard E. Andexler Thomas J. Casey Cyril J. Crane Lewis A. Goldman David J. Holbrook James P. Knotts Joseph L. Rupp
Machine Shop Supervisor	Francis L. Woodworth
Machinists	Kenneth J. Butler Thomas J. Green Harry A. Saunders John E. Wasik
Technicians	Lawrence A. Ristuccia, Jr. Charles E. DeAngelis
Mechanic	Almon J. Abbott
Stock Clerk	Richard E. Henderson
Draftsman	(Not filled)
Electronics Technician	David A. Lynch (One position not filled)

TABLE V-1 (Concluded)

Administrative Assistants	John L. Cochrane Deane B. Haskell
Secretaries	Marguerite J. Falco Kathleen E. LaCorcia Margaret L. Wolfe
Receptionist	Luz M. Honorato
Operations Assistant and Guide	Richard A. Farmer

TABLE V-2

RADIATION PROTECTION PERSONNEL

(June 30, 1968)

Radiation Protection Officer	Edward Karaian
Radiation Protection Technicians	Patrick A. Coggio Donald Searl (One position not filled)

TABLE V-3

BUILDING CUSTODIANS

(June 30, 1968)

Head Custodian	Charles Hamilton
Custodians	Joseph Keough Edward Zaniewski James S. Keegan (temporary)

TABLE V-4

MAJOR RESEARCH PROJECTS AT M.I.T. INVOLVING THE MITR

Reactor Lattice Research

Organic Coolant Loop

Reactor Physics Research

Gamma-Ray Spectroscopy

TABLE V-4 (Concluded)

Design of Radiation Effects Cryogenic Facility
Design and Fabrication of Cold Neutron Cryogenic Facility
Design of Fast Reactor Blanket Facility
Neutron Capture Therapy Research
Medical Applications of Neutron Activation Analysis
Neutron Diffraction Spectrometers:
    Physics Department Program
    Metallurgy Department Program
Installation and Start-up of Inelastic Scattering Spectrometer
Nuclear Chemistry
Activation Analysis in Geochemistry

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to list all of those associated with M.I.T. groups making limited use of the reactor or with groups in other universities, hospitals, etc.

The members of the M.I.T. Reactor Safeguard Committee conduct periodic safety reviews of the reactor operation and pass on the safety of the experimental program. Those who served during the year are shown in Table V-5. The majority have been active on the Committee since its inception in 1957.

TABLE V-5

M.I.T. REACTOR SAFEGUARD COMMITTEE

(June 30, 1968)

Manson Benedict, Chairman	Head, Department of Nuclear Engineering, M.I.T.
Harvey Brooks	Dean, Division of Engineering and Applied Physics, Harvard University
Mark J. Dondero	Head, Safety Office, M.I.T.
Carl F. Floe	Vice President, Research Administration, M.I.T.

TABLE V-5 (Concluded)

James W. Gosnell	Assistant Director for Operations, M.I.T. Reactor
Harriet L. Hardy	Assistant Director, Medical Department, M.I.T.
Samuel Levin	Radiation Protection Officer, M.I.T.
Constantine J. Maletskos	Senior Scientist, Cancer Research Institute, New England Deaconess Hospital, and Lecturer, Department of Pathology, Harvard Medical School
John J. O'Connor	Director, Army Materials Research Reactor, Watertown, Massachusetts
Theos J. Thompson	Director, M.I.T. Reactor, and Professor, Department of Nuclear Engineering, M.I.T.
Lawrence T. Papay, Secretary	Senior Shift Supervisor, M.I.T. Reactor

There were several promotions for members of the reactor staff and several additions during fiscal year 1968. James W. Gosnell was promoted from Operations Superintendent to Assistant Director for Operations and David F. Frech from Assistant Superintendent to Operations Superintendent, both on August 1, 1967. Kenneth D. Collins moved from Shift Supervisor to Assistant Superintendent on February 1, 1968, and Paul T. Menadier, formerly a Reactor Operator, became a Shift Supervisor on November 1, 1968.

We are happy to welcome the following six people who joined the reactor staff during the year: John L. Cochrane, Administrative Assistant, came to us from the U. S. Navy's nuclear submarine program. Charles E. DeAngelis, formerly at Bond Research Laboratory, Inc., Somerville, Massachusetts, joined the staff as a Technician (E-M). Richard A. Farmer, a student in the Department of Nuclear

Engineering, served as Operations Assistant and Reactor Guide. Deane B. Haskell, Administrative Assistant, transferred from MIT's Lincoln Laboratory, where he worked as an electronics technician in the daytime while studying business administration nights at Boston College. Luz M. Honorato had been a secretary and ground hostess in Chile for Panagra Airlines before coming to Massachusetts in 1967 and shortly thereafter to the MITR. Alfred Torri recently obtained his Senior Operator license and is serving as a shift supervisor. He is studying part-time for the Doctor's degree, having earned his Bachelor's in Mechanical Engineering at the Swiss Federal Institute of Technology in 1964 and his Master's in Nuclear Engineering at M.I.T. in 1967.

For those who make their careers in the dynamic fields of nuclear science and engineering, continuing education is almost a necessity. Fortunately, opportunities to improve one's educational background are abundant in the Boston area. M.I.T. promotes job-related training through a tuition assistance program for employees of the Institute, and the reactor lists among its supervisory personnel several who are pursuing advanced degrees in nuclear engineering on a part-time basis at M.I.T.

Participation in job-related training courses at all levels is strongly encouraged at the M.I.T. Research Reactor. This is one important way in which our organization will continue to be capable of providing competent reactor and related services to the research and teaching community both within and outside the borders of M.I.T. Furthermore, activities at the M.I.T. Research Reactor, particularly because of its location in a metropolitan area, must always be conducted in a thoroughly safe manner in order to eliminate the possible existence of any conditions which might be harmful to the health or safety both of the on-site personnel and of the general public. Courses to improve knowledge and skills in nuclear and related fields are considered important in maintaining a high level of competence for the successful achievement of the above requirements.

During fiscal year 1968, 18 members of the reactor staff successfully participated in more than 40 courses of study. This count does not include Professor Thompson's teaching of "Thermal Power Reactors," M.I.T. subject number 22.29, nor "Nuclear Power Reactor Safety," subject number 22.93S, a special two-week summer course designed primarily for those engaged full time in reactor design, fabrication, operation, teaching, and regulation. Those reactor personnel taking courses and the topics studied are listed in Table V-6.

TABLE V-6

OUTSIDE STUDY BY REACTOR STAFF

Name	Institution	Course
K. J. Butler	North Andover Regional Technical High School	Welding
T. J. Casey	Northeastern University, Boston, Cooperative Student	Courses toward Bachelor's Degree in Electrical Engineering
L. Clark, Jr.	M.I.T.	Economics of Nuclear Power
K. D. Collins	M.I.T.	Circuit Theory
C. J. Crane, Jr.	Northeastern University, Boston	Courses toward Bachelor's Degree in Electrical Engineering
M. J. Falco	Waltham High School Adult Education	Advanced Shorthand
R. A. Farmer	M.I.T.	Numerical Analysis, thesis research on two-phase flow
D. F. Frech	M.I.T.	Nuclear Reactor Design, Nuclear Reactor Engineering, thesis research in reactor physics of heavy water lattices; received SM in Nuclear Engineering

TABLE V-6 (Concluded)

Name	Institution	Course
J. W. Gosnell	M.I.T.	Thesis research in the reactor physics of two-region lattices
D. A. Gwinn	M.I.T.	Thermal Power Reactors
D. B. Haskell	Boston College	Courses toward Bachelor's Degree in Business Administration
D. J. Holbrook	Northeastern University, Boston	Courses toward Bachelor's Degree in Electrical Engineering
D. A. Lynch	Northeastern University Boston	Courses toward Bachelor's Degree in Industrial Engineering
L. T. Papay	M.I.T.	Thesis research in reactor physics using pulsed neutron techniques
L. R. Ristuccia, Jr.	Northeastern University Boston	Cryogenic Equipment Design
J. L. Rupp	Northeastern University, Boston Cooperative Student	Courses toward Bachelor's Degree in Electrical Engineering
H. A. Saunders	Northeastern Unversity, Boston	Courses toward Associate's Degree in Mechanical Engineering
A. Torri	M.I.T.	Thesis research in fast reactor fuel depletion

Continuous and refresher training for operating personnel is accomplished in a variety of ways. A weekly rotation of the working hours, insuring each member of the regular operations staff of frequent participation in reactor start-ups and shut-downs, serves as a perpetual retraining program in the reactor systems and components. Drills in emergency procedures are held periodically to maintain the familiarity necessary for their successful implementation.

In addition to these training programs directly related to the daily job, operators and supervisors participate in numerous special projects including revisions to the operating manual, measurement of the neutron flux in reactor facilities, advice to customers on technical problems, evaluation, design, and construction of electronic and mechanical equipment to increase the safety or improve the operation of the reactor, review and analysis of unusual occurrences, and preparation of presentations to the MITR Safeguard Committee and the AEC Division of Regulation. Some of the less routine projects of this nature are described in the following Section VI. Often in the course of such projects, new skills are learned or old skills are sharpened and applied in new directions.

At this point, it is appropriate to recognize again the contributions of all those in the reactor organization. Efficient and safe operation of the reactor week after week according to the announced schedule has been the result of a loyal willingness by everyone to accept responsibility for his share of the daily tasks which, in the aggregate, have constituted a successful record of performance. Many have demonstrated their ability to work hard and frequently to work long extra hours in order to meet experiment installation deadlines or to carry out lengthy preventive maintenance checks on the facility and its related equipment. Often it has been necessary to work at wholly unscheduled hours during nights or weekends, and always these people have demonstrated that conscientious attention to detail -- whether safety system calibrations, machining tolerances, or administrative red tape--so important to the successful operation of a research reactor facility. Everyone listed in the tables of this section, as well

as others who have been involved in operation of the facility, may justly take pride in the record of performance of the M.I.T. Research Reactor.

The operating record of the MITR may also, in no small measure, be attributed to the continual cooperation manifested by the research investigators at the reactor. They have demonstrated a willing aptitude for coordinating experiment activities not only within the framework of reactor operating and maintenance limitations but also with full recognition of the requirements of other investigators. The MITR Staff wishes to express its appreciation to all those reactor users who in this manner have contributed to making the past 12 months not only a productive and rewarding year but also a pleasurable experience.

We are likewise indebted to the many individuals who have been connected with reactor operation or utilization in the past. Without the solid foundation which they prepared and then passed on to their successors, the accomplishments of 1967-68 would, if anything, have been merely in the planning stages in 1968-69 or in later years. They have gone on to serve effectively in many capacities and constitute a growing body of MITR alumni scattered, literally, all over the world. An "alumni directory" may be found in Section IX (Table IX-2).

VI. RECORD OF OPERATION

In partial fulfillment of its mission as one of the Institute's major research facilities, the reactor continued during fiscal year 1968 its record of safe and reliable operation, averaging 92 hours per week of full power operation. The normal weekly schedule permits a maximum of 102 hours approximately, but experiment changes, major maintenance, holidays, and so forth, reduce the average over the year to the first figure mentioned above.

The normal operating schedule calls for raising power to 5 MW, usually late Monday morning, after completion of mechanical and electronic start-up checklists, experiment changes, and preventive maintenance. Operation is normally continuous until 5 p.m. on Friday when the reactor is shut down for the weekend, giving 100 hours or slightly more at full power during a typical week. About ten holidays per year affect this schedule. The reactor runs through minor ones which fall on Tuesday, Wednesday or Thursday but is usually shut down for Monday and Friday holidays and for occasional four-day weekends which include a major holiday such as Thanksgiving.

Most weekends are busy times at the reactor. Saturdays are invariably used for maintenance, modification of reactor systems, and installation or removal of major experiments. Preventive maintenance is regularly performed on Saturdays and Monday mornings. Friday nights and Sundays are frequently used also when jobs become too numerous or too lengthy to be handled on Saturday or Monday morning. Some, such as the pressure test of the containment building, require round-the-clock scheduling. Fresh fuel is added to the core, one or two elements at a time, and so this is still another weekend activity which takes place once and sometimes twice each month. Operation of the reactor by trainees, either students or license candidates, takes place on Friday nights and weekends to supplement the minimal experience it is possible to gain during the regular start-ups.

Following initial criticality on July 21, 1958, the first year was one primarily of low power operation for the purpose of studying in detail the behavior of the reactor. Flux plots were made and numerous reactivity effects were measured. The maximum amount of information considered feasible was obtained before the core was made substantially radioactive by operation at higher powers. A level of 1 MW was first achieved on February 20, 1959, and the reactor was operated for a total of 241 hours at this power level, as well as for many additional hours at lower powers, between that date and the start of three-shift operation on July 20, 1959.

Table VI-1 gives a summary of operations during the nine-year period commencing July 20, 1959 and ending June 30, 1968. The information is given in four columns in order to provide the more detailed breakdown of reactor utilization available from the operating records beginning July 1, 1961 and in order to show separately the statistics for the past two years. Noteworthy is Item 1a., the 23,844 MWH representing a new fiscal year record. Item 4 shows that full power operation averaged close to 93 hours/week over the past seven years in spite of time lost due to holidays and due to weekday shut-downs for experiment changes, essential maintenance, or other reasons.

The number of samples irradiated, Item 5, continues to run at a high level. The figures on this line represent irradiations both by the research projects described in Section VIII and by organizations outside M.I.T. Information concerning these latter groups and the types of materials irradiated is provided in Section X and in Appendices G, H, and I. U-235 burnup (Item 6) is calculated by the MITBRN computer program[15], a general description of which appears in Appendix F.

Since two shipments of spent fuel were made in fiscal year 1967, none were required during the past year. Two more are planned for fiscal year 1969.

With one minor exception there has been no recurrence of the heat exchange leaks which forced operation at 2 MW for a period

TABLE VI-1

SUMMARY OF OPERATIONS

	7/20/59-6/30/61 (Approx. 2 Years)	7/1/61-6/30/66 (5 Years)	7/1/66-6/30/67 (1 Year)	7/1/67-6/30/68 (1 Year)
1. Megawatt Hours:				
a. For period, MWH	8,762	57,679	19,655	23,844
b. Cumulative from 7/21/58, MWH[1]	9,003	66,682	86,337	110,181
2. Hours of Reactor Operation:				
a. At full power[2]	8,740	24,279	4,830	4,790
b. Subcritical and critical (less than full power) for operator training	(3)	16[4]	18	16
c. Same - for teaching, experimental and other purposes	464	597	46	74
d. Approaching full power (including startup checks)	(3)	1,130	233	235
e. Completing shutdown	(3)	240[4]	194	255
Subtotal 2a-2e		26,262	5,321	5,370
3. Hours for Reactor Maintenance and Other:				
a. Refueling	(3)	91[4]	65	69
b. Maintenance and changing experiments	(3)	3,454	737	626
c. Not in use, no maintenance[5]	(3)	14,017	2,637	2,719
Subtotal 3a-3c		17,562	3,439	3,414
Total Hours in Period	17,064	43,824	8,760	8,784
4. Hours/Week at Full Power-Average	86.2	93.4	92.9	91.8
5. Samples Irradiated	(3)	9,581	1,527	2,625
6. U-235 Burnup, Grams	476	3,047	1,040	1,245

NOTES: See next page.

NOTES to Table VI-1:

(1) 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.

(2) 1MW -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 6/30/68.

(3) Hours not classified prior to 7/1/61.

(4) These classifications started 1/1/65; prior to that date, these hours were included elsewhere.

(5) Usually Friday and Saturday nights, Sundays, and major holidays.

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during fiscal year 1967, using one of the two exchangers normally in service. Nevertheless, a new heat exchanger has been obtained, and it will be used as a replacement if further trouble of this type develops.

Not only does the radioactivity induced in the heavy water make undesirable its escape from the system but also, because of its high monetary value, every effort is made to conserve this valuable inventory. From the beginning of operation the flanges, valves, pump seals, and other potential sources of leaks in the primary coolant system have been protected with leak indicators which furnish an alarm in the control room for as little as one drop of D_2O. Over the years a few hundred pounds of heavy water have accumulated as the result of routine system sampling, ion column deuterizations, a relatively few minor spills, system maintenance and various other activities related to reactor operation. Much of this material has retained essentially its isotopic purity but may have become slightly contaminated with dirt or other foreign materials. It has been possible to salvage a major fraction of this D_2O by circulating it through clean-up equipment assembled and placed in operation during the past year by Cy Crane with the help of the Mechanical Group.

Also, in connection with the use and evaluation of heavy water, the Reactor Lattice Research Project (USAEC Contract AT (30-1)-2344) designed, assembled, and calibrated an infrared absorption spectrometer for the measurement of heavy water purity in the range of 99.00-99.90 mole % D_2O[16]. Accuracies of $\pm$ 0.03 mole % D_2O are obtained. The equipment has been made available to the MITR, and it is now being utilized by Lew Goldman of the Operations Group for routine measurements of the isotopic purity of reactor D_2O samples.

The MITBRN computer program mentioned above was orginally written in FORTRAN II language and was run on an IBM 7094. Computer programs of this nature are now run at MIT on an IBM 360/67, requiring the FORTRAN IV language. Consequently, substantial revisions in the detail of the MITBRN program were accomplished during the year by Ken Collins in order to accommodate this change in equipment.

The shielded storage holes had become nearly filled over the years with a large assortment of radioactive items ranging from relatively hot in-pile irradiation thimbles and loops to mildly active flux wires and other materials. This inventory was reviewed and checked, primarily by Len Andexler and the Radiation Protection Group, and a substantial portion was culled out, packed, and shipped for burial. Plans are being made for disposal of those remaining items which will probably be of no future use.

Dave Gwinn and Dave Lynch have designed and assembled a reactivity meter which utilizes a boron-lined ion chamber in the graphite reflector to provide a signal to an analog computation circuit followed by a digital divider and readout. The resulting reactivity information will be a useful adjunct to calculations of, and to other means of measuring, reactivity effects. Preliminary tests of the system have shown that it can save substantial amounts of time in calibrating control rods and in measuring the reactivity of experimental apparatus, and that it should be helpful in training exercises. It was used as a principal measurement method in the thesis work of L. Papay[17] for void coefficient measurements in a simulated pressure tube reactor fuel element cooled by H_2O, D_2O and organic coolants.

There are a number of regulatory documents, issued by the AEC, which give MIT authority to operate a research reactor and to possess the fuel and other nuclear materials necessary to its effective operation. These consist primarily of licenses authorizing specific activities. They are amended frequently to reflect changing conditions and, in most cases, must be renewed periodically. Licenses currently in effect are listed in Table VI-2 with a brief description of the purpose of each.

TABLE VI-2

USAEC LICENSES REQUIRED FOR REACTOR ACTIVITIES

License Number	Activity Authorized
R-37	Operation of MIT Research Reactor; possession and use of U-235 in fuel elements for the MITR
SNM-81	Possession and use of Pu in Pu-Be neutron sources for use in teaching laboratories, in research, and for health physics instrument calibration.
SNM-83	Possession and use of U-235 in fission counters for the MITR.
SNM-171	Possession and use of U-235 in reactivity calibrating rods, in fission plates and in other forms for teaching and research utilizing the MITR. Also possession and use of Pu in neutron filters employed in neutron diffraction spectrometers.
SNM-985	Shipment of MITR spent fuel elements to a processing plant using National Lead Company cask No. NL-BF-MTR-775.
SNM-986	Possession and use of normal U, U-235, and Pu for conduct of subcritical reactor lattice experiments, and additional U-235 and U-233 for nuclear chemistry research.

Considerable time has been spent by the reactor staff in past years preparing a revised set of Technical Specifications for the MIT

Reactor. The set developed initially in 1965 was the first set prepared for any reactor in the United States and was done to demonstrate the feasibility of the method for the AEC task force set up to formulate a policy in this matter. Later the procedures were published in proposed AEC Regulation 10 CFR 50.36. The first version was initially submitted to the Commission's Division of Reactor Licensing on August 20, 1965. A revised version following the final 10 CFR 50.36 format was resubmitted on June 23, 1967, and has been under review by the AEC since that time.

While the purpose of the above licenses is to be certain that the authorized activities are conducted with sufficient precautions and safeguards to insure the health and safety of persons directly involved and of the general public, accountability for the substantial asset value of the nuclear materials lent by the AEC to MIT for research under contract with the Government is maintained through Accountability Station MBM. Book inventory records are maintained by each person to whom material is distributed for use, quarterly reports are filed with the AEC on seven classifications of materials, and supervised annual inventories are performed. During the past year, John Cochrane has maintained the records required for materials held under license and accounted for under Station MBM and also has prepared the related reports to the AEC.

VII. USAEC RESEARCH AND TRAINING CONTRACT

Round-the-clock operation of a 5-MW research and training reactor entails costs running to many hundreds of thousands of dollars. In carrying out its mandate under the Atomic Energy Act of 1954 "to insure the continued conduct of research and development and training," it is the policy of the U.S. Atomic Energy Commission to provide to educational institutions certain assistance in return for their operation of research and training reactors. The amount of this assistance is in the neighborhood of 10% of total operating costs, depending on the type of reactor and its operating schedule.

Under this program, Contract AT(30-1)-1967, entitled "Research and Training Program and Loan of Certain Commission Materials in Connection Therewith," sets forth the nature and scope of the agreement between MIT and the AEC. 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. Appendices A through E furnish the list of publications for fiscal year 1968. Theses in progress at the end of June, 1968 are also included insofar as known in order to make the list as current as possible and to provide further information concerning present activities. They will be listed again in future reports covering the year when completed.

As mentioned in the Introduction, a complete bibliography of theses, reports, journal articles, and conference papers (in excess of 600) concerning research related to the MITR up until June 30, 1967,

was contained in a similar document issued a year ago, i. e., "Research and Educational Activities at the MIT Research Reactor To and Including Fiscal Year 1967", report number MITNE-91. The current list brings that bibliography up to date.

In consideration of the performance of these activities by MIT, the AEC provides reimbursement for fuel element fabrication and for return shipping of spent fuel; lends without use charge the uranium for the elements, the heavy water coolant and moderator, and an antimony-beryllium neutron source employed for the reactor start-up; and waives charges for consumption and normal operational loss of uranium, neutron source, and heavy water during fabrication, use, and reprocessing.

Between August 15, 1957, the effective date of the contract, and June 30, 1967, a total of 165 fuel elements containing 24.0 kilograms of uranium-235 were purchased. The last 20 of these were received during fiscal year 1968. These are expected to last until February 1969, necessitating another purchase early in fiscal 1969.

Burnup amounted to 4.6 KG of U-235 from start-up through June 30, 1967, and it was 1.2 KG for FY68. The first returns of spent fuel were made during FY1967, when 56 elements containing 5.5 KG of U-235 and averaging 31% burnup were returned to the Commission's Savannah River Reprocessing Plant in South Carolina. No fuel was returned in FY 1968, but two more shipments are planned for spring 1969.

Approximately 10,000 pounds of heavy water are utilized in the reactor system as coolant and moderator. Additional quantities are required for process uses such as deuterizing ion columns or making analyses and for replacement of operational losses. Of the 14,000 pounds provided through June 30, 1968, consumption,losses, and transfers over ten years of operation have totaled 900 pounds, leaving 13,100 pounds as the June 30, 1968 inventory on hand.

VIII. M.I.T. RESEARCH ACTIVITIES USING THE REACTOR

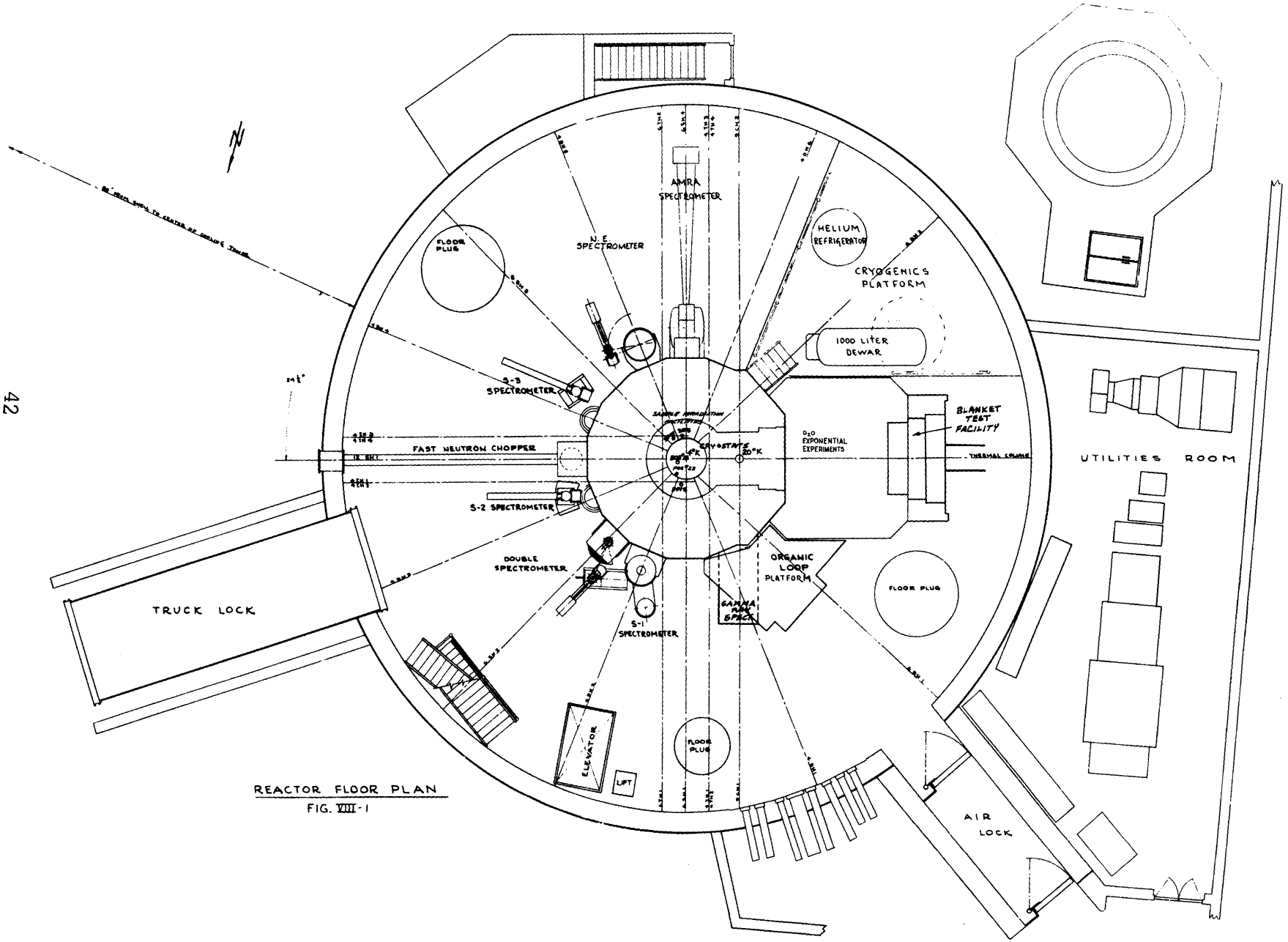
This section summarizes the general types of research which utilize the MIT Reactor, lists the MIT departments, centers, and laboratories participating in such use, provides statistics on the number of faculty members, students, and others engaged in major reactor-oriented projects at MIT, and describes briefly the fiscal year 1968 major programs conducted by Institute research investigators.

Recent and current programs of research utilizing the MIT Reactor cover a broad range of nuclear sciences and engineering topics. They may be classified under the following general headings:

Nuclear Physics	Radiation Therapy
NeutronPhysics	Biomedical Studies
Thermal Reactor Physics	Radiochemistry
Fast Reactor Physics	Fission Process Studies
Reactor Engineering	Neutron Diffraction
Solid State Physics	Radiation Damage
Neutron Activation Analysis	Cryogenic Experiments

These categories overlap in some areas, but the list is intended to suggest the diversity and scope of experimental work made possible by the reactor. Descriptions of specific investigations are given later in the section. The general layout of experimental facilities around the reactor is illustrated in Fig. VIII-1.

Utilization of the reactor is by no means limited to the Department of Nuclear Engineering at MIT. Within the Institute, several other departments maintain important reactor research programs; and at one time or another since the reactor began operation and up until June 30, 1967, a total of 19 departments, study centers, and interdepartmental laboratories at MIT listed in TABLE VIII-1, had utilized its facilities. Ten of these made further use of reactor services during fiscal year 1968. The major research projects conducted under their auspices



REACTOR FLOOR PLAN

FIG. VIII-1

during fiscal year 1968 (academic year 1967-68) are described below in Sections VIII-1 through VIII-5, and the publications resulting from these projects are listed in Appendices A through E.

TABLE VIII-1

DEPARTMENTS AND INTERDEPARTMENTAL LABORATORIES AT M.I.T. THAT HAVE USED THE M.I.T. REACTOR

(*indicates use in fiscal year 1968)

1. Departments, and Laboratories within Departments

* Aeronautics and Astronautics
  Instrumentation Laboratory

  Chemical Engineering

* Chemistry

* Civil Engineering
  Hydrodynamics Laboratory

  Electrical Engineering
  Insulation Research Laboratory
  Electronic Systems Laboratory

* Geology and Geophysics

* Mechanical Engineering
  Lubrication Laboratory
  Materials Processing Division

* Metallurgy

  Meteorology

  Naval Architecture and Marine Engineering

* Nuclear Engineering
  Nuclear Reactor Laboratories

* Physics
  Radioactivity Center

2. Centers and Interdepartmental Laboratories

  Center for Advanced Engineering Studies

  Center for Materials Science and Engineering

  Lincoln Laboratory

* Laboratory for Nuclear Science

  National Magnet Laboratory

* Radiological Safety Office

  Research Laboratory for Electronics

Table VIII-2 is an attempt to tabulate the number of MIT faculty, students, technicians, and others participating in the major research programs which concerned the reactor during the fiscal year. Not included in the tabulation are 39 of the 44 people listed in Tables V-1, V-2, and V-3, since their duties are primarily related to operation of the reactor facility and not to research. Five did contribute directly to the research and are included. The figures of Table VIII-2 understate the actual total number of individuals participating in all MIT research activities involving the reactor because it is not always possible to determine how many, in addition to the investigator for whom an irradiation is performed, may actually be engaged in the project using the irradiated material. Note that students constitute more than half of the tabulated personnel.

The following subsections describe research programs in which the various MIT departments engaged during the academic year 1967-1968. In those programs where several students are involved, the project is generally subdivided into a corresponding number of subprojects. In general, no attempt has been made to describe these individually, but some idea of the subproject topics may be obtained through an examination of the titles of the student theses listed in the appendices.

1. DEPARTMENT OF NUCLEAR ENGINEERING

By way of introduction, it might be noted that the Department of Nuclear Engineering offers subjects in both fission technology and applied plasma physics. Students may major in either option and, of those electing the former, many choose to carry out thesis work of a theoretical nature, which is generally unrelated to the MITR, or experimental work in other areas such as fluid flow, heat transfer, deuterium separation, metallurgy, etc. Nevertheless, it is significant to note that a substantial fraction carry out experimental thesis investigations utilizing the reactor, and a few additional students have written theoretical theses based on some aspect of the MITR. During the eleven-year period ending June 30, 1968, 138 theses, or 35% of

TABLE VIII-2

NUMBER OF INDIVIDUALS IN FIVE DEPARTMENTS AT M.I.T.
DOING RESEARCH INVOLVING THE M.I.T. REACTOR
1967-68

Department	Faculty	Students	Engineering Assistants	Technicians	Others	Total
Chemistry	4	14	10		2	30
Geology and Geophysics	1	4				5
Metallurgy	3	3				6
Nuclear Engineering	10	40	5	6	13	74
Physics	1	4	1	1		7
TOTALS	19	65	16	7	15	122

the total submitted to the Department of Nuclear Engineering, were MITR-related, mostly experimentally but a few theoretically. Theses by students from other departments are in addition to these totals. It is only this MITR-oriented research with which we are concerned here.

1.1 MIT Lattice Project

Since 1959, experimental and theoretical research has been done on subcritical assemblies of low-enrichment uranium fuel rods in a D_2O moderator. On September 30, 1967, the experimental work of this project was completed, and final reports were subsequently published. Two doctoral theses begun during the contract period are being completed under M.I.T. asupices and will be published during the current year.

The program began with construction of a facility based upon the cavity or "hohlraum" technique for delivering well-thermalized, high-intensity neutrons from the MIT Reactor to a tank containing heavy water and the lattice to be investigated.

The objectives of this research were:

1. To develop and improve experimental and theoretical techniques for investigation of slightly enriched uranium rods in D_2O moderated lattices.
2. To catalog a broad range of experimental data for important reactor physics parameters in uniform lattices.
3. To develop and test theoretical methods for independent prediction of, correlation of, and interpolation between the experimental results.
4. To develop methods, such as single rod and substituted or miniature lattice techniques, which would permit collecting data on new lattices in this area with a minimal additional expenditure of resources.

Most of the lattice measurements involved high-precision foil activation techniques. Radial and axial gold foil activation traverses were made to determine the material buckling. Natural and depleted uranium foils were irradiated in the fuel rods to investigate relative U-238 and U-235 neutron reaction rates; bare and cadmium-covered measurements were used to separate the thermal and epithermal contributions. Other approaches such as pulsed neutron techniques were also employed to determine parameters such as K_∞. In the final year, emphasis was placed upon the development of single-rod methods for the determination of lattice fuel parameters. Five sets of uranium metal fuel rods have been studied, each for three different lattice spacings. Five lattice spacings using UO_2 fuel were also completed.

The objectives of the project have been fulfilled, namely:

1. New experimental techniques have been developed, e.g., in the area of fast fission measurements. In addition, a large number of improvements and modifications in existing experimental techniques have been developed with particular emphasis on error analysis and reduction. At present, most key parameters can be measured to within approximately ±0.5% to 1.0%, which is beginning to approach the present irreducible minimum. Comparison of careful experimental work with theoretical results has also led to improvements in the latter: for example, in the development of the important THERMOS code.

2. An important fraction of all the existing detailed fuel parameter measurements on low enrichment uranium, D_2O moderated, uniform lattices was obtained at MIT. Most other previous and comtemporary studies have been focused on determination of the material buckling; the MIT lattice project has, in addition,

put considerable effort into determination of the parameters of the "experimental four-factor formula" — C^*, δ_{28}, δ_{25}, ρ_{28}.

3. Correlation of results has been quite successful, so that it is now possible to interpolate and extrapolate data to cover variations in rod spacing, rod diameter, U-235 enrichment, and other important variables.

4. Theoretical and experimental work has made it possible to utilize miniature lattices or, even more importantly, a few rods to predict the properties of an entire lattice.

Ultimately, these results may be utilized to predict the reactivity of reactor lattices of specified sizes and the ratio of conversion of uranium-235 to plutonium without the need for experimental work requiring a large number of fuel rods.

The lattice project provided an opportunity for many students to do challenging graduate thesis research. Some 16 doctoral theses have been carried out, and 24 Master's theses have been completed. In addition, of more than 100 student projects in the reactor laboratory course (Subject 22.42), many have been connected with and contributed to the lattice project. We consider that the lattice project in many ways serves as a good example of how a continuing program, using both graduate thesis research and a nucleus of supporting technicians, can definitely explore a well-defined technical area.

Personnel during FY 1968

Professors: I. Kaplan
T. J. Thompson
F. M. Clikeman
M. J. Driscoll

Professors formerly associated with the Project:

E. A. Profio, Jr.
D. D. Lanning

Students:	J. Gosnell L. Papay S. Seth H. S. Cheng D. Frech I. Forbes H. Massin C. H. Chung J. N. Donohew, Jr. R. L. Ricketts D. J. Kennedy E. J. Chase M. Higgins R. Sonstelie A. Wight R. Donovan R. Hlista
Technical Assistant:	Barbara A. Kelley
Technicians:	N. L. J. Berube R. R. DiMartino A. T. Supple, Jr.

Support

USAEC

Some students doing theses on this project have AEC, MIT, or NSF fellowships.

Related Academic Subjects

22.21	Nuclear Reactor Physics I
22.22	Nuclear Reactor Physics II
22.25	Special Topics in Reactor Physics
22.41	Nuclear Reactor Physics Laboratory
22.43	Reactor and Neutron Physics Laboratory

1.2 Reactor Physics Project

The Reactor Physics Project is an experimental and theoretical investigation, using slightly enriched uranium fuel rods and a heavy water moderator, which has as its primary objective the perfection of single-rod techniques and their application to scarce fuel types, such as plutonium recycle fuel elements, and hard-to-handle materials, such as highly radioactive partially-burned fuel elements. These areas of study were among several proposed to the Atomic Energy Commission, and work in them commenced during the winter of 1968. Although

the level of activity for this project is only about one-half that of its predecessor described in the preceding section, it does serve as a very appropriate follow-on study since it utilizes many of the same techniques, facilities, and personnel.

Emphasis in the present work is on the experimental determination of the parameters used in heterogeneous reactor physics theory to characterize a fuel element. Concurrent theoretical and numerical work is primarily designed to help plan and interpret the experiments. Previous work at M.I.T. has shown that some of the parameters can be inferred from in-rod foil activation. The present program has as its objective the determination of parameters by means of measurements made on the rod surface or in the surrounding moderator. This should obviate the need for cutting into rods containing plutonium and fission products, with the attendant contamination problem.

Two parallel experimental approaches are being pursued in the development of parameter measurement methods. The first involves classical foil activation, or activity traverse experiments; the second, high resolution gamma-ray spectroscopy using Ge(Li) detectors

With regard to the activation and traverse experiments, the development work on determination of Γ, the asymptotic thermal flux, has led to good agreement between theory and experiment, and the method is now considered completely satisfactory for application. Two different methods i.e., foil and gamma spectrometric, are being investigated for the experimental determination of the single rod neutron yield, η. A foil activation method is being pursued to overcome the complications involved in the measurement of $\mathbf{A}$, the epithermal absorption parameter.

For the high resolution gamma spectroscopy studies, a Ge(Li) gamma spectrometer has been set up in front of an MITR throughport to permit measurement of the prompt and delayed spectra emitted by fuel rods. Non-coincident, triple coincident, and Compton suppression modes of operation are possible. Based on work at M.I.T. and elsewhere, it is now anticipated that relative fertile and fissile capture and fission rates can be measured, thereby providing data

for determination of the parameters Γ, η, and A. Following demonstration applications on enriched U-235 in UO_2 fuel, the method will be applied to Pu-239 in simulated burned U rods. Experimental determination of prompt gamma spectra for Pu isotopes is also being planned as groundwork for the fuel rod applications. Finally, the information being obtained is to be used to determine the feasibility of using gamma spectrometry in-pile and on partially burned fuel where high backgrounds exist.

The computer program GAMANL, written in FORTRAN IV for the IBM 360-65 and based on an earlier code developed at M.I.T., is being optimized to suit the specific needs of the present work for analysis of both prompt and decay gamma spectra. A "Single Rod Assembly" code, adopted from a multigroup diffusion theory code, is being used for the planning and interpretation of single rod experiments. It is also intended to modify an existing S_N code (ANISN) to permit evaluation of transport effects.

Results of previous single rod experiments which employed pulsed neutron techniques were re-analyzed to determine more accurately, by application of a moments method and by other means, the change in the prompt neutron decay constant. This can be related to η through an approximate expression based on one-group perturbation and heterogeneous reactor theory. At present it does not appear that this approach can compete favorably with foil activation methods.

Personnel

Professors:	M. J. Driscoll T. J. Thompson I. Kaplan N. C. Rasmussen
Students:	Y. Hukai C. H. Kim T. C. Leung C. S. Rim S. Seth

Support

USAEC

Some students doing theses on this project have AEC, MIT, or NSF fellowships.

Related Academic Subjects

22.21 Nuclear Reactor Physics I
22.22 Nuclear Reactor Physics II
22.25 Special Topics in Reactor Physics
22.41 Nuclear Reactor Physics Laboratory
22.43 Reactor and Neutron Physics Laboratory

1.3 Organic Coolant Project

The heavy-water moderated, organic-cooled reactor is an advanced converter which makes more efficient use of natural uranium than light-water reactors do and which is potentially capable of generating electricity at a lower cost than they do. Organic fluids are also of interest as coolants because, although they undergo some decomposition in the reactor environment, they have a low vapor pressure and are compatible with ordinary steel.

Euratom has had a large program for the development of this reactor type since 1958, and the United States also had an extensive program which was cancelled in early spring, 1967. As part of the United States effort, the effects of neutron and gamma radiation on organic fluids suitable for use as coolants in these reactors were determined experimentally in the Organic Coolant Project at MIT. An in-pile loop, constructed and installed in the MIT Reactor and operated since August 1961, has been used to measure the irradiation degradation rate of organic coolants and the effect of the degradation products on such characteristics of the coolant as density, viscosity, thermal conductivity, heat capacity, and heat transfer rates. The loop consisted of an in-pile irradiation capsule located inside a 10-plate fuel element in the MIT Reactor and an out-of-pile section with provisions for pumping the coolant, making heat transfer measurements, and taking coolant samples for chemical composition and physical

property measurements. The loop was capable of testing organics to temperatures of 800°F.

Coupled with operation of the loop have been development and use of methods of analyzing the coolant composition and of determining the fast neutron and gamma energy absorption rates (dose rates) in the organic coolant. The primary analytical tool for chemical analysis of the coolant was gas chromatography, and methods have been developed for measuring not only the content of undegraded organic in the coolant but also a large number of the degradation products produced on irradiation. For dosimetry, foil activation techniques have been developed and used to determine the fast neutron spectrum to which the organic was exposed. Direct measurements of the enrgy absorption rate due to fast neutron and gamma interactions in the coolant have been made using calorimetric techniques largely developed at MIT under this program.

Since August 1961, a number of runs on three proposed coolants have been carried out covering a temperature range of 425°F to 800°F and a range of undegraded organic concentrations from 50% to 90%. The coolants have been three different commercially available mixtures of terphenyl isomers. During the past year, irradiations have been made using Santowax OM, which has a high isomeric ratio of ortho terphenyl to meta terphenyl. The results were compared with earlier results on Santowax WR, which has a high isomeric ratio of meta terphenyl to ortho terphenyl. Thus the relative stabilities of ortho and meta terphenyl to fast neutrons, gamma rays, and heat at different levels of operating temperature have been determined. The effects of varying dose rate at high temperatures (750°F to 800°F) on terphenyls has also been determined. The data obtained fills out the experimental basis for a correlation to predict the effects of neutron to gamma-ray dose ratio, dose rate, temperature, degradation product concentration on the rate of degradation and physical and heat transfer properties of terphenyl coolants.

The program was terminated June 30, 1968, as a result of the cancellation of the USAEC program on heavy-water moderated, organic-cooled reactors. Since it does not appear likely that future research at

the MITR will utilize the equipment and facilities of this project, they are currently being disposed of through excess property channels.

Personnel

Professors:	E. A. Mason D. T. Morgan (Visiting)
Students:	M. L. Lee G. Yadigaroglu H. Spierling R. Sanders G. Rigamonti
Research Associate:	W. N. Bley
Research Staff:	S. H. Brewer
Northeastern University Cooperative Students:	S. N. Parkhurst E. A. Pembroke D. S. Safran B. W. Stone
Technicians:	J. F. Howard, Jr. J. H. Larson A. J. Pierni

Support

USAEC

Related Academic Subjects

22.231 Nuclear Reactor Engineering
22.26 Nuclear Reactor Design

1.4 Gamma-Ray Spectroscopy

This program in high-resolution gamma-ray spectroscopy has been active for a number of years under NSF and then USAF sponsorship. MIT has provided funds for interim work and for improvement of the facilities. Because of its application to the reactor physics studies described earlier in subsection 1.2, indirect support has also been furnished by the USAEC.

The early work was done with bent quartz-crystal spectrometers and a scintillation triple-coincidence pair spectrometer. During the last two years most of the effort has been spent in the development and use of high-resolution, lithium-drifted germanium solid-state, gamma-ray detectors. Using techniques similar to those developed originally at the Chalk River Laboratory, we have recently succeeded in producing counters with active volumes as large as 40 cm^3. These new detectors have been used in two areas of investigation--the nondestructive analysis of spent reactor fuel and neutron-capture gamma-ray studies.

With these detectors, it is possible to resolve many of the fission product gamma-ray lines in the spectrum from a fuel element. A method has been developed which uses the measured ratios of intensities of certain lines to determine average flux during irradiation and length of irradiation. From this information the burnup can also be determined. This technique, developed and tried successfully on MITR fuel, is being further developed for use on spent fuel from power reactors. If it can, it could provide valuable information for the fuel reprocesser and the fuel designer. The method may also be useful in the international control of reactor fuel.

The detectors are also being used to study neutron-capture gamma rays. A facility was built at the reactor in which samples were irradiated in high fluxes of very thermal neutrons to study the capture gamma-ray spectra from 75 of the natural elements. The other 17 are noble gases and radioactive elements which could not be made into suitable targets. These capture gamma-ray spectra have recently been published as a compilation and represent the most complete study presently available. The initial temporary facility was replaced during the year by a permanent one designed to provide a more versatile irradiation cave in which to continue this and related studies.

Presently, the capture gamma-ray spectrometer is being used to study the possibilities of prompt activation analysis, with the emphasis being on the development of general equations which can be used to

predict the sensitivity of the measurement for any element in a given sample. The first measurements on coal samples have been quite successful. In addition, both the prompt and delayed gamma spectra are being measured in the new facility as a means of determing with single rods and non-destructively the reactor physics parameters under investigation in the project described in subsection 1.2

In conjunction with this work, a computer code is being utilized to analyze the complicated gamma spectra.

Personnel

Professors:	N. C. Rasmussen
Technical Assistant:	Bonnie R. Hites
Students:	C. Takahata T. Harper J. Hamawi Y. Hukai

Support

USAF, USAEC, Sloan Fund (MIT), General and Reserve Funds (MIT)

Related Academic Subjects

22.43 Reactor and Neutron Physics Laboratory

1.5 Reactor Cryogenic Facilities

For the past few years, several members of the Nuclear Engineering Department and other departments at MIT have expressed a strong interest in reactor-oriented research which would require cryogenic test chambers operated at the normal boiling point of helium ($4.2^{o}K$). The experiments of interest are in two fields: (1) neutron radiation damage in solids at cryogenic temperatures, and (2) the physical behavior of very slow ("cold") neutrons.

In the spring of 1967, the initiation of these programs was made possible when the AEC lent to MIT a large helium liquifier which had been constructed in 1962 at the Cambridge Electron Accelerator.

This plant, with overall dimensions of roughly 10 feet wide by 30 feet long by 12 feet high, was designed to supply 100 liters of liquid helium per hour. It is being modified to operate as a refrigerator at the MITR with a refrigeration capacity of 200 watts at 4.2°K. The equipment was dismantled and moved to MIT during May 1967. During FY 1968 a major part of this out-of-pile installation was completed. An application for an amendment to the MITR reactor license was submitted to the USAEC (and was approved in August 1968.) The National Science Foundation is partially supporting the installation costs for this equipment.

The reactor cryogenic facilities will be made available on a general basis to all users of the MIT reactor. A variety of experiments have been suggested, and those which are currently being initiated are described in the following two sections of this report. We believe, however, that many more experiements will evolve during fiscal year 1969 and 1970 when the cryostats have been installed and their operating capabilities are established and that the facility will significantly enchance the utility of the MIT reactor as a research center.

Personnel

Professors:	T. J. Thompson T. O. Ziebold J. L. Smith, Jr.
Research Associate:	E. J. Barnett
Students:	F. J. Berte T. P. Hulick
Technicians:	A. J. Abbott C. E. DeAngelis L. A. Ristuccia, Jr.

Support

NSF, Sloan Fund (MIT), Reserve Funds (MIT)

1.6 Radiation Effects in Solids

With the availability of an in-core cryostat, the primary interest in radiation effects will turn to low temperature irradiations. Because the defects which are induced by particle bombardment anneal out or rearrange themselves quite easily by thermal motion, the low temperature studies are essential to discriminate between the primary nature of radiation damage and the secondary nature of thermal redistribution.

Three groups at MIT have now made definite plans to use the materials irradiation cryostat. Professors Ziebold and Argon are initiating a program to study the neutron damage defect spectrum in structural metals. The specific areas of investigation are the size distribution of induced defects (from scattering of electrons, photons, and phonons and from microscopy); the strain fields associated with induced defects (from divergent beam X-ray diffraction and stress relaxation measurements); the relation of defect structure to deformation modes (scanning electron microscopy of irradiated tensile samples as they are stressed); the basic effect of the damage defect spectrum on plastic deformation (testing of samples with varying prestrain and thin film microscopy); and the effects of radiation damage on fracture (studies of fracture modes under different conditions of mean stress, temperature, and strain rate). The program is supported by the Office of Naval Research, and students will use the hot laboratory at the Naval Research Laboratory in Washington D. C. for the metallographic examination of irradiated samples.

A second area of low temperature irradiations research is under the supervision of Professor B. L. Averbach and R. Kaplow. Their program is directed to a study of changes in optical and electrical properties of amorphous or glassy semiconductors. One set of experiments will simulate very high flux conditions by irradiating samples in liquid helium, rapidly heating the samples to room temperature or above, and measuring short-time transient changes in structure and physical properties. In addition, X-ray and neutron diffraction will be used to measure near-neighbors strains produced by neutron bombardment of several glasses.

Professor Kingery is initiating the third program of low temperature irradiations. This work will examine damage in nonmetallic crystals such as sapphire and MgO. The pronounced anisotropy of lattice expansions, which Professor Kingery has encountered in previous work of this type, will be studied by measurements of density and lattice parameter changes.

Research on the effects of neutron bombardment of heat transfer from heated solids to boiling helium is currently progressing under the supervision of Professors Ziebold and Smith. These experiments were initiated both for the purpose of establishing design data for the in-core cryostat and for the purpose of extending a basic investigation on boiling heat transfer. It had been seen that the critical heat flux (transition from nucleate to film boiling) in pool boiling decreases when the thermal diffusivity of the heated wall decreases. In prior work this was studied by using different metals for the heated surface, but there was a possibility that surface structure may not be the same when various metals are used. In the current work this uncertainty will be removed, since the samples will all be identical but the thermal diffusivity will be changed in a controlled way by neutron bombardment. In addition, we are constructing arrayed thermal sensors -- small germanium patches deposited on copper -- to determine if there are local temperature fluctuations on a heated surface during the various regimes of boiling.

Personnel

Professors:	T. O. Ziebold A. S. Argon (Mech. Eng.) J. L. Smith, Jr. (Mech. Eng.) W. D. Kingery (Metallurgy) B. L. Averbach (Metallurgy) R. Kaplow (Metallurgy)
Students:	H. F. Bowman R. H. Koppe G. R. Odette K. Ohmae

Support

Office of Naval Research

Related Academic Subjects

3.72	Radiation Damage in Crystalling Solids
22.71	Metallurgy for Nuclear Engineers
22.72	Nuclear Fuels

1.7 Cold Neutron Sources

Since 1962 a small group associated with the MIT Reactor in the Nuclear Engineering Department have been carrying out investigations on possible methods to create and utilize beams of very slow neutrons.

The first step was demonstration in an S.M. thesis in 1963 that very slow neutrons could be totally internally reflected within slightly bent copper tubes of readily available types and that the possibility of fabricating the neutron analogue of a "light pipe" therefore existed.

The second step was design, construction and use of an out-of-pile liquid-helium cryostat (installed in the medical therapy room neutron beam) for studies of possible means to reduce the effective neutron temperature and to increase the number of neutrons at low temperatures within a given volume. This cryostat has now been used on two successive S.M. theses to check out qualitatively, and more recently semi-quantitatively, the value of using certain materials and geometries. This information was used to develop an optimized design for a liquid-helium cryostat to be located in the MITR thermal column at such a point that the energy absorption of the fast neutrons and gamma rays from the core will not be important, but still close enough to the core for large fluxes of thermal neutrons to be available. The point chosen makes it possible to utilize up to four separate beams for experiments from this single "cold neutron" source.

During FY 1968, some studies of materials and geometries for this unit were carried out by use of a Monte Carlo computer code. Design of the vacuum jacket and general handling system for the cryostat was completed and fabrication was pushed as rapidly as

possible because the availability of liquid helium is assured through the loan by the AEC of a large-capacity helium refrigerator to MIT. MIT has provided an allocation from its Sloan Fund to build and install the cryostat and to carry out the initial experiments with beams of very slow, cold neutrons from this facility.

Personnel

Professors:	T. J. Thompson N. T. Olson
Research Associate:	E. J. Barnett
Student:	E. Heimberg R. Sanders J. W. Synan

Support

Sloan Fund (MIT), General and Reserve Funds (MIT), I.B.M.

Related Academic Subjects

8.37 Neutron Diffraction
22.42 Reactor and Neutron Physics Laboratory

1.8 Biomedical Research

Studies on the possible use of the MIT Reactor for neutron capture therapy have continued. Our principle interest is the development of an epithermal beam to provide improved thermal neutron depth distribution. Experimental studies have also dealt with improved methods of dosimetry of the mixed beam appearing at the medical therapy facility. Recoil spectra from which fast neutron dose is determined is observed with a silicon semi-conductor detector. Other methods of dosimetry include tissue equivalent ionization chambers and semi-conductor degradation techniques.

Personnel

Professor:	G. L. Brownell

Staff: Dr. A. R. Reddy
(Mass. General Hospital)
Dr. K.M.M.S. Ayyangar
(Mass. General Hospital)

Support

U.S. National Institutes of Health, AEC

Related Academic Subject

22.20 Biological Effects of Nuclear Radiation

1.9 Activation Analysis

A lithium drifted germanium solid-state detector has been designed and built to investigate biological applications of thermal neutron activation analysis. Using this sytem it is possible to measure up to twenty trace elements in a biological sample without prior chemical processing.

Studies are currently under way to determine the role of trace elements in blood and tissues of experimental animals and in man and their relationship to the incidence and progression of various diseases. Further, studies are being undertaken on the role of trace elements in the action of certain biochemical substances such as RNA.

Personnel

Professor: G. L. Brownell
Staff: Dr. David M. Linekin
(Mass. General Hospital)

Support

U.S. National Institutes of Health

Related Academic Subject

22.81 Radiation and Radioisotope Application

1.10 Inelastic Scattering Spectrometer

During the past fiscal year, an inelastic scattering spectrometer has been installed. It was designed according to specification furnished by Picatinny Arsenal personnel stationed at the Army Materials and Mechanics Research Center, Watertown, and was fabricated by or under the supervision of the MIT Reactor Machine Shop personnel. Operation of the spectrometer will be by the Picatinny scientists. This brings to six the number of neutron spectrometers currently operable on the MITR. Funds for construction of a seventh have been allocated.

The spectrometer consists of a neutron collimator, a gamma shutter, a slow chopper, a crystal monochromator, a fast chopper, a sample holder section, a vacuum flight path, and a neutron detector bank. The detector arm, together with the vacuum flight path, swings through an angle of 120^{o} in the vertical plane. This unit will permit the observation of neutrons, as a function of angle and velocity, scattered inelastically from targets of molecular crystals. The incident beam on these targets is essentially monoenergetic, but of variable energy.

The general purpose for which the spectrometer will be used is high resolution studies of molecular dynamics of molecular crystals and liquids, both by incoherent and coherent inelastic scattering measurements. After a period of debugging and calibration, dispersion curve measurements were begun in the summer of 1968 on oriented polytetrafluorethylene (teflon). These studies should be completed early in 1969. Future studies will include dispersion curve measurements on stable metal azide salts, incoherent scattering studies of molecular crystals, hydrogen-bonded materials, and polymers, and "small-kappa" measurements on liquids.

Personnel

Design and Fabrication (MIT):

Research Associate:	E. J. Barnett
Shop Foreman:	F. L. Woodworth
Machinists:	K. J. Butler T. J. Green J. E. Wasik

Operation and Research (Picatinny):

Physicist, Explosive Res. Lab.	H. J. Prask
Physicist, Explosives Res. Lab	S. F. Trevino
Graduate Student, Boston College	V. E. LaGarde
Graduate Student, Boston College	R. D. Mical

Support

U. S. Army

1.11 Fast Blanket Test Facility

A new facility was designed during the past fiscal year to permit expanded research in the area of fast breeder reactor physics. The main component of the facility is a large fission plate, approximately 20 square feet, which will convert the thermal flux at the end of the reactor "hohlraum" (Figures IV-1 and IV-2) to a fission spectrum suitably degraded in energy so as to be typical of a fast reactor core. The resulting converter assembly feeds neutrons into an adjacent irradiation cave where fast reactor blanket materials, or devices which will use the fast flux, will be installed.

It will be possible to obtain a full range of neutron energies in this facility, from very high near the converter to relatively low deep in the blanket material. The converter fission power of 50 watts is about fifty times that of a typical fast critical assembly, and so the facility should be able to compete very favorably for many applications. Some of those planned and for which financial support is being sought

are the following:

1. Use as a test bed for development of fast neutron spectrometers.
2. Irradiation of simple blanket mock-ups of possible fast breeder reactors to provide integral results against which to test calculational methods.
3. Use as an irradiation facility by research workers studying the effect of fast neutron irradiation on transistorized equipment packages.
4. Development of methods to optimize the economics of breeding by modifications of the blanket region.

The USAEC has authorized use of some of its UO_2 fuel rods, aluminum clad, in the assembly of the converter plate, and application has been made to the AEC Division of Regulation for a license amendment to permit such use. The shielding blocks for the blanket cave were ordered during the year (and have since been received and installed). The facility should be in use by the winter of 1969. A budget of $25,000 from MITR reserve funds has been authorized for this important reactor modification.

While this new facility will have many applications, as outlined above, its use for the testing of fast reactor blanket compositions will be of particular significance. It is in the blanket region of fast reactors that much of the net plutonium is generated, and hence an accurate understanding of the blanket characteristics is very important to the economics of the fast breeder reactor concepts.

Personnel

Professors:	M. J. Driscoll T. J. Thompson
Student:	I. Forbes

Support

MITR Reserve Funds; USAEC Materials Loan

Related Academic Subjects

22.21 Nuclear Reactor Physics I
22.22 Nuclear Reactor Physics II
22.25 Special Topics in Reactor Physics
22.28 Fast Power Reactors
22.41 Nuclear Reactor Physics Laboratory
22.43 Reactor and Neutron Physics Laboratory

1.12 Nitrogen-16 Loop

During the past year a small loop was built in the thermal column of the MIT reactor to study the chemical form and reaction behavior of nitrogen-16, the principal short-lived radioisotope formed in the water used in water-cooled reactors. It was demonstrated that over 75% of the nitrogen-16 is in ionic form and hence can be removed by a mixed-bed ion exchanger.

Personnel

Professor:	M. J. Driscoll
Students:	E. Coppola R. Mestemaker

Support

Sloan Basic Research Fund (M.I.T.);
General Funds (M.I.T.)

Related Academic Subjects

22.31 Nuclear Chemical Engineering

2. DEPARTMENT OF PHYSICS

A broad program of basic research in nuclear and neutron physics has been conducted since the beginning of reactor operation

in 1958. The scope of the research has gradually increased during the intervening years, so that from three to five neutron diffraction spectrometers are now simultaneously utilized by this project. These instruments have all been designed by Professor C. G. Shull, the group supervisor, and fabricated in the MIT Reactor Machine Shop. The project staff maintains also a neutron diffraction laboratory and a precision machine shop in support of its work.

The five spectrometers now installed on the MITR have different characteristics and permit a variety of investigations. The main features of each are as follows:

S-1 Very high angular resolution spectrometer.

S-2 High resolution, low intensity spectrometer for use in powdered crystal work.

S-3 Polarized beam spectrometer.

S-4 Polarized beam spectrometer.

S-5 Flexible, multipurpose spectrometer.

Areas of investigation during the past fiscal year may be summarized briefly as follows.

2.1 Ferromagnetic Prism Refraction of Neutrons

The very high angular resolution of a double crystal spectrometer using a matched pair of perfect silicon crystals has been exploited in studying prism refraction effects with neutrons. Most effort has been concentrated on studies with ferromagnetic prisms where a spin splitting of an unpolarized incident beam is found, completely analogous to the historic Stern-Gerlach experiment. This has been exploited to yield an accurate determination of the forward magnetic scattering amplitude for pure iron which agrees with that calculated from bulk magnetization to better than one percent. Thus the 10 percent discrepancy between the expected forward amplitude (calculated from magnetization) and that extrapolated from the experimental Bragg amplitudes (3d-like) is confirmed and this substantiates further the presence of a non-3d-like negative magnetization component. The

refractive bending angles are very small (1 to 15 seconds of arc) and an accurate calibration of the angular sensitivity of the spectrometer system has been carried out with optical fringe measurements. Studies have also been performed on cascaded prism assemblies wherein double Stern-Gerlack splitting is investigated. Rotation of the neutron polarization by resonance means between separated Stern-Gerlach components has demonstrated the basic quantum-mechanical resolution of spin 1/2 states. (Schneider and Shull)

2.2 Refractive Bending of a Neutron Beam by a Magnetic Field

Studies similar to the above have been performed with pure magnetic fields shaped with prism and cylindrical geometry. The deflection and focussing effects are being remeasured making use of improved angular calibration data and the experimental results are being compared with those calculated from the field contour distribution determined by Bi-probe scanning. (Schneider, Just and Shull)

2.3 High Temperature Study of Iron Magnetic Scattering Amplitudes

The magnetic contribution to the Bragg structure factor for iron is being studied at high temperature (up to the Curie temperature) for comparison with the magnetization and for assessment of the temperature variation of spatial asymmetry of the magnetic 3d electrons. The high temperature vacuum furnace, mounted in a vertical field electromagnet on the polarized beam spectrometer, has been improved and a careful assessment of the crystal extinction, higher-order wavelength, beam depolarization and zero-field extrapolation effects has been made during the past period. (Maglic)

2.4 Single Slit Diffraction of Neutrons

The diffraction broadening of a neutron beam in passing through a fine slit has been studied by project personnel at M.I.T. using a high angular resolution spectrometer set up at Brookhaven National Laboratory. Long wavelength neutrons (4.4Å) were used

on a double crystal spectrometer (perfect silicon crystals in parallel orientation) and these were passed through slit openings ranging between 4 and 21 microns fabricated with metallic Gd edges for high absorption. The observed broadening (4 to 20 seconds of arc) agreed well with that calculated for Fraunhofer diffraction and demonstrated that the neutron wave front was coherent over a transverse length at least that of the largest slit opening used in the experiment. (Shull)

2.5 Studies of (222) Forbidden Germanium Reflection

A study of the (222) Bragg reflection in germanium is being carried out with neutrons at room temperature and at elevated temperatures. This Bragg reflection is normally forbidden (zero intensity is expected) by the lattice symmetry, which is that of the diamond structure. However, a number of x-ray experiments have shown the presence of a finite intensity which has been given interpretation in terms of (1) a non-centrosymmetric distortion of the electron charge density within the atoms or (2) a non-centrosymmetric type of thermal oscillation of the atom centers. An equivalent observation with neutrons would sense only the second of these interpretative models. Present neutron observations, carried out elsewhere and here, have shown no measurable neutron reflectivity at room temperature. Hence the bulk of the x-ray intensity effect must arise from model (1) above. There is good reason to believe however that model (2) should also be a contributing factor and present efforts are directed toward repeating the neutron experiment at high temperature (400-500^{o}C) where effects arising from model (2) will be considerably enhanced. Aside from the room temperature measurements and the preparation of a furnace for the high temperature measurements, theoretical analysis has been given to the high temperature case which will guide the eventual interpretation of the experiment. (Nunes)

2.6 Studies of Coherent Paramagnetic Scattering by Vanadium

The weak paramagnetism in vanadium metal can be studied by polarized neutron scattering in coherent Bragg reflections when a magnetic field is applied to the crystal. We have been interested in seeing whether this coherent paramagnetic scattering is modified below the superconducting transition (T_c about $5^{\circ}K$) thereby indicating an electron-spin pairing action as previously studied in superconducting V_3Si. Several specimen crystals of varying purity (residual resistance ratios varying between 20 and 120) were studied during the period with essentially identical results. The observations, when corrected for nuclear polarization effects at low temperature, suggest a modification of the paramagnetic scattering below T_c in spite of the presence on the crystal of a magnetic field of 14,000 gauss much higher than the critical field for vanadium. This observation would imply that electron-spin pairing is still effective below T_c even though the bulk, transport superconductivity effects have been suppressed by the applied field. It is recognized that the residual effects and their interpretation are sensitive to the nuclear polarization correction that must be applied to the data and that an error in applying this correction can remove the effect. Further work in confirming the degree of nuclear polarization is called for before the conclusion can be accepted. (Stassis, Just and Shull)

2.7 Study of Kondo Effect in Dilute Alloys

When magnetic impurity atoms are introduced into a non-magnetic host lattice in dilute form, there has arisen in the last few years considerable theoretical evidence, supported by some experiments, that an anti-ferromagnetic bound state exists between the impurity magnetic atom and the surrounding conduction electrons of the metal lattice. It may be possible to observe this coupling directly by polarized neutron scattering at low temperatures (below the Kondo temperature) and a start has been made at preparing suitable crystal specimens for study. Crystals of the alloy have been

grown and homogenized and exploratory neutron studies are about to begin. (Stassis and Shull)

2.8 Neutron Diffraction by Perfect Crystals

Experiments have been started which are designed to test implications of dynamical theory (in which the intimate relationship between Bragg reflected and forward reflected radiation within the perfect crystal volume is emphasized) for the neutron case. Experiments have been performed at Brookhaven National Laboratory with perfect silicon crystals which were prepared and studied at M. I. T. and for which there is very small neutron absorption; this permits novel testing of the theory compared with x-ray observations. Of interest in the experiments is the spatial distribution of Bragg intensity being released by the crystal as a function of incident ray direction. Two general conclusions have become available from the study: (1) Bragg reflected intensity always arises from crystal surface source points and not volume points and (2) all Bragg reflected beams contain within themselves an intimate Pendellosung interference fringe structure. The latter fringe structure is very sensitive to experimental parameters such as the neutron wavelength and nuclear scattering amplitude and has been used to determine the nuclear scattering amplitude for silicon with a precision much higher than previously available. In this way, the atomic scattering amplitude for silicon has been determined as $0.41646 \pm 0.00022 \cdot 10^{-12}$ cm. With this precision, the neutron-electron interaction amplitude of $-0.00140 \cdot 10^{-12}$ cm must be allowed for in arriving at the true nuclear scattering amplitude. The interference fringe effects that have been measured also yield novel information on the longitudinal extent of the coherently-split neutron wave packet as it travels through the crystal. (Shull, on leave at Brookhaven National Laboratory)

Personnel

Professor:	C. G. Shull (on leave - at Brookhaven National Laboratory during academic year)
Staff:	W. Just H. Alperin, BNL R. Nathans, BNL
Graduate Students:	R. Maglic A. C. Nunes C. S. Schneider C. Stassis
Technicians:	A. D'Addario

Support

USAEC and NSF

Related Academic Subjects

8.363	Theory of Solids
8.37	Neutron Diffraction
8.38	Special Problems in Neutron Diffraction

3. DEPARTMENT OF METALLURGY

The neutron diffraction spectrometers described in the preceding section are utilized also by the Department of Metallurgy for investigations of the solid-state physics of metals.

The arrangement of spins in ferromagnetic and antiferromagnetic materials is being investigated by means of neutron scattering observations. Work here has shown that there is considerable short range order above the critical temperature and the local arrangement of spins is being investigated at temperatures above and below the magnetic transition. Detailed studies have been made in single crystals of MnO and NiO, and work on CoO is now underway. It appears that short range antiferromagnetic order in these materials exists well above the critical temperature, and the situation is complicated by the presence of both magnetic twin and spin domains.

These spin waves change as the critical temperature is approached and the development of long range order from these modulated structures is being investigated.

Spin correlations are also being measured in permanent magnet materials. The magnetic properties of these materials are being measured, and attempts are being made to correlate the magnetic parameters with the spin arrangements.

Personnel

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Support

NSF

Related Academic Subjects

3.23 The Structure of Matter

4. DEPARTMENT OF CHEMISTRY

The Nuclear Chemistry Group of the Department of Chemistry is located in well-equipped laboratories situated adjacent to the MIT Reactor complex. In 1964 a pneumatic rabbit tube was run from the reactor containment building to one of the nuclear chemistry laboratories, thereby enabling transfer of radioactive materials from the reactor irradiation position to the laboratory in about six seconds. If this time period is too long compared to the half-lives of nuclides being studied, chemistry facilities are also available in the basement of the reactor building itself.

The reactor is continually utilized in a wide variety of applications by the Nuclear Chemistry Group. These may be broadly classed as decay-scheme, fission process, physico-chemical, and activation analysis studies. Brief descriptions of the research are given in the following subsections.

The report on the Department of Chemistry activities essentially covers a two-year period for the following reasons. For some of the investigations much of the work was performed in the prior fiscal year; but, since the projects were not individually described in the FY1967 report, summaries of them are included here. Also, other studies begun late in FY1968 and extending into FY1969 have been described, in order to make this report as current as possible. Only those studies in which the MIT Reactor was used are mentioned, although the Nuclear Chemistry Group carries out experiments using radioactive materials procured from the MIT Cyclotron and other sources as well.

Improvements made during the past two years in detectors and instrumentation also are briefly described.

4.1 Nuclear Decay-Schemes

In order to check on the levels of ^{69}Ga in connection with studies of the Zn fission products (see below in subsection 4.2), the decay schemes of 14-h ^{69m}Zn, 56-min ^{69}Zn, and 39-h ^{69}Ge to ^{69}Ga were investigated. By measurement of decay rates and γ-ray energies, it has been possible to augment the data on ^{69}Ga levels. ^{69m}Zn was found to have two weak β branches to ^{69}Ga levels. An additional weak (0.0015%) β decay of ^{69g}Zn was observed, which represents one of the largest known log ft values (8.6) for allowed β^- transitions. Ten γ's not previously reported were assigned to the decay of cyclotron-produced ^{69}Ge, and 12 levels are now established in ^{69}Ga up to 2043 keV. Improved values for half lives and for the isomer-yield ratio of the ^{68}Zn (n, γ) ^{69}Zn reaction were obtained. This and similar investigations underscore the value of being able readily to compare and combine the data developed in studies of the decay of neutron-rich nuclides produced in reactors and proton-rich species produced by charged-particle bombardment. (Zoller, Gordon, and Walters)

The decay of ^{81}Se to levels of ^{81}Br has been studied, and most of the disagreements existing in published data have been

explained. An additional γ ray at 767 keV has been ovserved, and a new decay scheme is proposed. (Zoller and Walters)

A study of ^{98}Zr decay has been undertaken in order to augment the relatively meager data available regarding the decay of ^{98}Zr, ^{98}Nb and the excited states of ^{98}Mo. Zr is separated from fission products by extraction. The γ-ray spectrum, started six minutes after irradiation, shows a weak γ ray at 793 keV which decayed with an apparent half life of about 8 minutes. Additional work is in progress. (Erten and Coryell)

Decay schemes of 40-d ^{103}Ru and 17-d ^{103}Pd have been proposed. The abstract of a paper submitted to Nuclear Physics follows: The structure and properties of the levels of ^{103}Rh have been further characterized by studying the electrons and γ rays emitted in the decay of 40-d ^{103}Ru and 17-d ^{103}Pd. K-conversion coefficients of 0.0043 ± 0.0006 and 0.0025 ± 0.0005 have been measured for the 497 and 610-keV γ transisitons respectively and indicate positive parity for the 537 and 650 keV levels. Using a time-to-amplitude conversion system, an upper limit of 0.4 nsec has been determined for the 93-keV level. Angular correlations have been observed for the 444-53 and 557-53 keV cascades and indicate spins of 5/2 or 7/2 for the levels at 537 and 650 keV. A weak 242-keV γ ray from the 537-keV level to the 3/2- level at 295 keV establishes the spin and parity of the 537-keV level as 5/2+. The log ft values for the β^- decay and E.C. decay to the levels of ^{103}Pd have been determined and sizeable hindrances noted. (Zoller, Macias, Perkal and Walters)

The β and γ decay of 13.5-h ^{109g}Pd to levels of ^{109}Ag were studied. Several excited states of ^{109}Ag not previously reported were detected; spin and parity assignments were made in most cases. (Graeffe and Gordon)

A tentative decay scheme has been proposed for the decay of 7.5-day ^{111}Ag to ^{111g}Cd. The following is the abstract of an article prepared for submission to The Physical Review: The decay schemes of 1.3-min and 7.5-day ^{111}Ag have been studied using Ge(Li) and NaI(Tl) detectors and a 4096 channel multiparameter pulse-height

analyzer system. The decay of 7.5-day ^{111}Ag was found to involve nine γ rays and to populate four excited states in ^{111}Cd at energies of 245.5, 342.1, 619.9, and 866.7 keV. In a separate experiment, the energy of the $11/2^-$ state in ^{111}Cd was found to be 396.1 $\pm$ 0.3 keV. The 1.3-min ^{111}Ag was found to decay almost exclusively (99.7%) by isomeric transition. A small fraction of this isomer (0.3%) was found to β-decay to the 245.5- and 417-keV levels in ^{111}Cd. (Hnatowich and Coryell)

The decays of 1.2-min ^{113m}Ag, 5.3-h ^{113g}Ag and $<$50-sec ^{115}Ag have been studied by making use of the rapid sample-transfer facilities of the MITR along with rapid chemical separation. The following is the abstract of an article prepared for submission to Nuclear Physics: The decay schemes of 1.2-min and 5.3-h ^{113}Ag have been studied using Ge(Li) and NaI(Tl) detectors and a 4096 channel multiparameter pulse-height analyzer system. The decay of 5.3-h ^{113g}Ag was found to involve 15 γ rays and to populate ten excited states in ^{113}Cd at energies of 264.7, 298.0, 315.6, 583.9, 604.6, 681.1, 883.6, 936.9, 989.0 and 1195.2 keV. The underlined energies refer to negative parity states, through which 1.3% of the decays go to yield the 14-y ^{113m}Cd(11/2-) isomer at 264.7 keV. The 604.6-keV level is thought to be a 9/2- level similar to those found in several odd-mass Te and Xe isotopes. The 1.2-min ^{113m}Ag decay was found to populate several of the same levels in Cd and two additional levels at 452 and 689 keV. The 1.2-min ^{113}Ag is the upper isomer with high spin, probably 7/2+. (Hnatowich, Coryell and Walters)

The decay of ^{117}In isomers have been investigated to search for 9/2- levels in the odd-mass isotopes of Sn, corresponding to those found for odd-mass Cd and Te. Analysis of the γ-ray spectra of ^{117}In, obtained from the decay of ^{117}Cd, failed to reveal such excited levels. (Studies of ^{117}Sb and ^{119}Sb decay are underway for the same purpose.) However, β feeding from the 1.9-h ^{117m}In to two levels at 1004 and 1020 keV were observed. Also, it was possible

to measure the feeding from 40-min ^{117g}In to the 14-d ^{117m}Sn isomer. (Baedecker and Walters)

The decay schemes of 42-min ^{123}Sn and 10-min ^{125m}Sn have been studied. Levels in ^{123}Sb were populated in the decay of the former, and levels in ^{125}Sb in the decay of the latter. In a paper accepted by Nuclear Physics for publication, the systematic behavior of low-lying levels of odd-mass Sb isotopes is discussed, and the levels observed in this study are compared to the levels calculated by Kisslinger and Sorensen[18]. (Baedecker and Walters)

Work with high-resolution Ge(Li) detection equipment has just begun on the study of the decay of 2.2-h ^{127}Sn (assumed to be 11/2- ground state) to levels of ^{127}Sb. The Sn is extracted from ^{235}U fission products (Apt and Walters)

A reexamination of the decay of an equilibrium mixture of 109-d ^{127m}Te and 9.4-h ^{127g}Te has been made. The singles spectra obtained with high resolution Ge(Li) detection equipment revealed two previously unreported γ rays at 649 keV and 375 keV, both corresponding to transitions to the ground state of ^{127}I. Based on absolute β and γ counting it was concluded that the fraction of β decay of ^{127g}Te to the 417-keV level of ^{127}I was 1.5% with a log ft of 5.9. A revised decay scheme of ^{127g}Te and ^{127m}Te has been proposed. The intensity of the 11/2- to 7/2+β transition is three times larger than previously accepted values. Furhter work is planned to check this intensity. (Apt and Walters)

The work of Beyer, Berzins, and Kelly[19] in which they investigated the decay of ^{131m}Te to ^{131}I, has been repeated, and several additional γ rays have been observed . These are compatible with the ^{131}I level scheme proposed by Beyer et al. Gamma-gamma angular correlations of the decay of 25-min ^{131g}Te and the decay of 67-min ^{129g}Te and 34-day ^{129m}Te are underway. The improvement of Ge(Li) detectors since earlier studies has allowed the determination of ^{131g}Te decay scheme in much greater detail. The use of Ge(Li)-NaI(Tl) systems coupled with high speed coincidence equipment permits

angular correlation studies that were previously quite difficult and unreliable. (Macias, Baedecker and Walters)

Sb was chemically separated from the fission products of irradiated normal U to provide 55.4-min ^{133m}Te and 12.5-min ^{133g}Te. The γ-ray spectra of these nuclides were analyzed to provide data on the energy levels of ^{133}I. A decay scheme with 25 γ rays has been constructed for ^{133g}Te; but that for ^{133m}Te is very complicated, and only a partial scheme was attempted. Q_β of ^{133}Te was measured as 3.52 $\pm$ 0.10 MeV. The low-lying levels of the odd-A iodine isotopes vary smoothly through the series ^{125}I through ^{133}I, and the levels of ^{133}I are fitted rather well by predictions based on quasiparticle-phonon coupling. (Parsa, Gordon and Walters)

6.7-h ^{135}I was separated from the other fission products of ^{235}U for purposes of studying the levels of odd-neutron ^{135}Xe. A tentative decay scheme, including 15 new γ rays and three new levels, has been constructed. It is in essential agreement with that based on the reaction ^{136}Xe (d, t) ^{135}Xe (20), and it provides an improvement in the accuracies of the energies. Beta-gamma coincidence studies have been used, and γ-γ angular correlations are in progress to determine the spins of the upper levels. (Op de Beeck, Macias and Walters)

During the above study strong evidence was obtained for a 158.2 keV-249.6 keV γ-ray cascade. The results of further study are contained in the following abstract of a paper published in Journal of Inorganic and Nuclear Chemistry[21]: The decay of 9.2-h ^{135}Xe has been studied using Ge(Li) detectors and coincidence techniques. Sources of ^{135}Xe were prepared by extracting Xe from purified sources of 6.7-h ^{135}I separated from fission products. Two new γ rays have been observed at 158.2 and 407.5 keV and a new level in ^{135}Cs proposed at 407.5 keV. Spin assignments are discussed and the levels of ^{135}Cs compared with the levels of ^{133}Cs. (Op de Beeck and Walters)

In order to resolve the conflicting reports for the half life of ^{52}Ti and to study the low-lying levels of ^{52}V, Li_2TiF_6 was irradiated with tritons produced by the ^{6}Li(n, α)t reaction. ^{50}Ti(t, p)^{52}Ti should

result in sufficient ^{52}Ti to provide the above information, but it has not been possible to date to accomplish this or to find any 3.7-min ^{52}V. (Zoller, Op de Beeck, Macias and Walters)

The levels of ^{88}Sr populated in the β decay of 17.8-min ^{88}Rb were investigated by γ-ray spectroscopy with Ge(Li) spectrometers and by γ-γ coincidence and angular correlations. A previously unreported level in ^{88}Sr was found at 4747 $\pm$ 2 keV, as well as three new weak transitions. Measurements of the angular correlation for γ rays from the 4515 keV and 4853 keV levels give a spin of 2^- for the former and rule out 1^- as a possibility for the latter. (Catz)

In collaboration with Dr. R. A. Meyer of the Lawrence Radiation Laboratory, the excited states of ^{124}Te have been studied by observing the γ rays following the β decay of the ^{124}Sb isomers and following the EC and positron decay of ^{124}I. The work based on irradiations in the MITR is summarized in an abstract of a paper submitted for publication to Nuclear Physics: The levels of ^{124}Te have been investigated by studying the γ rays emitted following the decay of the 60-d and 1.5-min isomers of ^{124}Sb. Using a Compton-suppressed Ge(Li) γ-ray detector and NaI(Tl) - Ge(Li) and Ge(Li)-Ge(Li) coincidence systems, 64 γ rays have been assigned to the 21 proposed levels of ^{124}Te populated in the decay of the 60-d isomer. The spin and parity of the 1.5-min isomer of ^{124}Sb are discussed as is the nature of the proposed second 3- level at 2693.87 keV. (Ragaini and Walters)

The γ-ray spectrum of I samples rapidly separated from fission products has been studied. Gamma rays of 198, 273 and 383 keV energies previously assigned to 83-sec ^{136}I (22) decayed with half lives different from that of ^{136}I. The 273-keV γ ray has a half life of 3.8 min., while the 847- and 885- keV γ rays of 58-min. ^{134}I show an initial growth with about the same half life. This suggests possible isomerism in ^{134}I, but it is not yet known if the 273- keV γ ray is associated with isomeric transition of the proposed ^{134m}I or if it follows β decay of the isomer. Further work is in progress to answer some of the questions raised and to determine

the origin of the other γ rays not properly assigned to 83-sec ^{136}I. (Erten and Coryell)

A 3- state of ^{144}Pr is 59 keV above the 0- ground state. Since the Weisskopf estimate of the lifetime for such an M3 transition is about 80-seconds, direct evidence for this isomer was sought. ^{144}Pr was extracted from ^{144}Ce, and the half life was measured by gating on the K_α x-rays of Pr. Preliminary measurements give 7.2 ± 0.3 min for the half life. The decay schemes of ^{144}Pr and ^{144}Ce are to be reinvestigated. (Fasching, Walters and Coryell)

Several reactions, including ^{153}Eu, (n,γ) ^{154m}Eu, have been used to produce the 47-min ^{154m}Eu. The low energy γ-ray spectrum confirmed four peaks previously reported by S. Orcher (23), and showed three additional ones. The 68 keV γ ray is reported (24) to have a 4 μsec lifetime, which makes difficult good coincidence measurements, and hence construction of a satisfactory decay scheme. (Zoller and Walters)

Ge(Li) detectors were used to examine two weak γ rays previously reported for the de-excitation of ^{55}Mn but measured with NaI scintillators (25). The weak β^- feeding was measured by three methods, which agreed within 15%, and indicated that the values, 0.037% and 0.0033% for the 1528 and 2252 keV levels respectively, are about seven times larger than previously reported. (Zoller, Botteron and Walters)

Similar detectors and methods were used for identifying a weak β^- transition to a 803.3 keV level in the decay of ^{206}Tl to ^{206}Pb. The intensity is 0.0055%, and the lot ft is 8.4. An upper limit of $\leq 0.001\%$ was set for the β^- feeding of the 1170 keV level. (Zoller, Botteron and Walters)

4.2 Nuclear Fission Studies

The mass yields from fission of ^{229}Th and ^{233}U with thermal neutrons are being studied by observing gross fission product γ-ray spectra with the Ge(Li) detectors. A 1-cm^3 detector has been

utilized to identify nuclides emitting γ rays in the 90-1000 keV region, based on the energies, intensities and half lives of prominent peaks. An 18-cm^3 detector is now being used to analyze the spectra up to about 3 meV, and a great improvement in the accuracy of the yields should be realized. The results obtained to date have been compared with the values obtained by Borisova et al (26), Ravindran et al (27), and Harvey et al (28). The first two were radiochemical studies and the third a mass-spectrometric study, no two of which are in good agreement with each other. Objectives of the present work are to connect various groups of relative yields into a complete yield mass curve, to supply missing yield data, to clarify disagreements between previous studies, and to compile accurate γ-ray energies and intensities for all the observable species. In the course of the above experiments, data has been taken also for ^{233}U fission, but the yields for that system have not yet been computed. (Kay, Gordon and Harvey)

As a side project to the work on decay of ^{133}Te isomers referred to in the previous subsection, the branching fraction of the decay of fission-product ^{133}Sb to isomers of ^{133}Te was determined. The 2.7 min ^{133}Sb decays to 55-min ^{133m}Te 42 $\pm$ 6% of the time and to 12.5-min ^{133g}Te 58 $\pm$ 6% of the time. The cumulative yield of ^{133}Sb in thermal-neutron fission of ^{235}U was measured as 1.7 $\pm$ 0.4%. An upper limit of 0.29% was determined for the yield of an 11-sec ^{134}Sb in the same type of fission. (Parsa, Wenzel and Walters)

A study of the yields and decay schemes of the Zn fission products is in progress. Work to date has been mainly on the decay schemes of the ^{71}Zn isomers, made by neutron irradiation of Zn enriched in ^{70}Zn, and ^{72}Zn made by bombardment of ^{238}U with 15-MeV deuterons in the M.I.T. cyclotron. Several γ-ray singles and γ-γ coincidence experiments have been performed on both 4-h ^{71m}Zn and 2.1-min ^{71}Zn. The energies and intensities of the γ-rays are rather well established, but more coincidence work, particularly β-γ, is needed before the decay schemes can be constructed. (Zoller and Gordon)

Studies have been made of the independent fission yields of La, Ce, and Pr isotopes following timed extractions by Hexone of fission cerium from short neutron irradiations of ^{235}U. More recently a new solvent extraction system using hydrogen di(2-ethyl-hexyl) phosphoric acid (HDEP) in n-heptane has been devised for fast extraction of carrier-free Ce(IV) from all fission products. With this method the fractional independent chain yield of ^{143}Ce was calculated to be 1.3×10^{-3} and that for 14-min ^{143}La was 0.12. The experiments are being repeated in an effort to reduce the statistical error. An upper limit of 0.03 has been obtained for 284-d ^{144}Ce, and experiments continue in an effort to determine a value for 3-min ^{145}Ce. (Fasching and Coryell)

Timed extraction of fission Ce from young fission products can be used to determine the half-lives of the La precursors. Preliminary analysis shows the half-life of ^{144}La to be 45 ± 10 sec., in agreement with a value of 41 ± 3 sec. reported by Amarel et al. [29] The studies, subject to further improvement, indicate a half-life of 46 sec. for ^{145}La and 15 ± 10 sec for ^{146}La. (Fasching and Coryell)

Average ranges in Al of shielded nuclides ^{86}Rb and ^{136}Cs and several chain-yield species from thermal-neutron fission of ^{233}U and ^{235}U have been measured. In agreement with previous work, the shielded nuclides are found to have smaller average kinetic energies ($\overline{E}_s$) than neighboring chain-yield species. The deficits of $\overline{E}_s$ are, for ^{233}U, 4 and 8 meV, and for ^{235}U, 8 and 10 meV, respectively, for ^{86}Rb and ^{136}Cs. Most of the range experiments were done with the thick-catcher method followed by conventional radiochemical treatment of the catcher foils. Ranges of 20 products from ^{233}U were determined in preliminary experiments in which γ-ray spectra of fission products in the catcher foils were observed with a Ge(Li) detector. The kinetic energy deficits of the shielded species are interpreted by Monte Carlo calculations of prompt-neutron emission. Two reasons previously advanced to explain the smaller $\overline{E}_s$ of the

shielded species plus one new reason are discussed in a paper prepared for submission to Canadian Journal of Physics. (Nakahara, Harvey and Gordon)

4.3 Physico-Chemical Studies

The distribution of chloride, perrhenate, and $AgCl_2^-$ ions between a eutectic molten salt mixture of $LiNO_3$-KNO_3 and a solution of tetraheptylammonium nitrate in a polyphenyl solvent was studied at 150°. ^{186}Re and ^{38}Cl, made in the MITR, and ^{110m}Ag obtained elsewhere were used as radioactive tracers to determine the distribution coefficients. The distribution of the anions has been interpreted in terms of a simple anion-exchange equilibrium followed by polymerization of some species in the organic phase. The equilibrium constants for the anion exchange and the dimerization constants were calculated, and the dependence of the perrhenate distribution on the temperature was determined. The stability constants of AgCl and $AgCl_2^-$ species in the nitrate melt were derived from the distribution data. The activity coefficients of the solute and nitrate salts follow, up to a solute mole fraction of 0.1, an expression derived from a simple model of molten salt mixtures. (Gal, Mendez and Irvine)

In addition to tetraheptylammonium nitrate, tetraoctylphosphonium nitrate and triphenyltin nitrate have been prepared and examined in the (Li, Na)NO_3-polyphenyl system with ReO_4^-. Extraction with the phosphonium salt is comparable to the ammonium salt and the former has greater thermal stability. The extraction with triphenyltin nitrate is much smaller than with the quaternary salts. Alpha-nitronaphthalene shows substantially higher extraction with the tin compound than does the polyphenyl mixture and this has been found to hold also for the quaternary salts. Synthetic methods have been perfected for the tetraoctylphosphonium nitrate and the triphenyltin nitrate. More recently the distribution of chloride, $AgCl_2^-$ ions and silver (I)-nitrate complexes have been studied. The distribution of the chloride with the phosphonium salt is comparable with that for the ammonium salt, while the distributions of $AgCl_2^-$ and

silver (I)-nitrate complexes are greater. Equilibrium and dimerization constants were calculated; dependence on temperature and solute concentration was studied. (Elhanan, Tan and Irvine)

An attempt has been made to observe a variation in the half life with change in chemical environment for the 3.7-keV isomeric transition in ~15-min ^{142m}Pr as described by J. Kern, G. Maron, and B. Michaud[30]. Samples of ^{141}Pr oxide and metal were simultaneously irradiated with neutrons and growth-decay curves for ^{142}Nd were obtained for each sample. Preliminary analysis indicates the same half life of 11 min for ^{142m}Pr in both oxide and metal samples. More detailed analyses will be made to determine if a statistically significant chemical effect on the half life of ^{142m}Pr has been observed. (Fasching,and Brenner, Sugihara and P. McNamee of Clark University)

More recently two papers [31] [32] report that the half life of 8.05-d ^{131}I in NaI crystals is not the same as in NaI solutions. Initial measurements to check these remarkable results show no variation with either physical or chemical state. (Zoller, Macias, Fasching, and Walters)

Angular correlations between K and L x rays in Tl have been measured, the x-ray cascade being initiated by the deexcitation via internal conversion of the ^{203}Tl level at 279 keV populated in the β decay of ^{203}Hg. The results agree generally with the theoretical predictions for these specific cases assuming unperturbed angular correlations. (Catz and Coryell)

4.4. Activation Analysis and Earth Science

In cooperation with the University of California, San Diego, methods have been developed for instrumental neutron activation analysis of standard rocks. Following neutron irradiation of the samples, γ-ray spectra are taken at several times with Ge(Li) detectors, and the observed γ rays are assigned to particular nuclides on the bases of half lives, γ-ray energies, and relative intensities. With this method, which involves no chemical

separations, it was possible to measure the abundances of over 20 elements, many of them in the 1 ppm range, in a wide spectrum of standard rocks. (Gordon and G. G. Goles of University of California)

In an extension of these studies at M.I.T. and in conjunction with the Department of Geology and Geophysics, similar methods have been applied to shorter-lived species than could be used in the initial work. Concentrations of Al, V, Mg, Ca and Ti, all with half lives of 10 min or less, can be determined in a wide range of rock types. (Dran, Gijbels, Anderson, Baedecker, Gordon and Frey)

The low energy spectra (<200 keV) of irradiated rocks have been studied by means of a Ge(Li) low-energy photon spectrometer (Ge-LEPS) on loan from Ortec, Inc. Such measurements are potentially very important for Instrumental Neutron Activation Analysis (INAA) because of the comparatively high resolution obtainable. Initial tests indicate that the elements Dy, Gd and Tm can probably only be determined with a Ge-LEPS, and the accuracy of determinations of Nd, Sm, Yb and Lu should be considerably improved with this equipment. Further work is needed on the elimination of errors due to self absorption, sample size and sample position. (Dran, Gijbels, and Gordon)

Sources of error in INAA, such as the following, are being investigated for the purpose of improving the accuracy of measurements.

a) Particularly for very small detectors means are being developed for preparing monitors having the same effective geometry as the samples.

b) The reasons for inaccuracies found in analyzer corrections for dead time, under conditions of very high count rates, are being investigated.

c) Secondary geometry effects, caused by purposely changing the sample and monitor positions to achieve convenient count rates, are being studied.

d) Coincidence summing effects where a $\gamma_1 + \gamma_2$ cascade is erroneously counted as a γ_3 photon when γ_1 and γ_2 are both detected and their total energy equals γ_3. (Gijbels, Dran, Erten, Zoller, Fasching and Gordon)

Thermal neutron activation analysis is being used to study trace metal concentrations of air masses in an ocean environment. Atmospheric particulate material was collected in Hawaii and on ships running from there to Alaska and to San Diego. Cu concentrations decrease about eight-fold going 600-1200 Km west from San Diego, and the results suggest that the Cu comes from West Coast pollution. Results for V and Al suggest that these elements derive largely from erosion of continental rocks. (Zoller, and Hoffman and Duce of the University of Hawaii)

In a study undertaken in conjunction with the Department of Geology and Geophysics, INAA using Ge(Li) detectors has been utilized to determine elemental abundances in some microtektites. The preliminary data agree quite closely with data for tektites found on the Australian continent. Additional work is being done on other types of microtekties which appear to be different from those initially analyzed. (Frey and Baedecker)

The Nuclear Chemistry Group has also had considerable interest in the composition of Mn nodules, particularly their rare-earth concentration patterns. In preliminary tests about 12 trace elements have been assayed, and this number can probably be increased to about 20. A comparison has been made with crustal average concentrations, and relatively high amounts of Th and Sb (in addition to the well-known high Ce enrichment) have been measured. (Dran and Gordon)

In another joint study with the Department of Geology and Geophysics, which is described below in subsection 5, additional experiments directed toward determining the abundances of rare earths in manganese nodules have been performed.

We have been able to improve our ability to detect and correlate radiations emitted in radioactive decay in four principle areas.

These improvements concern the procurement of large Ge(Li) detectors, the purchase of a low energy photon spectrometer (LEPS) and also the loan of a second such instrument, the purchase of a new 4096-channel analyzer and an analog-to-digital converter (ADC), and the purchase and operation of a time-to-amplitude (TAC) converter system. These are described further in the following paragraphs.

The first Ge(Li) detector with an active volume of about $30cm^3$ was prepared by drifting Li ions into a low-resistivity block of Ge. The FWHM for 662-kev γ rays from ^{137}Cs decay was about 7.0 keV. Additional detectors with active volumes of $26cm^3$ and $19cm^3$, 2.9 keV and 2.6 keV FWHM, were purchased. The latter detector will become part of a compton-suppressed γ-ray spectrometer. Preparation and use of these detectors has been accomplished with the assistance of personnel and equipment from the Department of Nuclear Engineering.

The low-energy photon spectrometer (LEPS) was purchased from the Technical Measurement Corporation and was guaranteed to give a full-width at half maximum of ≤ 600 eV for 12-keV γ rays. The system consists of a 30 mm^2 x 3 mm deep Si (Li) detector and a field-effect transistor (FET) and preamplifier in which the detector and FET are cooled by liquid N_2. The second LEPS has a small Ge(Li) detector and is on loan from Ortec, Inc.

We have also expanded our capacity to handle data by purchasing a second 4096-channel computer-memory, two 4096-channel analog-to-digital converters (ADC's), and a small magnetic tape temporary storage unit (with funds supplied by the MIT Chemistry Department) from the Packard Instrument Company. We are now capable of carrying out as many as three simultaneous experiments at which time the buffer system can be utilized to record coincidences between two detectors, and the two memories and 4096-channel ADC's may be used to record singles spectra from two other detectors.

The electronic modules required to determine the time difference between two pulses were delivered to us by EGG and Co. early this year; they have been used both in the study of nuclear lifetimes and in the study of positron lifetimes. The system works by

generating an output pulse whose height is proportional to the time difference between two input pulses. Most experiments are done by recording the output pulse heights in a multichannel anaylzer memory. It is also possible to use our buffer tape system to store both the time difference between two pulses as well as the pulse height of one of the two pulses. Such an experiment as β-γ coincidences in which both the γ-ray energy and time difference between the β-ray emission and the γ-ray emission permits the determination of several nuclear lifetimes in a single experiment.

The counting room has been enlarged in order to permit the flexible use of the multiparameter analyzer system in various experimental arrangements. (Walters)

Personnel

Professors:	C. D. Coryell G. E. Cordon J. W. Irvine, Jr. W. B. Walters
Guest:	R. Duce (University of Hawaii) G. Hoffman (University of Hawaii)
Research Associates:	P. A. Baedecker A. L. Catz J. C. Dran J. Elhanan I. H. Gal J. W. Harvey R. Gijbels M. Liquornik J. Mendez J. P. Op de Beeck
Students:	C. F. Anderson K. E. Apt C. Botteron A. M. Ehrlich H. M. Erten J. L. Fasching D. H. Hnatowich M. A. Kay E. S. Macias B. Parsa

R. C. Ragaini
C. H. Tan
A. Wenzel
W. H. Zoller

Support

USAEC, M.I.T. General Funds

Related Academic Subjects

5.09 Radiochemistry
5.091 Radiochemistry Laboratory
5.092 Special Topics in Nuclear Chemistry

5. DEPARTMENT OF GEOLOGY AND GEOPHYSICS

Well over 1,000 irradiations have been made by this department which has utilized the reactor since it first went to power. Both independently and in cooperation with the Nuclear Chemistry Group of the Chemistry Department, activation analysis techniques have been used to study variations in isotopic abundances in nature, concentrations of halogens in the atmosphere and in sea water, and the concentrations of rare earth elements in various geological environments.

5.1 Instrumentation

Existing instrumentation has been augmented through availability to the Department of the improved detecting and analyzing equipment described earlier in Nuclear Chemistry subsection 4.5. It is now possible by instrumental methods, without chemical separation, to measure the abundances of over 20 elements, many in the 1 ppm range. Following neutron irradiation, γ-ray spectra are taken at several times with Ge(Li) detectors, and the observed γ rays are assigned to particular nuclides on the basis of half lives, γ rays energies, and their relative intensities.

Work to date with the new equipment has been mainly preparatory, such as making up and checking the purity of monitor solutions and investigating flux variations within the sample container. Preliminary checks have been made on very short-lived products activated in a sample of standard rock. With improvement of the techniques,

it is expected that additional short-lived nuclides will be identified. The high-resolution Si(Li) detector will be used to look for low energy γ and/or x-rays soon after irradiation. The use of Ge(Li) - NaI(Tl) coincidence counting may prove helpful.

For analyzing the γ spectra and identifying the peaks, a computer program, written by P. A. Baedecker of the Nuclear Chemistry Group, searches out the photopeaks, calculates their areas, centroids and energies. A correction is made for detector efficiency.

5.2 Elemental Abundances

Sediments:

A procedure has been developed for the determination of iodine, bromine, and chlorine in sediments and sedimentary rocks using thermal neutron activation analysis. Employing a combination of pre-irradiation sample preparation and post-irradiation chemistry, four degrees of binding of chlorine, bromine, and iodine in sediments have been defined. The results show a gradual change in the degree of binding of the halogens in sediments, which occurs in going from the interstitial water to the grain interior. Investigation of the geochemistry of the halogens in sediments and sedimentary rocks shows the following: (1) The analyses of all samples studied show that the Br/Cl ratio in the water soluble fraction has not changed significantly since Pennsylvanian time. (2) In all samples analyzed, the I/Br ratio in the surface bound fraction was of the order of unity. (3) The surface bound and internally bound halogen concentration of sedimentary rocks from the Cherokee Group and the Carbondale formation all increase going from non-marine to marine environments. Phosphate content was found to be important for estimating the marine versus non-marine character of the sediments within a cyclothem. (4) Studies on recent sediments show that the geochemistry of iodine and to a slight extent the geochemistry of bromine are different from that of chlorine in sediments. (5) The data suggest that the following cycle is followed by iodine and bromine in the first few meters of recent clay sediments: a) Iodine and bromine are incorporated into the

sediments as organic iodides and bromides upon the death and burial of marine organisms. b) As these organisms decompose, iodide and bromide are released to the interstitial water. c) The interstitial iodide and bromide are returned to the sea as the sediment undergoes compaction.

Manganese Modules:

Concentrations of the rare earths have been determined in ten modern manganese nodules from the major oceans and from other locations. The analyses were carried out by pre-irradiation group separation, neutron activation, and post-irradiation partition chromatography. Most of the samples had rare earth distribution patterns typical of marine sediments. Factors effecting the concentrations of the rare earths in general and of cerium and lanthanum in particular were noted, and a model for incorporation of the rare earths into nodules has been proposed.

Metamorphic Rocks:

To aid in an understanding of the crustal evolution of the earth, the abundance pattern of rare earth elements in lower crustal materials has been studied by instrumental neutron activation analysis. Charnockite specimens from India (Madras State) were analyzed in this manner. The results are presented in Report No. MIT-1381-16 (listed in Appendix E of this report), along with information on the flux monitor solutions used.

Ultrabasic Rocks:

Previous work in rare earth element abundances and distributions in ultrabasic rocks has indicated that a wide variety of rare earth distributions occur in ultrabasic rocks. Two ultrabasic areas (St. Paul's Rocks and Lizard, Cornwall) were chosen for further rare earth element study. Mineralogy and major element compositions are known for the samples studied. The variety of ultrabasic rocks that form St. Paul's Rocks exhibit a wide range of rare earth absolute abundances and distributions. All rocks investigated are

enriched in the light lanthanides when normalized to the distribution of chondritic meteorites. The rare earths in the brown-hornblende mylonites are very similar in abundance and distribution to the rare earths in alkali-olivine basalt dredged from the ocean floor in this area. The peridotite rocks and minerals of the high-temperature peridotite intrusion at Lizard, Cornwall, have been analyzed for rare earths. All the peridotite rocks in this intrusion are depleted in light rare earths when normalized to the chondritic distribution. In several of the samples distribution coefficients have been determined for the coexisting mafic minerals (orthopyroxene, clinopyroxene, olivine and spinel).

Basic Rocks:

Samples of basic rock previously analyzed have been reanalyzed using improved techniques. New basic rock samples, composites of chondrites, and composites of shales have also been subjected to the improved methods. The results of this work are contained in a paper submitted to the Journal of Geophysical Research, an abstract of which follows: Rare-earth (RE) abundances are reported for several basalts, diabases, and gabbros. Compared with the RE distribution in chondritic meteorites, continental basic rocks are characterized by an enrichment of the light lanthanides. Intrusive basic rocks have lower RE contents and less fractionated RE distributions than continental basalts. Chill zones of the Stillwater and Bushveld complexes have different distributions which are Eu enriched and light RE depleted. Oceanic island basalts have RE abundances similar to those of continental basalts. Abyssal sub-alkaline basalts dredged from the mid-Atlantic ridge and Eastern Pacific rise have RE distributions which are nearly chondritic. There is a depletion in La, Ce, Pr, and a broad maximum from Sm to Tb. Similar patterns are found in fresh basalts, slightly altered basalts, and in greenstones. Abyssal basalts that are more alkalic are not depleted in La, Ce, and Pr. The relationship of the RE data to hypotheses for the origin of ridge basalts is considered.

Personnel

Professor:	F. A. Frey
Students:	R. Copeland
	C. M. Spooner
	L. J. Walters
	R. Zielinski

Support

M.I.T. General Funds

Related Academic Subjects

12.511T Geochemistry
12.921 Chemical Oceanography I
12.922 Chemical Oceanography II

IX. M.I.T. EDUCATIONAL ACTIVITIES USING THE REACTOR

The primary objectives of the activities described in this section are the conduct, enhancement and promotion of education and training in nuclear science, nuclear engineering, and related fields. In the research programs described in the preceding section, research results were the primary objective, but educational benefits constituted a condition precedent in all cases. In many circumstances, however, the reactor is utilized primarily for educational activities which may, but usually do not, have research benefits as a byproduct.

Within this definition of educational use, the reactor is employed for many activities initiated by several of the departments at MIT, by groups at other educational institutions, by professional societies, and by many other organizations. Not only are educational benefits derived as a result of its use in formal courses of instruction, but they also result from the fact that the reactor is readily accessible for tours by interested individuals and groups; and on periodic "open house" days, the general public is encouraged to visit. Such activities, which are related primarily to MIT educational programs, are summarized in this section. Where other organizations or the general public are involved, the activities are described in Section X.

The MIT Reactor, as mentioned in an earlier section, comes naturally under the jurisdiction of the Department of Nuclear Engineering. A curriculum of 28 subjects was offered by the Department in 1967-68 covering a wide range of science and technology in the fields of both fission and applied plasma physics. There were 136 students, all candidates for advances degrees, since the Department provides only graduate-level curricula. In addition, registration in Nuclear Engineering courses by students from other departments, and vice versa, is encouraged. As was mentioned in Section VIII, 35% of the thesis research performed by Nuclear Engineering students involves the use of, or is based on, the MIT Reactor.

Many of the academic courses related to fission technology benefit from the example of a research reactor on the campus. In Nuclear Engineering, two of these courses made important use of the MIT Reactor during the school year 1967-68. The subject numbers, titles, and catalog descriptions are as follows:

Subject 22.41 Nuclear Reactor Physics Laboratory

Properties of the particles and radiations resulting from the fission process. Use of scintillation counters, ionization chambers, proportional counters, Geiger counters, Ge (Li) detectors, health physics instruments, and other detection devices employed in reactor technology. Experimental methods for determining the macroscopic properties of nuclear reactors, including cross-section measurements, cadmium ratios, diffusion lengths, albedos, Fermi age, and neutron multiplication of the subcritical assembly. Radioactive chemical separation methods.

Subject 22.42 Nuclear Reactor Operations

Techniques of nuclear reactor operation, initial fuel loading, criticality considerations, startup reactivity effect measurements, measurements at power. Operating experience at power reactor facilities including hazards evaluation and accident experience. Group and individual participation in startup and operations at the MIT Nuclear Reactor, investigation of MIT Reactor operational problems.

The Departments of Chemistry and Physics each offer a course which uses the MIT Reactor. The former makes radioisotopes for its Radiochemistry Laboratory. The latter makes available one or more of the neutron diffraction spectrometers on the reactor for the performance of five or six experiments by each of the students enrolled.

Chemistry, Electrical Engineering, and Metallurgy students, as well as Physics students, register for this laboratory. In both of these cases also, the laboratories are taught primarily for graduate students:

Subject 5.091 Radiochemistry Laboratory

Laboratory study of special topics including radiochemical analysis, the fission process, and the reactions following nucleogenesis.

Subject 8.37 Neutron Diffraction

Neutron properties, sources, and apparatus. Absorption and scattering of neutrons by isolated atoms. Transmission through and scattering by assemblages of atoms. Diffraction by single crystal and polycrystalline specimens. Crystallographic and magnetic structure analyses. Long wavelength methods and applications. Refractive index characteristics. Neutron polarization. Inelastic scattering. Laboratory experiments offered.

Table IX-1 provides statistics on enrollment for the above laboratories.

TABLE IX-1

ENROLLMENT IN COURSES USING THE M.I.T. REACTOR

Subject	Term	10 Years 1957-67	Academic Year 1967-68	11 Years Total
22.41	Fall	159	7	328
	Spring	150	12	
22.42	Fall	67	-	193
	Spring	114	12	
8.37	Alternate Years	66	(not offered in 1967-68)	66
5.091	Fall only	74	6	80
Totals		630	37	667

The MIT Reactor plays an important part in other types of training programs conducted both by MIT and by outside organizations. MIT freshmen and sophomores may register for undergraduate seminars conducted by those departments which offer undergraduate curricula. These furnish an opportunity for study with a high degree of flexibility and individual responsibility, and they have included the MIT Reactor as part of the seminar schedule in seven terms beginning in 1961.

In addition to the formal courses of instruction, it has been possible at the reactor to provide a substantial number of MIT students with part-time or full-time employment which, at the same time, gives them invaluable, practical experience in reactor operation and utilization. Six present or former students are currently part of the reactor staff, listed in Table V-1. Four of these--Gosnell, Gwinn, Papay and Torri--were formerly full-time MIT students who are now performing full-time supervisory duties in operations or electronics while pursuing Doctor's degrees on a part-time basis. A fifth, Clark, has received his Master's degree, and the sixth, Frech, will earn his shortly.

In the past, also, a significant number of students, mostly part-time but some full-time, have held responsible jobs on the reactor staff or in related research projects while studying for advanced degrees. These and a number of faculty (MIT and other universities), guests and others (totaling more than 50) who were closely associated with MITR activities but have since departed MIT are listed in Table IX-2. This table illustrates the various capacities in which people, other than regular, full-time students, can gain experience in reactor operation or research, and it shows the wide spectrum of activities and geographic locations to which they carry their acquired knowledge. No attempt is made in this report to document in a similar manner the positions in industry, education and government which have been taken by regular, full-time students (about 130 from the Department of Nuclear Engineering alone) whose association with the MITR has been the conduct of reactor-related research for the thesis credit.

TABLE IX-2

FORMER STUDENTS, FACULTY, GUESTS AND OTHERS WHO WORKED AT MITR

Name	Status at MIT	MITR Activity	Subsequent Organization
C. A. Anderson	Part-time Student	Reactor Operator	Sandia Engineering Reactor Facility, Sandia Base, New Mexico; Chief, Reactor Physics, Advanced Reactors, Westinghouse Electric Corp.
W. N. Bley	Part-time Student	Research and Administration, Organic Coolant Project	Stone and Webster Boston, Massachusetts
S. Brewer	Part-time Student	Research Staff, Organic Coolant Project	Stone and Webster Boston, Massachusetts
T. Cantwell	Part-time Student	Business Manager	Geoscience, Inc. Cambridge, Massachusetts
W. R. Devoto	Part-time Student	Reactor Shift Supervisor	McKinsey and Company Washington, D. C.
L. R. Enstice	Part-time Student	Reactor Operations Superintendent	Texas A and M Maritime Institute, Galveston, Texas
W. D. Hinkle	Part-time Student	Reactor Shift Supervisor	Yankee Atomic Electric Co. Boston, Massachusetts
A. H. Kazi	Student, part-time and full-time	Reactor Operator and Research in Gamma Spectroscopy	Army Pulse Radiation Facility Aberdeen Proving Ground, Maryland
C. Porter	Part-time Student	Research in Medical Neutron Therapy	Nuclear Engineering Department, Oregon State University, Corvallis, Oregon

TABLE IX-2 Continued

Name	Status at MIT	MITR Activity	Subsequent Organization
A. E. Profio	Part-time Student	Reactor Shift Supervisor and Principal Investigator on Reactor Lattic Project	Gulf General Atomic San Diego, California
D. Schwartz	Part-time Student	Reactor Shift Supervisor	Jackson and Moreland Boston, Massachusetts
R. Stanfield	Part-time Student	Electronics Supervisor	Esso Mathematics and Systems, Inc., Florham Park, N. Y.
A. W. Swan	Part-time Student	Research, Organic Coolant Project	Combustion Engineering Windsor, Connecticut
S. Wilensky	Part-time Student	Reactor Operations Assistant	Massachusetts General Hospital, Boston, Massachusetts
G. L. Woodruff	Part-time Student	Reactor Shift Supervisor	Nuclear Engineering Department, University of Washington, Seattle, Washington
J. R. Bauman	Student	Part-time Operator	U. S. Navy
W. L. Brassert	Student	Part-time Operator	Northern Research and Engineering Corp., Cambridge, Mass.
H. Christensen	Student	Reactor Start-up and Part-time Operator	Institutt for Atomenergi, Kjeller Research Establishment, Kjeller, Norway
C. L. Larson	Student	Reactor Start-up and Part-time Operator	General Electric, APO Sunnyvale, California
J. Lewins	Student	Reactor Start-up and Part-time Operator	British Army

TABLE IX-2 Continued

Name	Status at MIT	MITR Activity	Subsequent Organization
J. T. Madell	Student	Reactor Start-up and Part-time Operator	Argonne National Laboratory Argonne, Illinois
R. L. Mathews	Student	Reactor Start-up and Part-time Operator	Knolls Atomic Power Laboratory, General Electric Co. Schenectady, New York
S. A. Mayman	Student	Reactor Operations Assistant	Atomic Energy of Canada Manitoba, Canada
N. B. McLeod	Student	Reactor Start-up and Part-time Operator	Nuclear Utility Services Washington D. C.
L. I. Moss	Student	Reactor Start-up and Part-time Operator	Atomics International Canoga Park, California
P. F. Palmedo	Student and Instructor Nuclear Engineering MIT	Reactor Operator and Research on Reactor Lattice Project	Brookhaven National Laboratory, Upton, New York
D. D. Lanning	Part-time Student and Faculty, Nuclear Engineering, MIT	Assistant Director for Reactor Operations	Battelle Northwest, Applied Reactor Physics Section, Richland, Washington
H. Mark	Faculty, Physics, MIT	Principal Investigator Gamma Spectrometry	Nuclear Engineering Department, University of California, Berkeley, California; Director, Ames Research Center, NASA
D. T. Morgan	Student, Later Faculty, Nuclear Engineering MIT	Research, Organic Coolant Project	Avco Corporation Wilmington, Massachusetts; Thermo Electron Corp., Waltham, Massachusetts
J. W. Winchester	Faculty, Geology and Geophysics, MIT	Principal Investigator, Neutron Activation Analysis	Department of Oceanography and Meteorology, University of Michigan, Ann Arbor, Michigan

TABLE IX-2 Continued

Name	Status at MIT	MITR Activity	Subsequent Organization
A. Bracci	Guest	Reactor Start-up	Comitato Nazionale Per L'Energia Nucleare, Rome, Italy
R. A. Duce	Student, Later Guest, Chemistry, MIT	Neutron Activation Analysis of Geologic Samples	University of Hawaii, Honolulu, Hawaii
G. Franco	Guest	Reactor Construction	Comitato Nazionale Per L'Energia Nucleare, Rome, Italy
T. Hyodo	Guest, Nuclear Engineering, MIT	Spectroscopy of Prompt Gamma Rays	Nuclear Engineering Department, Kyoto University Kyoto, Japan
T. Inouye	Guest, Nuclear Engineering, MIT	Spectroscopy of Prompt Gamma Rays	Tokyo Shibaura Electric Co. Kamasaki, Japan
L. Leifer	Research Staff and Guest	Principal Investigator, X-rays in Fission	Boston College Chestnut Hill, Massachusetts
P. J. Lloyd	Guest, Nuclear Engineering, MIT	Research in Solvent Extraction of Uranium and Fission Products	Government Metallurgical Laboratories, Johannesburg, South Africa
R. M. Stanton	Guest	Reactor Operator Trainee	Army Materials Research Agency Reactor, Watertown Massachusetts; Lowell Technological Institute Reactor, Lowell, Massachusetts
A. Sutter	Student-Guest	Reactor Construction and Start-up	Institutt for Atomenergi Kjeller Research Establishment, Kjeller, Norway

TABLE IX-2 Continued

Name	Status at MIT	MITR Activity	Subsequent Organization
A. M. Arena	Reactor Staff	Business Manager	Addison C. Getchell + Son Boston, Massachusetts
J. Cornwell	Reactor Staff	Mechanical Design and Drafting	American Science and Engineering, Inc. Cambridge, Massachusetts
W. M. Trenholme	Reactor Staff	Electronics Supervisor	Arizona Atomic Energy Commission, Phoenix, Arizona
J. W. Harvey	Radiation Protection Office Staff	Radiation Protection Duties for MIT and Reactor	Health Physics Department McMaster University Hamilton Ontario, Canada
C. J. Maletskos	Radiation Protection Office Staff	Radiation Protection Officer for Reactor	New England Deaconess Hospital and Harvard Medical School, Boston, Massachusetts
T. Carroll	Research Staff	Research, Organic Coolant Project	Sloan School of Management MIT
A. Christensen	Research Staff	Research on Irradiation of Hydrocarbons	Department of Chemistry University of Aarhus Aarhus, Denmark
R. B. Ciszewski	Research Staff	Research, Neutron Spectroscopy Project	Instytut Fizyki Politechniki Warsaw, Poland
G. Mazzone	Research Staff	Research, Neutron Spectroscopy Project	Comitato Nazionale Per L'Energia Nucleare Rome, Italy

TABLE IX-2 Continued

Name	Status at MIT	MITR Activity	Subsequent Organization
I. Rahman	Student and Research Staff	Research in Gamma Spectroscopy	Pakistan Institute of Nuclear Science and Engineering, Rawalpindi, West Pakistan
R. Sanders	Research Staff	Research	Edgerton, Germeshausen and Grier, Inc., Santa Barbara, California
J. W. Steiner	Research Staff	Research, Organic Coolant Project	B. B. Chemical Co. Cambridge, Massachusetts
T. J. Swierzawski	Research Staff	Research, Organic Coolant Project	Nuclear Engineering Department, University of Gliwice, Gliwice, Poland
F. A. Wedgewood	Research Staff	Research, Neutron Spectroscopy Project	U. K. Atomic Energy Research Establishment Harwell, England
S. Kojima	Guest	Reactor electronics	Tokyo Shibaura Electric Co. Tokyo, Japan

X. RESEARCH AND EDUCATIONAL UTILIZATION OF THE M.I.T. REACTOR BY OTHERS

As was mentioned in Section III, "Objectives of the MIT Research Reactor," the University recognizes an obligation to help meet the requirements of other educational institutions, of hospitals, and of industry, particularly in the local area. MIT's policy in this regard was stated therein. This Section X provides, insofar as is feasible, information concerning the utilization of the reactor by groups from outside MIT, both for research and for educational purposes.

1. RESEARCH UTILIZATION

Research utilization has consisted almost entirely of irradiations for the purpose of producing radioactivity or other radiation effects in the exposed materials. Included in this category are not only those irratiations which provide radioactive tracers, radiation damage specimens, radioisotope sources, etc., for use in research investigations but also a few which are for diagnostic, therapeutic or other routine activities which are no longer considered to be of a research nature.

In order to provide an indication of the extent of such non-MIT use of the reactor, statistics have been accumulated on the number of organizations which have utilized materials irradiated in the MITR and on the number and nature of the irradiations. These are given below in Table X-1 and in the appendices. These figures, of course, do not include the irradiations performed for the research projects described in Section VIII, which generally have been three to four times as numerous as those tabulated in this section for groups outside MIT. The total number of irradiations performed during various periods of reactor operation was given in Table VI-1.

Table X-1 and comparison with last year's report show that the number of samples irradiated for outside users during fiscal year 1968 was up substantially from the average of the previous nine years and from the level of fiscal 1967. The first two categories made many more irradiations than a year ago, while industrial firms requested about the same number.

TABLE X-1

Type of Organization	Nine Fiscal Years 1959-67 Organizations	Nine Fiscal Years 1959-67 Irradiations	Fiscal Year 1968 Organizations	Fiscal Year 1968 Irradiations
Universities and Research Centers	23	506	11	247
Hospitals	3	1,442	2	1,046
Industrial Firms	30	1,668	6	100
	56	3,616	19	1,393

The 11 universities and research centers which have had occasion to use the MIT Reactor in connection with their own research projects during fiscal 1968, and materials irradiated, are listed in Appendix G. Nine of these were among the 23 former users, and there were two new ones. Their utilization of the MIT Reactor is a natural consequence of the fact that reactor facilities at New England colleges are somewhat limited, the only others in the area being at the University of Rhode Island and at Worcester Polytechnic Institute, which operate 1-MW and 10-KW facilities, respectively. The U.S. Army Materials and Mechanics Research Center operates a 2-MW light-water reactor at Watertown, Massachusetts.

None of the universities has undertaken experimental projects at the MIT Reactor (although this is encouraged), the extent of their reactor use being limited to the irradiation of samples for the purposes mentioned above. Since arrangemants can be made to provide office and laboratory facilities in conjunction with a major reactor research program, it is believed that other factors are responsible for this situation. Distance may be the problem in many cases, but it is a negligible one for the several major universities in and around Cambridge. In our opinion, the difficulty of obtaining the substantial research funds required to pay the reactor facility rental charges MIT is obliged to make is the principal deterrent as far as researchers from off the MIT campus are concerned (just as it has frequently been a deterrent for some of the experimentalists at MIT). If Government funds can be made available to defray all costs of operating the reactor, we believe that much more extensive use would be made of the reactor for research by groups at other universities as well as at MIT. This undesirable condition has existed from the very beginning of MITR operation, and it is not related to the budget restrictions imposed on Government Agencies during fiscal years 1968 and 1969. However, these recent limitations have undoubtedly aggravated the situation.

In addition to educational institutions, other organizations making use of the MIT Reactor are the local hospitals and industrial companies. The former are enumerated, for fiscal 1968, in Appendix H and the latter in Appendix I. Massachusetts General Hospital has conducted a continuing research program in neutron capture for cancer therapy and in other areas. One of these, an intensive program in the biomedical applications of neutron activation analysis, is primarily responsible for the large increase in the number of irradiations performed annually for hospitals (Table X-1). Since MIT students are frequently involved in these studies, current MGH programs consequently are described in Sections VIII-1.8 and 1.9. Except for these few cases, MIT is not involved in the work of the other universities, hospitals and industrial companies except to perform the requested reactor irradiations. As a result, no description of the research is contained herein, although

Appendices G, H and I give some indication of the nature of current and past research by listing the materials irradiated in fiscal year 1968.

2. EDUCATIONAL UTILIZATION

The MIT Reactor plays an important part in various types of training, indoctrination, and general information programs sponsored both by MIT and by other organizations. These are not the academic courses conducted at MIT and described in Section IX but rather work-study programs, class visits, open houses, and so forth. They are not internal MIT affairs but, on the contrary, involve students from other educational institutions, scientists and others from professional societies, military reservists from many training units, and the general public from the New England area.

Work-study programs are an important example of such education utilization and they have proven mutually beneficial to MIT and to the participating students. Northeastern University's Cooperative students have been continuously employed on an alternating work-study basis in two different capacities at the MIT Reactor. The larger group, which worked initially on a deuterium separation investigation, has been utilized in recent years by the Organic Coolant Loop Project. Since 1962 when Co-operative students were first employed, eight students have averaged in excess of eleven months of full-time employment at the MIT Reactor while working toward their Bachelor's degrees. The Loop Project was supported as part of the AEC's program for development of organic reactors, but it terminated early in 1968 due to reorientation of the Commission's reactor development program. Since this was a major research unit and since the prospects of replacing it with a similar project, especially under today's conditions, are not favorable, the possibilities of implementing similar Co-operative programs at the MIT Reactor appear remote for the near future.

In the second program, two Northeastern Co-operative students are currently employed as reactor operators. T. J. Casey and J. L. Rupp, graduates of Wentworth's Nuclear Technology Program in

June 1963, worked full time as operators until late 1965. They enrolled together in the Co-operative Program, now alternate about every 13 weeks as operators, and are scheduled to earn their Bachelor of Science degrees in Electrical Engineering in June 1969. Their services as reactor operators will be badly missed when they embark on new carrers.

Educational institutions, professional societies, military reserve training units, and other organizations frequently request permission to bring groups of varying size to the reactor for guided tours. Statistics on the number of registered visitors to the MIT Reactor are summarized below in Table X-3 with details in Appendices J and K.

TABLE X-3

STATISTICS FOR TOURS AND VISITS
TO THE MIT REACTOR

Academic Year	Educational Groups		Professional, Military and Other Groups		Total Visitors
	Number	Invidivuals	Number	Individual	
9 years, 1958-67	127	2260	87	1709	22,800
1967-68	20	316	11	202	1,500
10 year Total	147	2576	98	1911	24,300

The table in last year's report, which showed a breakdown by years, revealed that there were more visits during the first few years of reactor operation, as might be expected, with a gradual decrease in recent years. The 1967-68 figures, however, not only reverse the trend but they also exceed the averages for the ten-year period.

MIT and the Reactor Staff have recognized the value of these tours and also the benefits accruing from the frequent visits by individuals working in or passing through the Cambridge area. Regular visiting hours have been established, and a graduate student is employed for the specific purpose of serving as a guide for such visitors.

To the 24,300 registered visitors shown in Table X-3 should be added an estimated 10,000 more who have visited the MIT Reactor on open-house occasions. The reactor always participates in the biennial MIT Open House. This was most recently held on April 22, 1967, when an estimated 1,500 people of all ages toured the reactor, viewed special displays in the laboratories and shops, and watched a moving picture film depicting the construction of the MIT Reactor during 1956-58. It is planned again for the spring of 1969. In addition to these biennial Institute-wide programs, the reactor was opened to the public on several occasions during the first four years of operation in order to promote good relations with the Cambridge community and hopefully to instill a degree of familiarity with the world of nuclear energy.

It is likely that these tours and open-house visits will assume increased significance as the rapid growth of the nuclear utility industry is brought to the attention of the general public through plant construction and through the expanding amount of publicity devoted to the subject.

APPENDICES XI.

APPENDIX A

DEPARTMENT OF NUCLEAR ENGINEERING PUBLICATIONS

THESES

1. Gagnon, R. L., "A Compton Rejection Gamma Ray Spectrometer," S. M. Thesis (September 1967).

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4. Wight, A., "Measurement of Lattice Parameters Using a Unit Cell Simulator," S. M. Thesis (September 1967).

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9. Donovan, R. E., "Determination of the Heterogeneous Parameters Γ, A and η by measurements on a single fuel element," S. M. Thesis (February 1968).

10. Frech, D. F., "Use of Lutetium Foil Activation for Determination of Effective Neutron Temperatures for Slightly Enriched Uranium Oxide Fuel Rods Moderated by Heavy Water," S. M. Thesis (February 1968).

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21. Berte, F., "An In-Pile Cryogenic Irradiation Facility for the MIT Reactor," Sc. D. Thesis (in progress).

22. Donohew, J. N., "Elastic and Inelastic Scattering In Fast Reactor Media," Sc. D. Thesis (in progress).

23. Forbes, I.,"A Quasi Exponential Method for the Simulation of Fast Reactor Blankets," Sc. D. Thesis (in progress).

24. Gosnell, James W., "Studies of Two-Region, Subcritical, Uranium Heavy Water Lattices," Ph. D. Thesis (in progress).

25. Harper, T., "Spectral Analysis and Yields From Thermal Neutron Capture Gamma Rays," Ph. D. Thesis (in progress).

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26. Heimberg, E. C., "Monte Carlo Studies," S. M. Thesis (in progress).

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APPENDIX C

DEPARTMENT OF METALLURGY PUBLICATIONS

THESES

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DEPARTMENT OF CHEMISTRY

PUBLICATIONS AND ADDRESSES

THESES

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APPENDIX E

DEPARTMENT OF GEOLOGY AND GEOPHYSICS - PUBLICATIONS

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APPENDIX F
MITBRN COMPUTER PROGRAM

In 1964 a computer program[15] was written by the Operations Group to replace the tedious hand calculations previously performed to determine the burnup in the MITR core. The MITBRN program calculates the burnup for each element in the core, provides listings on all pertinent data both for elements in the core and for those discharged to the spent fuel storage tank, prints a semigraphical plot of the core, and moves elements within a list or from one to another in accordance with the periodic fuel changes. Originally written in FORTRAN II, it was recently revised to FORTRAN IV.

The MITBRN program uses weighting coefficients calculated by "Modified TWENTY GRAND" to determine the relative burnup/gm. of all fuel elements in the core at the start of any given calculation. It then finds the actual burnup per element over a specified time period at a specified power level and adjusts the fuel loading accordingly for the next time period. The weighting coefficients are dependent on fuel element loading, shim bank position, and the loading of elements in the vicinity, as well as the position of the element in the core.

The program includes the following special features:

1. A complete input deck for the next time period can be punched by the code at the end of any time period. If no changes are made in fuel element locations or special conditions in the core the only additions to this deck required are those data cards giving the duration, power level, and shim bank position during the following periods.

2. A listing of fuel element locations, burnup, power production, higher isotope content, and other data of interest can be printed out at

the end of any time period. The code will automatically take this as the end of a core period and will begin the calculation of period burnup, period production, etc. from zero at the start of the next time period. A semigraphical representation of the core configuration can also be printed, if desired, at the same time.

3. The code can be instructed to move fuel elements into or out of the core, reactor top storage, or the fuel transfer flask, can place fuel in the storage tank but not remove it from there, and can receive fuel from fresh fuel storage but not replace it there -- before or after any time period. The fuel changes performed are printed out at the time they are made. If the fuel change is performed after a time period a complete printed output must be produced as well. If no output is desired the refueling can be performed at the start of the next period -- giving the same result.

4. The printed listing will not include any refueling performed at the end of the last time period covered, in order to give the results for the core configuration just completed. The punched output and the semigraphical plot will be produced for the latest fuel positions, in order to show the next core configuration. Separate identification cards are available for labeling these two outputs, as well.

5. A central absorber with a reactivity effect up to 1.2β can be inserted in the core at the beginning of any time period.

6. Any fuel element may have its burnup/gm. corrected by an assigned factor which can be supplied with the input data.

7. Any fuel element may be labelled in the output listing as "Special", "Partial Plate", or "Thermocouple Attached".

8. A core position containing no fuel can be labelled in the semigraphical plot with any combination of four symbols or less, e.g. S. C., SAMP, FLOT, 2/3.

9. The two core positions closest to the regulating rod may have their burnup/gm. corrected if a correction factor is determined.

10. Up to 99,999 time periods may be run at one time.

11. Up to 99 copies of either the printed listing or the semigraphical plot, or both, can be obtained. At least one printed listing must be produced in order to obtain copies of the plot.

12. A sub-program is now being written which will print out the entire reactor fuel inventory in a form useful for preparation of the semiannual AEC Material Status Reports (Form AEC-578).

APPENDIX G

IRRADIATIONS FOR OTHER UNIVERSITIES AND RESEARCH CENTERS

Institution	Fiscal Year 1968
Amerst College Amerst, Massachusetts	He
Boston College Chestnut Hill, Massachusetts	U^{235}
Brandeis University Waltham, Massachusetts	Cu
Carnegie Mellon University Pittsburg, Pennsylvania	I_2
Harvard University Cambridge, Massachusetts	Brain Tissue
University of Hawaii Honolulu, Hawaii	H_2O samples for activation analysis
NASA Electronics Research Center Cambridge, Massachusetts	SiO_2
University of New Hampshire Durham, New Hampshire	Li
University of Rhode Island (Narragansett Marine Laboratory) Kingston, Rhode Island	Ca, Eu
U. S. Air Force Electronic Systems Division Bedford, Massachusetts	Al, Fe, Ge, Li, Mg, N_2, Na, Nd, Se, Semiconductors, Si, Transistors, U, W.
Woods Hole Oceanographic Institute Woods Hole, Massachusetts	Coral, Plant Ash, quartz

APPENDIX H

IRRADIATIONS FOR HOSPITALS

Hospital	Fiscal Year 1968
Massachusetts General Hospital Boston, Massachusetts	Au, Cell in Culture, Cellulose, Cu, Fe, Li, Live rats, Mn, Na, Plastic chamber, Semiconductor, Si, Tissue, Tissue Ash
New England Deaconess Hospital Boston, Massachusetts	Al, B, Cl, Co, Cr, Na, Poly vials, Tissue

APPENDIX I

IRRADIATIONS FOR INDUSTRIAL FIRMS

Firm	Fiscal Year 1968
Arthur D. Little, Incorporated Cambridge, Massachusetts	Acrylic Plastic
Fram Corporation Providence, Rhode Island	Bearings
Isoserve Division Cambridge Nuclear Corporation Cambridge, Massachusetts	Br, K, Na
Lexington Laboratory Cambridge, Massachusetts	Al
Microwave, Incorporated Burlington, Massachusetts	U-235
Tracerlab, Incorporated Waltham, Massachusetts	Ag, Eu, Organic film Se, Ta

APPENDIX J

NON-M.I.T. EDUCATIONAL TOURS

(Groups of four or less not tabulated)

Organization	Visits	Number of Students
Beaver Country Day School, Brookline, Mass.	1	35
Belmont High School, Belmont, Mass.	1	7
Belmont Junior High School, Belmont, Mass.	1	8
Boothbay Region High School, Boothbay Harbor, Me.	1	43
Boston College, Chestnut Hill, Mass.	1	26
Boston University, Boston, Mass.	1	8
Bridgewater State College, Bridgewater, Mass.	1	13
Crossroads Africa	1	12
Dennis-Yarmouth Regional High School, Cape Cod, Mass.	1	9
Harvard Medical School, Boston, Mass.	1	6
Junior Chamber of Commerce, Lexington, Mass. and foreign high school students from Camp Rising Sun, New York	2	26
Lincoln-Sudbury Regional High School, Sudbury, Mass.	1	35
Lowell Technological Institute, Lowell, Mass.	1	5
Mount Alvernia Academy, Newton, Mass.	1	40
Newton South High School, Newton, Mass.	1	5
University of Massachusetts, Amherst, Mass.	1	10

Organization	Visits	Number of Students
Wentworth Institute, Boston, Mass.	1	10
Winthrop High School, Winthrop, Mass.	1	13
Yale University, New Haven, Conn.	1	5
	20	316

APPENDIX K

NON-M.I.T. PROFESSIONAL AND MISCELLANEOUS TOURS

(Groups of four or less not tabulated)

Organization	Visits	Number of Visitors
American Ordnance Association, Eastern Massachusetts Chapter	2	32
Annual Conference on Engineering in Medicine and Biology, Boston, Mass.	1	14
Army Materials and Mechanics Research Agency, Watertown, Mass.	1	5
Army Pictorial Centre, Long Island City, N.Y.	3	19
Association of Security Analysts, Annual Meeting, Boston, Mass.	1	50
Jackson and Moreland, Inc., Boston, Mass.	1	65
International Conference on Magnetism, Bedford, Mass.	2	17
	11	202

APPENDIX L
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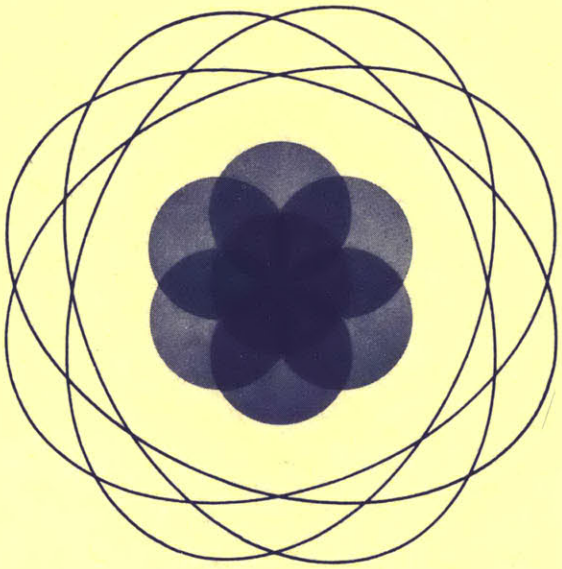

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