RESEARCH AND EDUCATIONAL ACTIVITIES
at the MIT RESEARCH REACTOR
Fiscal years 1969 and 1970

Report No. MITNE-119 for the
Period July 1, 1968-June 30, 1970
for the United States
Atomic Energy Commission
under Contract No. AT(30-1)-1967

Prepared by the MITR Staff
September 1970

MASSACHUSETTS INSTITUTE OF TECHNOLOGY • DEPARTMENT OF NUCLEAR ENGINEERING
Cambridge, Massachusetts 02139
RESEARCH AND EDUCATIONAL ACTIVITIES
AT THE
MIT RESEARCH REACTOR
FISCAL YEARS 1969 AND 1970

Report No. MITNE-119
for the two-year period July 1, 1968 - June 30, 1970
for the United States Atomic Energy Commission
under Contract No. AT(30-1)-1967

Prepared by the MITR Staff
September 1970
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section Number</th>
<th>Subject</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Abstract</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>Introduction</td>
<td>3</td>
</tr>
<tr>
<td>III</td>
<td>Objectives of the MIT Research Reactor</td>
<td>7</td>
</tr>
<tr>
<td>IV</td>
<td>Description of the MIT Research Reactor</td>
<td>11</td>
</tr>
<tr>
<td>V</td>
<td>Organization</td>
<td>25</td>
</tr>
<tr>
<td>VI</td>
<td>Record of Operation</td>
<td>45</td>
</tr>
<tr>
<td>VII</td>
<td>USAEC Research and Training Contract</td>
<td>53</td>
</tr>
<tr>
<td>VIII</td>
<td>MIT Research Activities Using the Reactor</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>1. Department of Nuclear Engineering</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>2. Department of Physics</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>3. Department of Metallurgy and Materials Science</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>4. Department of Chemistry</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>5. Department of Earth and Planetary Sciences</td>
<td>127</td>
</tr>
<tr>
<td>IX</td>
<td>MIT Educational Activities Using the Reactor</td>
<td>137</td>
</tr>
<tr>
<td>X</td>
<td>Research and Educational Utilization of the MIT Reactor by Others</td>
<td>145</td>
</tr>
<tr>
<td>XI</td>
<td>Appendices</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A. Department of Nuclear Engineering</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>Publications</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B. Department of Physics</td>
<td>163</td>
</tr>
<tr>
<td></td>
<td>Publications</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C. Department of Metallurgy and Materials Science Publications</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>Publications</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D. Department of Chemistry</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>Publications and Addresses</td>
<td></td>
</tr>
<tr>
<td>Section Number</td>
<td>Subject</td>
<td>Page</td>
</tr>
<tr>
<td>----------------</td>
<td>-------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>E</td>
<td>Department of Earth and Planetary Science Publications</td>
<td>171</td>
</tr>
<tr>
<td>F</td>
<td>MITBRN Computer Program</td>
<td>175</td>
</tr>
<tr>
<td>G</td>
<td>Irradiations for Other Universities and Research Centers</td>
<td>179</td>
</tr>
<tr>
<td>H</td>
<td>Irradiations for Hospitals</td>
<td>181</td>
</tr>
<tr>
<td>I</td>
<td>Irradiations for Industrial Firms</td>
<td>183</td>
</tr>
<tr>
<td>J</td>
<td>Non-MIT Educational Tours</td>
<td>185</td>
</tr>
<tr>
<td>K</td>
<td>Non-MIT Professional and Miscellaneous Tours</td>
<td>187</td>
</tr>
<tr>
<td>L</td>
<td>References</td>
<td>189</td>
</tr>
</tbody>
</table>
I. ABSTRACT

A report of research and educational activities which utilized the Massachusetts Institute of Technology, five-megawatt, heavy water, research reactor during fiscal years 1969 and 1970 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 years 1969 and 1970. Comprehensive bibliographies of earlier publications are contained in Report No. MITNE-91 "Research and Educational Activities at the MIT Research Reactor To and Including Fiscal Year 1967" and in MITNE-98, a similar document covering fiscal year 1968. These reports list essentially all publications of those 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, 1968.

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, and it completed essentially ten years of successful operation by the close of fiscal year 1968, i.e., by June 30, 1968. Fiscal years 1969 and 1970, the subject of this report, represent therefore the beginning of our second decade.

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 weekend 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 past two years of operation, i.e., fiscal years 1969 and 1970. Also, under the terms of Contract AT(30-1)-1967 between the U.S. Atomic Energy Commission and MIT, the Institute agrees to furnish the AEC with a current list of published reports of activities which involve the reactor. Such reports for fiscal years 1969 and 1970 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 1968-69 and 1969-70 operating records.

A similar report, MITNE-91, "Research and Educational Activities at the MIT Research Reactor To and Including Fiscal Year 1967", was published three years ago. 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. A second report MITNE-98, bearing a similar title and covering fiscal year 1968, was issued two years ago and contained a listing of then current work. This report brings the bibliography up-to-date.

Some of the descriptive material presented in MITNE-91 and MITNE-98 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 years 1969 and 1970. 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 MIT policy, the construction and operation of the reactor can be justified only on the basis of its contributions to the educational objectives of the Institute. 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 uses 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 MIT RESEARCH REACTOR

The MIT Research Reactor was built to serve the Institute's research and teaching requirements in the many fields encompassed by the general terms "nuclear science and technology". The reactor serves as a principal facility for strong programs of fundamental research in several of the basic 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 MIT, the Institute recognizes an obligation to help meet the requirements of other universities, of hospitals, and of industry, particularly in the local area. The reactor is available to other institutions whose 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. MIT 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, MIT does not desire to compete with commercial reactors for this work. However, where the half-lives of radioisotopes are short or where other factors dictate irradiations in the MITR, the Institute is happy to provide the required services. As mentioned above in connection with research, services are usually limited to making the irradiations.

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

The MIT Research Reactor was designed so that a large number of experiments could be simultaneously accommodated in its experimental facilities. In total, there are over 70 neutron irradiation and beam positions. While it would not 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 MIT RESEARCH REACTOR

The research reactor which has been in use since 1958 is heavy-water cooled and moderated and operates at powers up to 5 MW. Consideration is now being given to the possibility of replacing the present core with one which would be reflected with heavy water but cooled and moderated by light water. Feasibility studies initiated by Professor T.J. Thompson in fiscal years 1967 and 1968 and continuing under Professor D.D. Lanning indicate that such a design should produce beam port fluxes nearly three times those currently available without any increase in reactor power.

This section is devoted to a description of the present reactor and associated facilities. The MITR has been delineated in some detail in previous publications (Ref. 1-14, Appendix L). Research related to the proposed new design is described in Section VIII-1, and papers on it have been published (Ref. 15-18, Appendix L). The modification will probably be made during fiscal year 1972.

The MITR presently in use, 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 MIT 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
FIG. 11 - VIEW OF M.I.T. RESEARCH REACTOR SHOWING MAJOR COMPONENTS AND EXPERIMENTAL FACILITIES
FIG. IV-2 HORIZONTAL SECTION THROUGH REACTOR AND EXPONENTIAL EXPERIMENT
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 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$_2$O 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.\(^{(19)}\)

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$_2$O exponential experiment and the Blanket Test Facility 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 fiscal year 1968. The necessary AEC regulatory approvals were obtained the following year, and the equipment made liquid helium during the past fiscal year.

The helium plant will refrigerate two cryogenic chambers in the MITR. One of these is a materials irradiation thimble.
### TABLE IV-1 CHARACTERISTICS OF IRRADIATION FACILITIES

<table>
<thead>
<tr>
<th>Facility</th>
<th>No. Available</th>
<th>Size</th>
<th>Estimated Thermal Flux at 5MW n/cm²·sec</th>
<th>Special Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Beam Ports</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4&quot;</td>
<td>6</td>
<td>4⅜&quot; i.d.</td>
<td>at tank wall</td>
<td>All ports have readily available the following services:</td>
</tr>
<tr>
<td>6&quot;</td>
<td>4</td>
<td>6⅜&quot; i.d.</td>
<td>2 × 10⁻¹³</td>
<td>1. Demineralized cooling water</td>
</tr>
<tr>
<td>12&quot;</td>
<td>1</td>
<td>12⅜&quot; i.d.</td>
<td></td>
<td>2. 110 V AC</td>
</tr>
<tr>
<td>Rotary Horizontal Ports</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6&quot;</td>
<td>2</td>
<td>6⅜&quot; i.d.</td>
<td>at tank wall, 2 × 10⁻¹³</td>
<td></td>
</tr>
<tr>
<td>Horizontal Thru Ports</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6&quot;</td>
<td>1</td>
<td>6⅜&quot; i.d.</td>
<td>2 × 10⁻¹³ at point closest to tank</td>
<td></td>
</tr>
<tr>
<td>4&quot;</td>
<td>1</td>
<td>4⅜&quot; i.d.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Thimbles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite 3½&quot;*</td>
<td>6 up to 10</td>
<td>3½&quot; i.d. up to 12&quot; long</td>
<td>1 - 3 × 10¹³</td>
<td>Exposure to fast neutrons is possible in in-tank thimbles (also gammas up to 8 × 10⁸ r./hr.)</td>
</tr>
<tr>
<td>In-tank 1&quot; (in reflector) *</td>
<td></td>
<td>1&quot; i.d. up to 24&quot; long</td>
<td>5 × 10¹³</td>
<td></td>
</tr>
<tr>
<td>In-tank 1&quot; (in core)*</td>
<td>up to 3</td>
<td>same size</td>
<td>8 × 10¹³</td>
<td></td>
</tr>
<tr>
<td>Thermal Column</td>
<td>1</td>
<td>Holes up to 14&quot; × 14&quot; extend into thermal column. Larger holes can be made if needed</td>
<td>10⁹ - 10¹²</td>
<td>The thermal column has lead and steel shutters</td>
</tr>
<tr>
<td>Pneumatic Rabbit Tubes</td>
<td>4</td>
<td>Space for sample 1&quot; dia. × 2½&quot; long</td>
<td>2 × 10⁻¹³</td>
<td>&quot;In&quot; to &quot;out&quot; travel time is 0.5 sec.</td>
</tr>
<tr>
<td>Medical Therapy Facility</td>
<td>1</td>
<td>---</td>
<td>Thermal 2 × 10¹⁰ Fast 2 × 10⁷</td>
<td>Opens into operating room beneath reactor</td>
</tr>
<tr>
<td>Gamma Facility</td>
<td>Many</td>
<td>Flexible</td>
<td>10⁴ - 10⁵ r./hr.</td>
<td>Spent fuel storage</td>
</tr>
</tbody>
</table>

* 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 (½" i.d. x 1½" or 2½" long).
located within a fuel element in the core. The fast flux in the thimble (for neutron energies above 0.5 MeV) is about $1.5 \times 10^{13}$ 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 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 MIT. The in-core 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
have been constructed. The first cryostat test chamber has been designed and fabricated. It is now being tested and is scheduled for installation in the thermal column in the near future. Experimental work leading to these two facilities had been undertaken in previous years.

An important addition designed during fiscal year 1968 and installed during 1969 is a facility to permit expanded research in the area of fast breeder reactor physics.\(^{(20)}\) 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 can be installed in an irradiation cave located at the end of the thermal column (Figures IV-1 and IV-2). The assembly feeds neutrons into an adjacent blanket test assembly or into other materials. By appropriate arrangement of components, it is 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 per unit volume than that of typical fast critical assemblies, and thus the facility is capable of serving very effectively in many applications.

Another modification to the reactor during fiscal year 1969 was the installation of a facility, 6CH1, which permits exposure of test samples to neutron fluxes having primarily a fission energy spectrum.\(^{(21)}\) 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 4" in diameter by 4' long. In the previous year, a similar facility, 2CH1, with an inside diameter of 1-1/8" was installed.
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 is available.

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 MIT 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 MIT Computation Center, including use of an IBM 360/67 computer, are available for use by students and staff in Nuclear Engineering. Further, the MIT 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 MIT cyclotron. The Laboratory is building a high-intensity linear accelerator for 400-MeV electrons, to be in operation in 1970. The Laboratory and Harvard University operate jointly the 6-BeV Cambridge Electron Accelerator on the Harvard campus.

MIT'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 MIT 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.
MIT 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 MIT Research Reactor is part of the Department of Nuclear Engineering, one of several departments in the School of Engineering at MIT. The Reactor Director, who reports to the Department Head, Professor Manson Benedict, was Professor T.J. Thompson until June 10, 1969, when he was appointed to be a Commissioner of the USAEC. He was succeeded as Reactor Director by Lincoln Clark, Jr., formerly Associate Director.

The normal complement for the reactor staff and the names of the individuals serving in the various positions on June 30, 1969 and on June 30, 1970 are given in Tables V-la and V-lb. A number of the individuals listed devote fractions of their time to other activities, such as student academic programs, 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 12-13 of the above, and 8-9 of these are Senior Operator Licenses.

In order to insure organizational independence for the health physics group assigned to the reactor and to the associated research projects and teaching laboratories, the radiation protection personnel report directly to the MIT Medical Department's Environmental 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
<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Director</td>
<td>Lincoln Clark, Jr.</td>
</tr>
<tr>
<td>Assistant Director for Engineering and Design</td>
<td>Edward J. Barnett</td>
</tr>
<tr>
<td>Assistant Director for Operations</td>
<td>James W. Gosnell</td>
</tr>
<tr>
<td>Operations Superintendent</td>
<td>David F. Frech</td>
</tr>
<tr>
<td>Electronics Supervisor</td>
<td>David A. Gwinn</td>
</tr>
<tr>
<td>Assistant Superintendent</td>
<td>Kenneth D. Collins</td>
</tr>
<tr>
<td>Senior Shift Supervisor</td>
<td>Alfred Torri</td>
</tr>
<tr>
<td>Shift Supervisors</td>
<td>William E. McDermott</td>
</tr>
<tr>
<td></td>
<td>Paul T. Menadier</td>
</tr>
<tr>
<td>Reactor Operators</td>
<td>Leonard E. Andexler</td>
</tr>
<tr>
<td></td>
<td>Thomas J. Casey</td>
</tr>
<tr>
<td></td>
<td>Cyril J. Crane</td>
</tr>
<tr>
<td></td>
<td>Lewis A. Goldman</td>
</tr>
<tr>
<td></td>
<td>Joseph L. Rubo</td>
</tr>
<tr>
<td></td>
<td>David W. Cannon</td>
</tr>
<tr>
<td></td>
<td>Brian E. Champagne</td>
</tr>
<tr>
<td></td>
<td>Arthur Porter</td>
</tr>
<tr>
<td></td>
<td>Robert W. Vreeland</td>
</tr>
<tr>
<td>Reactor Operator Trainees</td>
<td>James P. Knotts</td>
</tr>
<tr>
<td>Operations Assistant</td>
<td>Francis L. Woodworth</td>
</tr>
<tr>
<td>Machine Shop Supervisor</td>
<td>Kenneth J. Butler</td>
</tr>
<tr>
<td>Machinists</td>
<td>Thomas J. Green</td>
</tr>
<tr>
<td></td>
<td>John E. Wasik</td>
</tr>
<tr>
<td></td>
<td>(one position not filled)</td>
</tr>
<tr>
<td></td>
<td>Almon J. Abbott</td>
</tr>
<tr>
<td></td>
<td>Charles E. DeAngelis</td>
</tr>
<tr>
<td></td>
<td>James Rosati</td>
</tr>
<tr>
<td></td>
<td>Richard E. Henderson</td>
</tr>
<tr>
<td></td>
<td>Harry A. Saunders</td>
</tr>
<tr>
<td></td>
<td>David A. Lynch</td>
</tr>
<tr>
<td></td>
<td>(one position not filled)</td>
</tr>
<tr>
<td>Stock Clerk</td>
<td></td>
</tr>
<tr>
<td>Draftsman</td>
<td></td>
</tr>
<tr>
<td>Electronics Technician</td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>Names</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Administrative Assistants</td>
<td>John L. Cochrane</td>
</tr>
<tr>
<td></td>
<td>Deane B. Haskell</td>
</tr>
<tr>
<td>Secretaries</td>
<td>Marguerite J. Falco</td>
</tr>
<tr>
<td></td>
<td>Pamela Thing</td>
</tr>
<tr>
<td></td>
<td>Margaret L. Wolfe</td>
</tr>
<tr>
<td>Receptionist</td>
<td>Luz Maria Honorato</td>
</tr>
<tr>
<td>Operations Assistant and Guide</td>
<td>Brunn Roysden</td>
</tr>
</tbody>
</table>
**TABLE V-1b**

**REACTOR STAFF**

(June 30, 1970)

<table>
<thead>
<tr>
<th>Position</th>
<th>Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>Director</td>
<td>Lincoln Clark, Jr.</td>
</tr>
<tr>
<td>Assistant Director for Engineering and Design</td>
<td>Edward J. Barnett</td>
</tr>
<tr>
<td>Assistant Director for Operations</td>
<td>James W. Gosnell</td>
</tr>
<tr>
<td>Operations Superintendent</td>
<td>Kenneth D. Collins</td>
</tr>
<tr>
<td>Electronics Supervisor</td>
<td>David A. Gwinn</td>
</tr>
<tr>
<td>Senior Shift Supervisor</td>
<td>Alfred Torri</td>
</tr>
<tr>
<td></td>
<td>(one position not filled)</td>
</tr>
<tr>
<td>Shift Supervisors</td>
<td>William E. McDermott</td>
</tr>
<tr>
<td></td>
<td>Paul T. Menadier</td>
</tr>
<tr>
<td>Reactor Operators</td>
<td>Leonard E. Andexler</td>
</tr>
<tr>
<td></td>
<td>Thomas J. Casey</td>
</tr>
<tr>
<td></td>
<td>Cyril J. Crane</td>
</tr>
<tr>
<td></td>
<td>Brian E. Champagne</td>
</tr>
<tr>
<td></td>
<td>Lewis A. Goldman</td>
</tr>
<tr>
<td>Reactor Operator Trainees</td>
<td>Eric P. Ascoli</td>
</tr>
<tr>
<td></td>
<td>George Bolen</td>
</tr>
<tr>
<td></td>
<td>Margaret A. Frerking</td>
</tr>
<tr>
<td></td>
<td>Paulo M. Furtado</td>
</tr>
<tr>
<td></td>
<td>Robin Staffin</td>
</tr>
<tr>
<td></td>
<td>Philip A. Smith</td>
</tr>
<tr>
<td>Operations Assistant</td>
<td>James P. Knotts</td>
</tr>
<tr>
<td>Machine Shop Supervisor</td>
<td>Francis L. Woodworth</td>
</tr>
<tr>
<td>Machinists</td>
<td>Kenneth J. Butler</td>
</tr>
<tr>
<td></td>
<td>Frank L. Bingham</td>
</tr>
<tr>
<td></td>
<td>Thomas J. Green</td>
</tr>
<tr>
<td></td>
<td>John E. Wasik</td>
</tr>
<tr>
<td>Mechanics</td>
<td>Almon J. Abbott</td>
</tr>
<tr>
<td></td>
<td>Charles E. DeAngelis</td>
</tr>
<tr>
<td></td>
<td>James J. Rosati</td>
</tr>
<tr>
<td>Stock Clerk</td>
<td>Richard E. Henderson</td>
</tr>
<tr>
<td>Draftsman</td>
<td>Harry A. Saunders</td>
</tr>
</tbody>
</table>
TABLE V-1b

(Concluded)

<table>
<thead>
<tr>
<th>Electronics Technicians</th>
<th>Joseph J. DiPadova</th>
<th>David A. Lynch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrative Assistants</td>
<td>John L. Cochrane</td>
<td>Deane B. Haskell</td>
</tr>
<tr>
<td>Secretaries</td>
<td>Marguerite J. Falco</td>
<td>Virginia O'Keefe</td>
</tr>
<tr>
<td>Receptionist</td>
<td>Margaret L. Wolfe</td>
<td></td>
</tr>
<tr>
<td>Operations Assistant and Guide</td>
<td>Cynthia Mitaras</td>
<td>Peter Hendrick</td>
</tr>
</tbody>
</table>
separately because they are administratively part of the Physical Plant Department at MIT. These groups are listed in Tables V-2a and V-2b and Tables V-3a and V-3b.

**TABLE V-2a**

**RADIATION PROTECTION PERSONNEL**

(June 30, 1969)

Radiation Protection Officer: Edward Karaian
Radiation Protection Technicians: Patrick Coggio
Donald Searl
(one position not filled)

**TABLE V-2b**

**RADIATION PROTECTION PERSONNEL**

(June 30, 1970)

Radiation Protection Officer: Edward Karaian
Radiation Protection Technicians: Walter Caithness
Patrick Coggio
Donald Searl

**TABLE V-3a**

**BUILDING CUSTODIANS**

(June 30, 1969)

Head Custodian: Charles Hamilton
Custodians: Joseph Keough
Edward Zaniewski

**TABLE V-3b**

**BUILDING CUSTODIANS**

(June 30, 1970)

Head Custodian: Charles Hamilton
Custodians: Joseph Keough
George O'Connell (temporary)
Edward Zaniewski
The several research projects at MIT which utilized the reactor in a major way during fiscal years 1969 and 1970 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 to list all of those associated with MIT groups making limited use of the reactor or with groups in other universities, hospitals, etc.

TABLE V-4

MAJOR RESEARCH PROJECTS AT MIT INVOLVING THE MITR

Reactor Physics Research
Gamma-Ray Spectroscopy
Neutron Diffraction Spectrometers:
  Physics Department Program
  Metallurgy Department Program
Fast Reactor Blanket Research
Design of Radiation Effects Cryogenic Facility
Design and Fabrication of Cold Neutron Cryogenic Facility
Neutron Capture Therapy Research
Medical Applications of Neutron Activation Analysis
Inelastic Scattering Spectrometer for Molecular Dynamics
Nuclear Chemistry
Activation Analysis in Air Pollution
Activation Analysis in Geochemistry
Design Studies for MITR-II Research Reactor

The members of the MIT Reactor Safeguard Committee conduct periodic safety reviews of the reactor operation and pass on the safety of proposed experimental programs and reactor modifications. Those who served during the two-year period are shown in Table V-5. The majority have been active on the Committee since its inception in 1957.
TABLE V-5

MIT REACTOR SAFEGUARD COMMITTEE

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manson Benedict, Chairman</td>
<td>Head, Department of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Harvey Brooks</td>
<td>Dean, Division of Engineering and Applied Physics, Harvard University</td>
</tr>
<tr>
<td>Carl F. Floe (until June 18, 1970)</td>
<td>Vice President, Research Administration, MIT</td>
</tr>
<tr>
<td>John M. Fresina (for Mark J. Dondero)</td>
<td>Assistant Safety Engineer, MIT (Head, Safety Office, MIT)</td>
</tr>
<tr>
<td>Albert G. Hill (starting June 18, 1970)</td>
<td>Vice President for Research, MIT</td>
</tr>
<tr>
<td>James W. Gosnell</td>
<td>Assistant Director for Operations, MIT Reactor</td>
</tr>
<tr>
<td>Harriet L. Hardy</td>
<td>Assistant Director, Medical Department, MIT</td>
</tr>
<tr>
<td>Samuel Levin</td>
<td>Radiation Protection Officer, MIT</td>
</tr>
<tr>
<td>Constantine J. Maletskos</td>
<td>Senior Scientist, Cancer Research Institute, New England Deaconess Hospital, and Lecturer, Department of Pathology, Harvard Medical School</td>
</tr>
<tr>
<td>John J. O'Connor</td>
<td>Director, Army Materials Research Reactor, Watertown, Massachusetts</td>
</tr>
<tr>
<td>Theos J. Thompson (until May 1, 1969)</td>
<td>Director, MIT Reactor, and Professor, Department of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Lincoln Clark, Jr. (starting May 1, 1969)</td>
<td>Director, MIT Reactor, and Research Associate, Department of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Alfred Torri</td>
<td>Senior Shift Supervisor, MIT Reactor</td>
</tr>
<tr>
<td>Secretary</td>
<td></td>
</tr>
</tbody>
</table>

32
A new committee, established in September 1969, is the MIT Reactor Utilization Council. The diversified utilization of the reactor involves many disciplines, and it is believed that the optimum use of the reactor can best be established by involving people whose different talents range over a variety of fields. The Council met several times during fiscal year 1970 to learn about the progress of the various research projects and to recommend new projects and improved utilization. Those who served on the Council during the year are listed below.

**TABLE V-6**

**MIT REACTOR UTILIZATION COUNCIL**

<table>
<thead>
<tr>
<th>Name</th>
<th>Position and Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gordon L. Brownell</td>
<td>Professor of Nuclear Engineering, and Head, Physics Research Laboratory, Massachusetts General Hospital</td>
</tr>
<tr>
<td>Sow-Hsin Chen</td>
<td>Associate Professor of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Lincoln Clark, Jr.</td>
<td>Director, MIT Reactor</td>
</tr>
<tr>
<td>Franklyn M. Clikeman</td>
<td>Associate Professor of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Michael J. Driscoll</td>
<td>Associate Professor of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Allan F. Henry</td>
<td>Professor of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>David D. Lanning (Chairman)</td>
<td>Professor of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Edward A. Mason</td>
<td>Professor of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Norman Rasmussen</td>
<td>Professor of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Clifford Shull</td>
<td>Professor, Physics Department, MIT</td>
</tr>
<tr>
<td>Thomas O. Ziebold</td>
<td>Professor of Nuclear Engineering, MIT</td>
</tr>
<tr>
<td>Joseph Baron (Secretary)</td>
<td>Student, Nuclear Engineering Department, MIT</td>
</tr>
</tbody>
</table>
There were several promotions for members of the reactor staff and several additions during fiscal years 1969 and 1970. Lincoln Clark, Jr. succeeded Professor T.J. Thompson as Director on June 10, 1969, when the latter became a Commissioner of the USAEC. James W. Gosnell, Assistant Director for Operations, was appointed Assistant Professor in the Department of Nuclear Engineering on July 1, 1970. Kenneth D. Collins was promoted from Assistant Superintendent to Operations Superintendent on August 8, 1969, to succeed David F. Frech, who went to Duke Power Company, South Carolina. Marguerite Falco was advanced on April 1, 1970 to Senior Secretary and assigned administrative supervisory responsibility for all secretarial activities in the Nuclear Engineering Center in Building NW12. Margaret Wolfe became Senior Accounting Clerk in the Reactor Business Office.

We are happy to welcome the following people who joined the reactor staff during the year: Frank L. Bingham, formerly at Bond Research Laboratory, Inc., Somerville, Massachusetts, joined the Reactor Machine Shop as a Machinist A, and Joseph J. DiPadova transferred from the Draper Laboratory to the Electronics Shop as a Technician A. Brunn Roysden succeeded Richard A. Farmer as Operations Assistant and Guide on June 16, 1969 and, in turn, was succeeded by Peter Hendrick on June 16, 1970; all three are or were graduate students in the Department of Nuclear Engineering. In November 1969, Virginia O'Keefe joined the secretarial staff, replacing Pamela Thing and in May 1970 Cynthia Mitaras succeeded Luz Honorato as receptionist.

In April 1970 Paulo Furtado, graduate student in Nuclear Engineering, began training for his Reactor Operator License. In the same month Philip Smith and, later in June,
Thomas Bleazard, both recently discharged from active duty with the USN nuclear submarine navy, also began training. All three expect to receive licenses early in the new fiscal year.

Toward the end of the 1970 spring term, four MIT undergraduates began part-time operator training, which is continuing on a full-time basis during the summer. It is expected that they will qualify for licenses prior to the fall term and will then be available on a part-time basis to serve as operators. We look forward to having Eric Ascoli, George Bolen, Margaret Frerking and Robin Staffin as members of the operating staff.

Members of the various research groups which utilize the MITR are named in Section VIII, but we wish to include here a group of students who have been working closely with the reactor staff on plans to modify and upgrade the present reactor core, as was mentioned in Section IV. Originally under the direction of Professor T.J. Thompson, they have been supervised since July 1969 by Professor D.D. Lanning and have provided the experimental and theoretical information necessary for the design of the new core configuration. They constitute a truly international group. Throughout this two-year period Andrews Addae, a native of Ghana who will shortly receive his ScD from MIT, has performed a series of neutronic calculations using Exterminator, PDQ-7 and other codes. He has been aided during recent months by Roberto Hukai, from Brazil, who completed his ScD requirements in May 1970. During fiscal year 1969 Dennis Spurgeon, assisted by Donald Uhl, conducted experimental and theoretical investigations of heat transfer in thin channels such as exist in plate-type fuel elements, for both smooth and ribbed heat transfer surfaces. During that year, Ernest Heimberg wrote Monte Carlo codes for studying thermal
column fluxes and Robert Sanders investigated means for optimizing the neutron flux both in the medical therapy room port and in the thermal column. Daniel Kennedy, a Canadian, studied the perturbations in the neutron flux caused by the introduction of beam ports into the D₂O reflector. All of the last four have since graduated with Nuclear Engineer, two M.S., and two ScD degrees respectively.

Several additional students participated in the design work for the MITR-II core in fiscal 1970. Dug Choi, whose home is in Korea, carried out studies on the removal of decay heat by convective cooling. Bruce Luxford analyzed the process system to determine safety limits, and Ron Chin is assisting with the neutron spectrum analysis of the thermal column cold source. Heat transfer and flow studies are being continued by Paulo Furtado, a native of Brazil. Tolga Yarman, from Turkey, is doing a reactivity transient analysis and Andrew Kadak is making a computer study of fuel management in the new core. The first three projects above in this paragraph are M.S. thesis topics, while the last three are ScD investigations.

Six other students, who have been or are assisting the redesign project, are the following: Alfred Torri on preparation of the Safety Analysis Report to the AEC, Yves Lefevre on neutron lifetime calculations, John Tuohy on reactivity transient studies, Terrance Rieck on a criticality computer code, and Joseph Kearney and Shivaji Seth on running of other computer programs.

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. MIT 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 MIT.

Participation in job-related training courses at all levels is strongly encouraged at the MIT 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 MIT. Furthermore, activities at the MIT 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 years 1969 and 1970, 18 and 19 members, respectively, of the reactor staff successfully participated in various courses of study and in thesis research. This count does not include Professor Thompson's teaching of "Fast Power Reactors," MIT subject number 22.28 in 1969, nor "Nuclear Power Reactor Safety," subject numbers 22.94s-22.96s in 1968. The latter is a special three-week summer course designed primarily for those engaged full time in reactor design, fabrication, operation, teaching, and regulation, and it has been continued in subsequent summers under the supervision of Professor Norman C. Rasmussen of the Department's faculty. Those reactor personnel taking courses and the topics studied are listed in Tables V-6a and V-6b. During fiscal year 1969, this outside study led to one bachelor's degree and three doctoral degrees; in fiscal 1970 it resulted in one associate's, one bachelor's and one master's.
**TABLE V-6a**

**OUTSIDE STUDY BY REACTOR STAFF, FY 1969**

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.J. Casey</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Bachelor's Degree in Electrical Engineering</td>
</tr>
<tr>
<td>B.E. Champagne</td>
<td>U.S. Army</td>
<td>Field Wireman's School</td>
</tr>
<tr>
<td>J.L. Cochrane</td>
<td>Boston College</td>
<td>Courses toward Bachelor's Degree in Business Administration</td>
</tr>
<tr>
<td>K.D. Collins</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Associate's Degree in Mathematics and Physics</td>
</tr>
<tr>
<td>C.J. Crane, Jr.</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Bachelor's Degree in Electrical Engineering</td>
</tr>
<tr>
<td>M.J. Falco</td>
<td>Boston College</td>
<td>Courses toward Bachelor's Degree in Business Administration</td>
</tr>
<tr>
<td>R.A. Farmer</td>
<td>MIT</td>
<td>Thesis research in two-phase flow, Received PhD in Nuclear Engineering</td>
</tr>
<tr>
<td>J.W. Gosnell</td>
<td>MIT</td>
<td>Thesis research in The Reactor Physics of Two-Region Lattices - received PhD in Nuclear Engineering</td>
</tr>
<tr>
<td>D.A. Gwinn</td>
<td>MIT</td>
<td>Thesis research in neutron interferometry</td>
</tr>
<tr>
<td>D.B. Haskell</td>
<td>Boston College</td>
<td>Courses toward Bachelor's Degree in Business Administration</td>
</tr>
<tr>
<td>Name</td>
<td>Institution</td>
<td>Course</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>D.J. Holbrook</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Bachelor's Degree in Electrical Engineering</td>
</tr>
<tr>
<td>D.A. Lynch</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Bachelor's Degree in Industrial Engineering</td>
</tr>
<tr>
<td>W. McDermott</td>
<td>Lowell Institute, Cambridge</td>
<td>Computer Programming</td>
</tr>
<tr>
<td>L.T. Papay</td>
<td>MIT</td>
<td>Thesis research in Reactor Physics Using Pulsed Neutron Techniques, received PhD in Nuclear Engineering</td>
</tr>
<tr>
<td>B. Roysden</td>
<td>MIT</td>
<td>Thesis research in Stress Analysis of Large Fusion Devices</td>
</tr>
<tr>
<td>J.L. Rupp</td>
<td>Northeastern University, Boston</td>
<td>Received Bachelor of Science Degree in Electrical Engineering</td>
</tr>
<tr>
<td>H.A. Saunders</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Associate's Degree in Mechanical Engineering</td>
</tr>
<tr>
<td>A. Torri</td>
<td>MIT</td>
<td>Thesis research in Fast Reactor Fuel Depletion</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>E.R. Ascoli</td>
<td>MIT</td>
<td>Courses toward Bachelor's Degree in Electrical Engineering</td>
</tr>
<tr>
<td>G. Bolen</td>
<td>MIT</td>
<td>Courses toward Bachelor's Degree in Physics</td>
</tr>
<tr>
<td>T.J. Casey</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Bachelor's Degree in Electrical Engineering</td>
</tr>
<tr>
<td>B.E. Champagne</td>
<td>Northeastern University, Boston</td>
<td>Calculus</td>
</tr>
<tr>
<td>J.L. Cochrane</td>
<td>Boston College</td>
<td>Courses toward Bachelor's Degree in Business Administration</td>
</tr>
<tr>
<td>K.D. Collins</td>
<td>Northeastern University, Boston</td>
<td>Received Associates Degree in Science in Math-Physics Technology</td>
</tr>
<tr>
<td>C.J. Crane</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Bachelor's Degree in Electrical Engineering</td>
</tr>
<tr>
<td>M.J. Falco</td>
<td>Boston College</td>
<td>Courses toward Bachelor's Degree in Business Administration</td>
</tr>
<tr>
<td>M.A. Frerking</td>
<td>MIT</td>
<td>Courses toward Bachelor's Degree in Physics</td>
</tr>
<tr>
<td>P.M. Furtado</td>
<td>MIT</td>
<td>Thesis research in plutonium recycle in boiling water reactors</td>
</tr>
<tr>
<td>Name</td>
<td>Institution</td>
<td>Course</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>D.A. Gwinn</td>
<td>MIT</td>
<td>Thesis research in neutron interferometry</td>
</tr>
<tr>
<td>D.B. Haskell</td>
<td>Boston College</td>
<td>Received Bachelor of Science Degree in Business Administration</td>
</tr>
<tr>
<td>P. Hendrick</td>
<td>MIT</td>
<td>Courses toward Master of Science Degree in Engineering</td>
</tr>
<tr>
<td>D.A. Lynch</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Bachelor's Degree in Industrial Engineering</td>
</tr>
<tr>
<td>B. Roysden</td>
<td>MIT</td>
<td>Received Master of Science Degree in Nuclear Engineering</td>
</tr>
<tr>
<td>H.A. Saunders</td>
<td>Northeastern University, Boston</td>
<td>Courses toward Associate's Degree in Mechanical Engineering</td>
</tr>
<tr>
<td>R. Staffin</td>
<td>MIT</td>
<td>Courses toward Bachelor's Degree in Physics</td>
</tr>
<tr>
<td>A. Torri</td>
<td>MIT</td>
<td>Thesis research in fast reactor fuel depletion</td>
</tr>
<tr>
<td>R. Vreeland</td>
<td>Boston College</td>
<td>Courses toward Bachelor's Degree in Business Administration</td>
</tr>
</tbody>
</table>
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 startups and shutdowns, 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. 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 MIT 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 24 months not only productive and rewarding years 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 1968-1970 would, if anything, be only in the planning stages now 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) of the 1967-1968 report, MITNE-98.
VI. RECORD OF OPERATION

In partial fulfillment of its mission as one of the Institute's major research facilities, the reactor continued during fiscal years 1969 and 1970 its record of safe and reliable operation, averaging about 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 startup 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 startups.

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 eleven-year period commencing July 20, 1959 and ending June 30, 1970. 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. Item 4 shows that full power operation averaged better than 92 hours/week over the past nine years in spite of time lost due to holidays and due to weekday shutdowns for experiment changes, essential maintenance, or other reasons.

The number of samples irradiated, Item 5, while down some from preceding years, 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 MIT. Information concerning these latter

46
### TABLE VI-1

#### SUMMARY OF OPERATIONS

<table>
<thead>
<tr>
<th></th>
<th>7/20/59-6/30/61 (≈ 2 Years)</th>
<th>7/1/61-6/30/68 (7 Years)</th>
<th>7/1/68-6/30/69 (1 Year)</th>
<th>7/1/69-6/30/70 (1 Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Megawatt Hours:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. For period, MWH</td>
<td>8,762</td>
<td>101,178</td>
<td>23,457</td>
<td>23,354</td>
</tr>
<tr>
<td>b. Cumulative from 7/21/58, MWH(1)</td>
<td>9,003</td>
<td>110,181</td>
<td>133,638</td>
<td>156,992</td>
</tr>
<tr>
<td>2. Hours of Reactor Operation:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. At full power (2)</td>
<td>8,740</td>
<td>33,899</td>
<td>4,789</td>
<td>4,738</td>
</tr>
<tr>
<td>b. Subcritical and critical (less than full power) for operator training (3)</td>
<td>50</td>
<td>40</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>c. Same - for teaching, experimental and other purposes (464)</td>
<td>717</td>
<td>50</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>d. Approaching full power (including startup checks) (3)</td>
<td>1,598</td>
<td>222</td>
<td>258</td>
<td></td>
</tr>
<tr>
<td>e. Completing shutdown (3)</td>
<td>689</td>
<td>242</td>
<td>252</td>
<td></td>
</tr>
<tr>
<td>Subtotal 2a-2e</td>
<td>36,953</td>
<td>5,343</td>
<td>5,339</td>
<td></td>
</tr>
<tr>
<td>3. Hours for Reactor Maintenance and Other:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Refueling (3)</td>
<td>225</td>
<td>85</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>b. Maintenance and changing experiments (3)</td>
<td>4,817</td>
<td>525</td>
<td>596</td>
<td></td>
</tr>
<tr>
<td>c. Not in use, no maintenance (5) (3)</td>
<td>19,373</td>
<td>2,807</td>
<td>2,767</td>
<td></td>
</tr>
<tr>
<td>Subtotal 3a-3c</td>
<td>24,415</td>
<td>3,417</td>
<td>3,421</td>
<td></td>
</tr>
<tr>
<td>Total Hours in Period</td>
<td>17,064</td>
<td>61,368</td>
<td>8,760</td>
<td>8,760</td>
</tr>
<tr>
<td>4. Hours/Week at Full Power-Average</td>
<td>86.2</td>
<td>92.6</td>
<td>92.1</td>
<td>91.1</td>
</tr>
<tr>
<td>5. Samples Irradiated</td>
<td>(3) 13,733</td>
<td>1,568</td>
<td>1,289</td>
<td></td>
</tr>
<tr>
<td>6. U-235 Burnup, Grams</td>
<td>476</td>
<td>5,332</td>
<td>1,242</td>
<td>1,251</td>
</tr>
</tbody>
</table>

**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) 1 MW - 2/20/59 to 7/12/61
  1.8 MW - 7/12/61 to 11/17/61
  1.95 MW - 11/20/61 to 10/15/65
  3.0 MW - 10/18/65 to 10/22/65
  4.0 MW - 10/25/65 to 10/29/65
  4.9 MW - 11/1/65 to 2/23/67
  1.95 MW - 3/1/67 to 6/2/67 (for heat exchanger repairs)
  4.9 MW - 6/5/67 to 6/30/70.

(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.

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(23), a general description of which appears in Appendix F.

Two shipments of spent fuel were made in the Spring of 1969. Each shipment contained 28 elements, averaging about 31% burnup, and represented about one year of operation at 5 MW. No shipments were made in fiscal year 1970, but two more will be required in either fiscal 1971 or 1972.

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

In order to provide for the continued safe operation and for the upgrading of the reactor, the Operations Group is regularly involved in a number of projects not directly related to the daily routine of reactor operation. Typical
of these is the review and revision of the reactor fire procedures by Bill McDermott, who also has coordinated the plan with the Cambridge Fire Department. Likewise, the Radiation Emergency Plan has been revised and updated by Fred Torri and Ken Collins. Tom Casey investigated methods for providing a separate, backup low-flow D_{2}O scram, design and installation of which were subsequently handled by the Electronics Group. Paul Menadier has assumed responsibility for custody and inventory of the reactor D_{2}O and also has been assisting with the arrangement and display of the controls and information for a proposed revision of the reactor safety system.

The Operations Group has also been active in projects essential to the development of the MITR-II design. Paulo Furtado and Lew Goldman, with assistance from Ed Barnett, Harry Saunders, and the Machine Shop, arranged for the flow tests which were conducted in the mockup of the new core. Jim Knotts, again assisted by the above group, performed drop time tests for the new core control blade design. Several members of the Operations Group have been involved in preparation of the Safety Analysis Report for the MITR-II, principally Fred Torri and Paulo Furtado.

In 1964 a computer program\(^{(23)}\) 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. Another revision, made during fiscal
year 1969, was the addition of a Subroutine, INVREP, which prints out the entire reactor fuel inventory in a form useful for preparation of the semiannual AEC Material Status Reports (Form AEC-578). It also prints lists of elements and fuel plates received or shipped during the period. Further details are provided in Appendix F.

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**

<table>
<thead>
<tr>
<th>License Number</th>
<th>Activity Authorized</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-37</td>
<td>Operation of MIT Research Reactor; possession and use of U-235 in fuel elements for the MITR</td>
</tr>
<tr>
<td>SNM-81</td>
<td>Possession and use of Pu in Pu-Be neutron sources for use in teaching laboratories, in research, and for health physics instrument calibration.</td>
</tr>
<tr>
<td>SNM-83</td>
<td>Possession and use of U-235 in fission counters for the MITR.</td>
</tr>
<tr>
<td>SNM-171</td>
<td>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.</td>
</tr>
</tbody>
</table>
TABLE VI-2  
(Continued)

<table>
<thead>
<tr>
<th>License Number</th>
<th>Activity Authorized</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNM-985</td>
<td>Shipment of MITR spent fuel elements to a processing plant using National Lead Company cask No. NL-BF-MTR-775.</td>
</tr>
<tr>
<td>SNM-986</td>
<td>Possession and use of normal U, U-235, and Pu for conduct of subcritical reactor lattice experiments, and for a thermal-to-fast neutron converter assembly used in the Blanket Test Facility; also additional U-235 and U-233 for nuclear chemistry research.</td>
</tr>
</tbody>
</table>

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 two years, John Cochrane, SS Representative for Station MBM, 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 years 1969 and 1970. Theses in progress at the end of June 1970 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 three years ago, i.e., "Research and Educational Activities at the MIT Research Reactor To and Including Fiscal Year 1967", report number MITNE-91. The fiscal year 1968 report, MITNE-98, and the current list bring 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 startup; 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, 1968, a total of 165 fuel elements containing 24.0 kilograms of uranium-235 were purchased. Fuel for operation during the latter part of FY 69 and during FY 70 was obtained in the form of excess Materials Testing Reactor plates, purchased from Idaho Nuclear Corporation and then assembled into elements by the MIT Reactor Machine Shop. The U-235 transferred to MIT amounted to 3.5 KG, enough for 20 elements. Plates for 25 more elements, 4.2 KG U-235, were purchased in FY 70 for use in FY 71 prior to modification of the MITR, as described at the beginning of Section IV.

Burnup amounted to 5.8 KG of U-235 from startup through June 30, 1968, and it was 1.2 KG in each of FY 69 and FY 70. The first returns of spent fuel were made during FY 1967.
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. Two more shipments made in the Spring of 1969 returned 6.0 KG of U-235 in 56 more elements, again averaging 31% burnup.

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, 1970, consumption, losses, and transfers over twelve years of operation have totaled 1200 pounds, leaving 12,800 pounds as the approximate June 30, 1970 inventory on hand.
VIII. MIT 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 major programs conducted during fiscal years 1969 and 1970 by Institute research investigators.

Recent and current programs of research utilizing the MIT Reactor cover a broad range of nuclear sciences and engineering topics, which may be briefly summarized as follows:

a) Reactor Physics

Research is conducted in the physics of thermal reactors, including studies utilizing the MIT reactor, exponential lattices or single rods, and also in the physics of fast reactors, particularly the measurement of neutron spectra and the optimization of breeding in the blankets surrounding these reactors.

b) Reactor Engineering

For this research, many engineering disciplines such as fluid flow, heat transfer, chemical and mechanical engineering, radiation detection methods, electronics, etc. are applied in studies of heat removal, power distribution, shielding, radiation effects on materials, measurement of fuel composition and burnup and in many other areas.

c) Nuclear Physics

A wide range of studies are possible such as the measurement and cataloging of the gamma spectra resulting from neutron capture (formerly with bent quartz crystals but more recently with the high-resolution Ge-Li semiconductor detectors), determination of the appropriate decay schemes, studies of the fission process and fission fragment yields for \((n,f)\) reactions, and measurement of the neutron interaction cross sections by time of flight, oscillator, or other methods.
d) Neutron Physics

A number of neutron diffraction spectrometers are used in a wide range of studies such as measurement of the neutron's magnetic dipole moment, the search for an electric charge and electric dipole moment, spin splitting with ferromagnetic prisms and shaped magnetic fields, single slit diffraction of neutrons and others. A 200K cold neutron source now being installed to provide neutrons of very low energy will make possible many additional studies.

e) Solid State

The same spectrometers are utilized in a variety of solid state studies, e.g. the Kondo effect, influence of non-centrosymmetric thermal oscillation of atom centers on neutron Bragg reflection, electron-spin pairing action in magnetic fields, and spin arrangements in magnetic materials. Specimen cryostats, ovens, and a superconducting magnet are available for use on the neutron spectrometers.

f) Neutron Activation Analysis

Methods of analysis utilizing both prompt and delayed emissions from irradiated materials are studied with particular emphasis on biomedical, geochemical, and air pollution studies. Multichannel analyzers with up to 4000 channels and detectors with resolutions up to those of the 3e-Li type are used.

g) Radiation Effects

Studies are made of the effects of fast and slow neutrons and of gamma rays (other radiations are possible through secondary reactions) on the heat transfer and other properties of fluids, by utilizing circulating loops in the reactor core, on the distribution of defects and the modification of deformation and other properties in solids, and on the performance of electronic components and circuits. A 100 liter/hour helium plant has recently been installed to permit low temperature studies in many of these areas.

h) Biomedical Research

In conjunction with local hospitals and medical schools where appropriate, studies are conducted in the field of neutron capture therapy and in the application of neutron activation analysis to a host of medical problems ranging from measurement of trace elements to whole body irradiations.
i) Molecular Dynamics

The inelastic scattering of neutrons is used in high resolution studies of the molecular dynamics of molecular crystals and liquids, both by incoherent and coherent scattering measurements.

The above 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 current 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, 1968, a total of 19 departments, study centers, and interdepartmental laboratories at MIT listed in Table VIII-1, had utilized its facilities. Twelve of these made further use of reactor services during fiscal years 1969 and 1970. The major research projects conducted under their auspices during this period are described below in Sections VIII-1 through VIII-5, and the publications resulting from these projects are listed in Appendices A through E.

Tables VIII-2a and VIII-2b are 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. With a few exceptions, the people listed in Tables V-1, V-2, and V-3, are not included in the tabulation since their duties are primarily related to operation of the reactor facility and not to research. The few who did contribute directly to the research are included. The figures of Tables VIII-2a and
<table>
<thead>
<tr>
<th>TABLE VIII-1</th>
<th>DEPARTMENTS AND INTERDEPARTMENTAL LABORATORIES AT MIT THAT HAVE USED THE MIT REACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Departments and Laboratories within Departments</td>
<td>Used in</td>
</tr>
<tr>
<td></td>
<td>1968-69</td>
</tr>
<tr>
<td>Aeronautics and Astronautics</td>
<td>*</td>
</tr>
<tr>
<td>Instrumentation Laboratory</td>
<td>*</td>
</tr>
<tr>
<td>Chemical Engineering</td>
<td></td>
</tr>
<tr>
<td>Chemistry</td>
<td>*</td>
</tr>
<tr>
<td>Civil Engineering</td>
<td></td>
</tr>
<tr>
<td>Hydrodynamics Laboratory</td>
<td>*</td>
</tr>
<tr>
<td>Earth and Planetary Sciences</td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Electrical Engineering</td>
<td></td>
</tr>
<tr>
<td>Insulation Research Laboratory</td>
<td></td>
</tr>
<tr>
<td>Electronic Systems Laboratory</td>
<td></td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td>*</td>
</tr>
<tr>
<td>Lubrication Laboratory</td>
<td></td>
</tr>
<tr>
<td>Materials Processing Division</td>
<td></td>
</tr>
<tr>
<td>Metallurgy</td>
<td></td>
</tr>
<tr>
<td>Meteorology</td>
<td></td>
</tr>
<tr>
<td>Naval Architecture and Marine Engineering</td>
<td>*</td>
</tr>
<tr>
<td>Nuclear Engineering</td>
<td>*</td>
</tr>
<tr>
<td>Nuclear Reactor Laboratories</td>
<td>*</td>
</tr>
<tr>
<td>Physics</td>
<td>*</td>
</tr>
<tr>
<td>Radioactivity Center</td>
<td></td>
</tr>
<tr>
<td>2. Centers and Interdepartmental Laboratories</td>
<td></td>
</tr>
<tr>
<td>Center for Advanced Engineering Studies</td>
<td></td>
</tr>
<tr>
<td>Center for Materials Science and Engineering</td>
<td></td>
</tr>
<tr>
<td>Lincoln Laboratory</td>
<td></td>
</tr>
<tr>
<td>Laboratory for Nuclear Science</td>
<td>*</td>
</tr>
<tr>
<td>National Magnet Laboratory</td>
<td></td>
</tr>
<tr>
<td>Radiological Safety Office</td>
<td>*</td>
</tr>
<tr>
<td>Research Laboratory for Electronics</td>
<td></td>
</tr>
</tbody>
</table>

61
### TABLE VIII-2a

**NUMBER OF INDIVIDUALS IN FIVE DEPARTMENTS AT MIT**

**DOING RESEARCH INVOLVING THE MIT REACTOR**

**1968-69**

<table>
<thead>
<tr>
<th>Department</th>
<th>Faculty Staff</th>
<th>Students</th>
<th>Engineering Assistants</th>
<th>Technicians</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry</td>
<td>13</td>
<td>12</td>
<td></td>
<td></td>
<td>3</td>
<td>28</td>
</tr>
<tr>
<td>Earth and Planetary Science</td>
<td>1</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Metallurgy and Material Science</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Nuclear Engineering</td>
<td>15</td>
<td>34</td>
<td>3</td>
<td>8</td>
<td>2</td>
<td>62</td>
</tr>
<tr>
<td>Physics</td>
<td>2</td>
<td>4</td>
<td></td>
<td>1</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td>32</td>
<td>59</td>
<td>3</td>
<td>9</td>
<td>5</td>
<td>108</td>
</tr>
</tbody>
</table>

**Note:** Individuals and small groups from other departments and laboratories not tabulated.
<table>
<thead>
<tr>
<th>Department</th>
<th>Faculty and Staff</th>
<th>Students</th>
<th>Engineering Assistants</th>
<th>Technicians</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry</td>
<td>8</td>
<td>15</td>
<td></td>
<td></td>
<td>3</td>
<td>26</td>
</tr>
<tr>
<td>Earth and Planetary Science</td>
<td>2</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Metallurgy and Materials Science</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Nuclear Engineering</td>
<td>17</td>
<td>43</td>
<td>3</td>
<td>8</td>
<td>5</td>
<td>76</td>
</tr>
<tr>
<td>Physics</td>
<td>2</td>
<td>6</td>
<td></td>
<td>1</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>TOTALS</td>
<td>30</td>
<td>73</td>
<td>3</td>
<td>9</td>
<td>8</td>
<td>123</td>
</tr>
</tbody>
</table>

Note: Individuals and small groups from other departments and laboratories not tabulated.
VIII-2b 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 fiscal years 1969 and 1970, which correspond to MIT's academic years 1968-69 and 1969-70. 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 35 subjects of instruction (a few in alternate years only). Although each student's program of study is arranged to suit his individual interests and objectives, most programs fall into one of the six fields of study listed below:

- Reactor Physics
- Reactor Engineering
- Nuclear Fuel
- Applied Plasma Physics
- Nuclear Materials Engineering
- Applied Radiation Physics

For thesis research, students may elect either theoretical or experimental topics and, in the latter case, these may or may not involve utilization of the MIT Reactor (in
Applied Plasma Physics invariably they do not). 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 thirteen-year period ending June 30, 1970, 138 theses, or 35% of 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. Including theses now in progress, over 300 MIT students were or are dependent upon the reactor for their thesis research, about two-thirds from Nuclear Engineering and one-third from other departments. It is only this MITR-oriented research with which we are concerned here. Other educational uses of the reactor are described in Sections IX and X.

1.1 Thermal Reactor Physics

Since 1959, under auspices of the U.S. Atomic Energy Commission, experimental research has been conducted at the MIT Reactor (MITR) on the neutronic characteristics of reactor lattices. Neutrons from the thermal column of the reactor are fed into subcritical exponential assemblies of the lattices to be investigated, and measurements are made of the neutron flux distribution and distribution of nuclear events in the lattice.

Between 1959 and 1968 a thorough investigation was made of uniform, multirod lattices of natural and slightly enriched uranium and uranium dioxide fuel rods in heavy water moderator. Definitive results were obtained and general correlations were developed for the principal reactor physics parameters of such heavy water-moderated lattices.
One of the most useful consequences of this work was the demonstration that many of the properties of a multi-rod reactor lattice could be measured reliably on a single rod or cluster of a few rods. These single or few-rod measurements have proved extremely useful for investigation of scarce, expensive or hard-to-handle fuel types. Theoretical methods have been perfected to derive lattice parameters for heterogeneous reactor assemblies from measurements on single or few rods.

In 1969 work was completed on 19 and 31 rod clusters of plutonium-containing fuel simulating one calandria tube of a D_2O moderated pressure-tube-type reactor. Fuel rods for this part of the work were made available through the AEC/AECL Cooperative Program Simulated Burned Fuel. Excellent agreement was obtained by Savannah River Laboratory on complete lattices of these same fuel elements.

Work was also completed on the application of high resolution Ge(Li) gamma ray spectrometry to fuel element assay, using both prompt and delayed gamma spectra. A variety of methods were developed to determine or confirm the composition of special fuel elements which might be used in single rod physics studies. A considerable amount of new basic prompt capture and fission gamma data for U-235, Pu-239, U-238 and Th-232 was developed in the course of this work.

In February 1970 the moderator in the MITR exponential facility was converted from heavy water to light water, and the concluding phase of this project was initiated. This involved demonstration applications of gamma spectroscopy (both prompt and delayed) and single rod physics measurements on actual burned fuel containing both fission products and plutonium; in this instance single fuel pins of approximately 20,000 MWD/T from the Dresden BWR were used.
AEC support of this research on thermal reactor physics terminates on September 30, 1970, owing principally to government policy that further research on thermal reactors be supported by industry rather than the AEC. Attempts have been made to develop new uses for the exponential facility used for thermal reactor research. Two approaches have been followed: The first has been to seek support for applications of the single-element method to light water reactors, such as to plutonium recycle fuel. The second has been to design a subcritical converter facility to generate a neutron spectrum representative of a liquid metal fast breeder reactor which could be used to study relative nuclear reaction rates in fast reactor core materials in fashion similar to the study of fast reactor blanket materials described in subsection 1.3, following. Although these seem fertile fields for research, support has not yet been obtained.

**Personnel** (Participated both in fiscal years 1969 and 1970, unless a single year is indicated.)

**Professors:**
- M.J. Driscoll
- T.J. Thompson ('69)
- I. Kaplan
- N.C. Rasmussen
- F.M. Clikeman
- D.D. Lanning ('70)

**Students:**
- V. Agarwala
- J. Donohew
- G. Hamilton
- Y. Hukai
- L. Izzo ('70)
- M. Kazimi ('70)
- T. Leung
- E. MacFarland
- W. Malec ('70)
- J. Sicilian ('70)

**Engineering Assistant:**
- A.T. Supple, Jr.

**Technician:**
- G. Sullivan
Support
USAEC

Related Academic Subjects

22.21 Nuclear Reactor Physics I
22.22 Nuclear Reactor Physics II
22.25 Special Topics in Reactor Physics
22.29 Thermal Power Reactors
22.41 Nuclear Reactor Physics Laboratory

1.2 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 1.1, 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 subsequent years most of the effort has been spent in the development and utilization 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 produced counters with active volumes as large as 40 cm$^3$. These detectors have been used in two areas of investigation - the nondestructive analysis of spent reactor fuel and neutron-capture gamma-ray studies. For the former application, a method was developed which uses the measured ratios of intensities of certain fission product gamma-ray lines to determine average flux during irradiation, length of irradiation, and burnup. In the latter application, the capture gamma-ray spectra from 75 of the natural elements were determined and have been published as a compilation. The
computer code GAMANL was developed and utilized in the analysis of the spectra.

During the last two years, the gamma-ray spectrometer has been used for both prompt and delayed activation analysis studies. These methods have been applied to unirradiated and to heavily irradiated fuel rods for the non-destructive measurement of the reactor physics parameters under investigation in the project described in subsection 1.1. For capture gamma rays, general equations have been developed which predict the sensitivity of the measurement for any element in a given sample. The gamma-ray data are now being reanalyzed to obtain the gamma ray yield as a function of energy for use in calculating the penetration through shields of secondary gamma rays emitted when neutrons are absorbed in the shield. The part of this work not previously done is analysis of the unresolved portion of each spectrum. In some cases this contributes 80% to the total gamma ray yield. This project, which is being done in cooperation with Gulf General Atomic, will result in a listing of gamma ray yields of some 75 elements in ENDF/B format.

**Personnel**

Professors: N.C. Rasmussen

Students: C. Takahata ('69)

T. Harper, Jr. ('69)

J. Hamawi

Y. Hukai

S. Ahmad Ali ('70)

**Support**

USAEC, Sloan Fund (MIT), General and Reserve Funds (MIT), Gulf General Atomic

69
1.3 Fast Blanket Test Facility

In the international program to develop an economical fast breeder reactor, considerable effort has been expended on experimental fast reactor physics. Most of this research has been conducted with low-power fast critical assemblies and has been core-oriented: measurements of such parameters as breeding and fission ratios, neutron spectra and heterogeneity effects have generally been limited to the core region, and very little work has been done in extending these measurements out into the breeding blanket region. In fact, in many of the assemblies no blanket is used, or a crude approximation to realistic blanket compositions is made, and reflector material at the outer periphery of the blanket is seldom included.

The axial and radial blankets of proposed LMFBR designs typically contribute one-quarter to one-third of the total breeding ratio, and thus, in a manner of speaking, the entire breeding gain. In addition, theoretical prediction of reactor physics parameters is considerably more complex and unreliable in the blanket region than it is in the core, due mainly to the strong spatial dependence of the neutron energy spectrum. It has consequently become increasingly evident that a systematic experimental study of the blanket region would be extremely desirable.

Early in 1967, steps were taken to initiate experimental fast reactor blanket research at MIT. To eliminate the necessity for a critical assembly, an investigation was made involving the use of a 4 ft. x 5 ft. x 16.5 cm thick uranium-loaded fission (or converter) plate powered by the thermal...
neutron flux from the MITR thermal column hohlraum (Figures IV-1 and IV-2) to generate a fast neutron flux for testing a blanket mockup. It was required as a primary design objective that the converter plate have a leakage spectrum and albedo typical of the core of a large LMFBR.

Analytical calculations showed that the spatial distribution of the neutron flux in the blanket assembly would closely simulate that in the radial blanket of a large LMFBR if the effective height and width of the blanket assembly were correctly chosen. Numerical multigroup calculations with the ANISN, AIM-6 and TWENTY GRAND codes showed that a converter assembly composed of a 20-cm-thick graphite external moderator region and a 16.5-cm-thick fuel region would generate a fast neutron leakage spectrum which closely approximated the leakage spectrum from an LMFBR core. It was found that the converter leakage spectrum could be varied to achieve a wide variety of energy distributions by changing the thicknesses of the graphite moderator and fuel regions. This suggested great flexibility in the converter concept, and the converter assembly was subsequently designed and built so as to permit changes in the graphite and UO$_2$ fuel loadings to be made easily.

Two-dimensional multigroup calculations made with the TWENTY GRAND code showed that backscattering from concrete shielding should perturb the blanket spectrum only in the outer 20 cm to 30 cm of the blanket assembly. The TWENTY GRAND calculations also indicated that the lateral shape of the fast neutron flux in the blanket assembly should be determined predominantly by the lateral shape of the thermal source flux incident upon the converter fuel.

Apart from the low cost and inherent safety, this type of facility has certain important advantages over a critical facility. First, it requires only about one-tenth of the
volume of blanket material needed for full-scale cylindrical critical mockup; second, at full-power operation (about 55 watts) the converter is capable of generating blanket region fluxes equivalent to those in a critical assembly operating at the relatively high power of 500 watts, which makes the current MITR facility more than competitive with existing critical facilities.

Construction of the Fast Blanket Test Facility was undertaken during fiscal year 1969, and it was completed during the past year. The construction cost of nearly $30,000 was paid from the MIT Reactor modification reserve funds, and UO₂ fuel rods for the converter assembly were loaned by the USAEC.

Beginning in June 1969, AEC-supported contract research was initiated as part of the U.S. program in LMFBR development. Startup tests were made on an ersatz blanket of 50 v/o iron and 50 v/o anhydrous boxax, which it was calculated would provide neutron spectra and spatial flux shapes reasonably similar to those in real blanket assemblies. Research on a simulated reference LMFBR blanket was initiated in January 1970. This blanket consists of 0.250 in. diameter uranium metal fuel rods clad in carbon steel and "moderated" by anhydrous sodium chromate. The resulting (homogenized) composition matches that of a UO₂ fueled, stainless steel clad, sodium cooled blanket on an almost exact nuclide-for-nuclide basis.

The test program now underway involves measurement of foil activation traverses, measurement of neutron spectra by both foil activation and instrumental methods, the use of prompt gamma analysis for inferring an in-pile neutron balance, and investigation of heterogeneous effects. Analytical and numerical studies are underway concurrently.
The results of these studies will provide the economic and physical basis for selection of more advanced blanket configurations, such as the use of moderating external reflectors, for future investigation.

**Personnel**

**Professors:**
- M.J. Driscoll
- T.J. Thompson ('69)
- I. Kaplan
- F.M. Clikeman
- N.C. Rasmussen
- D.D. Lanning ('70)

**Research Staff:**
- I.A. Forbes ('70)

**Students:**
- S.T. Brewer
- D. Choi
- W. Corcoran ('70)
- J.N. Donohew, Jr.
- C. Forsberg ('70)
- S.L. Ho
- C.S. Kang ('70)
- J. Klucar ('69)
- T. Leung
- N. Ortiz
- A. Pant ('70)
- N. Passman ('70)
- M. Sheaffer
- D. Shupe
- J. Synan ('69)
- W. Westlake ('70)

**Engineering Assistant:**
- A.T. Supple, Jr.

**Technician:**
- G. Sullivan

**Support**

MITR Reserve Funds; USAEC

**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
- 22.56 Fast Reactor Physics
1.4 Experiments in Fast Neutron Environments

Associated with the hohlraum described in Section IV and illustrated in Figure IV-1 are three facilities which provide fast neutron environments. These are designated 2CH1, 6CH1 and the Blanket Test Facility described in the previous subsection. All three use slightly enriched uranium oxide rods to convert the slow neutron flux in the hohlraum to a fast flux by fissioning of the U-235.

In 2CH1 and 6CH1 the rods are arranged in a cylindrical configuration, and sample capsules are placed inside the cylinders. The capsules have a boron lining which serves to shield out the slow neutrons, thereby minimizing activation of the sample materials and permitting exposure to a neutron environment having approximately a fission spectrum. The usable volumes in the capsules measure 11/16" diameter x 1-3/4" long for 2CH1 and 3.36" diameter x 11-3/4" long for 6CH1. The fuel rods are four feet long, so that special containers can be fabricated to accommodate larger volumes.

During the past two years 2CH1 and 6CH1 have been used by the MIT Instrumentation Laboratory for studies of fast neutron and gamma radiation on the properties of semiconductor devices. Although the research itself is not carried out by members of the Nuclear Engineering Department, as is also the case for the inelastic scattering spectrometer described in Subsection 1.9, the work in each instance is mentioned in this Section VIII-1 because of the Department's role in designing and fabricating the facilities used by the projects.

Two projects undertaken by the MIT Instrumentation Laboratory on these facilities during fiscal years 1969 and 1970 are described in the following abstracts from their
Report No. E-2415(21) and No. E-2419(22):

"Semiconductor Radiation Hardness Assurance Study

Two nondestructive electrical testing techniques, base transit time and D.C. parameter correlation, each capable of predicting transistor gain ($h_{FE}$) degradation in a neutron radiation environment, were evaluated to determine the feasibility of applying either or both techniques as a device selection method in a radiation performance assurance program.

Approximately eight hundred transistors of medium and thin base width types, representative of transistors to be used in future advanced hardened missile systems, were tested for neutron radiation hardness at the Army Pulse Radiation Facility at Aberdeen Proving Grounds and the MIT Research Reactor.

The base transit time prediction technique was demonstrated to be accurate to an average absolute error of 6% but is a fairly complicated measurement technique. The D.C. parameter prediction technique is accurate within a range of average absolute percent errors from 4 to 10 percent but only requires computer manipulation of data obtained by standard measurement techniques currently applied to all semiconductor devices made by semiconductor manufacturers.

Of the two, the D.C. parameter prediction technique appears to be the most promising with respect to being incorporated into a semiconductor manufacturers production line, but it still requires further development."

"Advanced Guidance Electronics Nuclear Hardness Report

This report contains information relating to the electronic design of hardened advanced guidance systems. Systems considerations as well as specific hardware implementations are discussed. The report emphasizes the areas of angular readout, multiplexing, hardened time generation, internal inertial instrument electronics, servo loops, brushless PM motor drives and power supplies. A discussion relating to components is also included with a detailed treatment of the problem of hardened voltage references."

Personnel
Design and Fabrication (Department of Nuclear Engineering)

Professor: M.J. Driscoll
Engineering Assistant: A.T. Supple, Jr.
Technician: G. Sullivan

75
Support

Department of Defense

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 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, based on a design by Professor J.L. Smith of MIT. 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 and FY 1969 the installations of the compressors and refrigerator were completed. An
application for an amendment to the MITR reactor license was submitted to the USAEC and was approved in August 1968. During the past year the plant made liquid helium, and it has been in operation a substantial part of the time for checking out of the system performance, for debugging, and for modification of several components.

Concurrently during the past two years an out-of-pile mockup of the 4°K irradiation facility was constructed, including electric heaters to simulate energy absorption in the reactor core. Runs with liquid helium, initiated during the past year, will provide data necessary for the design of an in-core cryostat, in which materials can be irradiated at liquid-helium temperatures. At these low temperatures structural defects caused by radiation are frozen in place and are not annealed, as would be the case at higher temperatures. This permits examination of the initial effects of radiation.

The in-core cryostat will be mounted in the center of the core where the flux of fast neutrons and gamma rays is highest. A sample tube will extend to the top of the reactor shielding where experiments can be made on irradiated specimens without warming the samples, or with controlled warming, if desired. Because the existing reactor is to be modified substantially in the near future, the cryostat will be designed for operation in the new core.

In another concurrent project during the past two years, a cryostat has been fabricated for use as a cold neutron source in the reactor thermal column. Cooled by helium gas at 20°K from the above plant, this facility and its uses are further described in subsection VIII.1.7.
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 experiments will evolve during fiscal years 1971 and 1972 when the cryostats have been installed and their operating capabilities established and that the facility will significantly enhance the utility of the MIT Reactor as a research center.

**Personnel**

- **Professors:**
  - D.D. Lanning ('70)
  - J.L. Smith, Jr. (Mech. Eng.)
  - T.J. Thompson ('69)
  - T.O. Ziebold

- **Research Associate:**
  - E.J. Barnett

- **Research Staff:**
  - D.A. Gwinn

- **Student:**
  - F.J. Berte

- **Technicians:**
  - A.J. Abbott
  - C.E. DeAngelis
  - J.J. Rosati

**Support**

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

**Related Academic Subjects**

- 22.721J Radiation Damage in Crystalline Solids
- 1.6 Radiation Effects in Solids

With the availability of the in-core cryostat planned for the reactor core (as described in the preceding section), 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.

Research during the past two years was in preparation for irradiations in the in-core cryostat. Considerable progress has been made in an effort to relate basic radiation damage mechanisms to the experimentally observed damage energy dependence. The experimental portion of the work consists of the irradiation of tensile test specimens and activation foils in various reactor spectra while keeping other experimental variables constant. GAML, ANSIN, and a modified SAND II code are then used to reduce the foil data and to unfold an experimental damage response function from the measured spectra and changes in tensile properties. Work has continued on the generation of analytical damage response functions for various defect models, and these are compared with the experimental data. While the results are not yet complete, it is hoped that they will permit a more accurate interpretation of engineering tests conducted in various test reactors and a more dependable extrapolation of test data to operating reactors where the neutron spectra may differ significantly.

A second project examined the role of impurity elements in the susceptibility of certain alloy steels to embrittlement by fast neutron damage. It seems evident from this work that certain impurities (such as phosphorus) which are dissolved in the alloy play a strong role whereas other impurities (such as sulfur) which are rejected from the alloy, but are still present as included phases, do not play a significant role. In a practical sense, the results indicate which impurities should be most closely controlled in casting steel ingots for nuclear pressure vessels.
In another area of current interest, we have investigated the possible simulation of high neutron fluxes. As nuclear reactors of very high fast neutron fluxes are developed ($10^{16}$ neutrons/cm$^2$ sec), we will need information about the behavior of structural materials under such intense neutron bombardment. Presently available testing reactors do not provide fluxes much above $10^{14}$ neutrons/cm$^2$ sec, but the effects of higher fluxes can be simulated by alternately irradiating specimens at very low temperatures, where incident damage will be "frozen in" then pulse heating the sample to permit partial relaxation of the damage, these cycles being repeated at short intervals during the course of the experiment.

The design of a satisfactory specimen holder, a sample heater, and ohmic contact for continued in-pile usage that can withstand hundreds of repeated heating-cooling cycles from 4.2°K to 270°K and the associated instrumentation necessary to provide controlled heating and cooling of the sample and continuous monitoring of resistance of the semiconductor sample are the accomplishments of a thesis completed by T.P. Hulick. For these experiments the sample was germanium, mounted on an insulating layer of quartz. The quartz was coated with a thin layer of tin oxide as a resistance heater. With suitable control instrumentation, it was possible to achieve transit times between liquid helium at 4.2°K and room temperature, 300°K, of a few hundred milliseconds. The apparatus is suitable for use in the in-core cryogenic facility of the MIT Reactor, and it should be quite feasible to simulate neutron fluxes of two or more orders of magnitude higher than the reactor provides.

Three groups at MIT have expressed interest in the use of the materials irradiation cryostat. Professors Ziebold
and Argon have initiated a program to study the neutron damage defect spectrum in structural metals. Professors Averbach and Kaplow will use the high neutron flux simulation method in a study of changes in the optical and electrical properties of amorphous or glassy semiconductors. Professor Kingery's program would examine damage induced at low temperatures during the irradiation of nonmetallic crystals such as sapphire and MgO.

**Personnel**

Professors:  
A.S. Argon (Mech. Eng.)  
B.L. Averbach (Metallurgy)  
R. Kaplow (Metallurgy)  
W.D. Kingery (Metallurgy)  
J.L. Smith, Jr. (Mech. Eng.)  
T.O. Ziebold

Students:  
T.P. Hulick ('69)  
G.R. Odette  
K. Ohmae

**Support**

Office of Naval Research, MIT General Funds

**Related Academic Subjects**

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.721J</td>
<td>Radiation Damage in Crystalline Solids</td>
</tr>
<tr>
<td>22.71</td>
<td>Metallurgy for Nuclear Engineers</td>
</tr>
<tr>
<td>22.72</td>
<td>Nuclear Fuels</td>
</tr>
</tbody>
</table>

**Cold Neutron Source**

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 demonstrated 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.

The information obtained from the first experiments was used to develop a 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. Some studies of materials and geometries for the first thermal column cryostat were carried out by use of a Monte Carlo computer code.

During FY 1969, design of the vacuum jacket and general handling system for the cryostat was completed, and fabrication was well along by the end of the year. Initial installation and testing were accomplished in FY 1970, and these indicate an enhancement of the cold neutron beam to about the value predicted. After a vacuum leak is repaired, the crystal will be re-installed in the thermal column and operated with liquid helium from the large-capacity helium refrigerator described in an earlier section.

The design of the thermal column cryostat has been made flexible so that experiments can be performed to develop
an optimum cold neutron source. The final design will be built and installed at the time that the MITR core is modified. MIT has provided an allocation from its Sloan Fund to build and install the present cryostat and to carry out the initial experiments with beams of very slow, cold neutrons from this facility.

Personnel
Professors: D.D. Lanning ('70)
N.T. Olson
T.J. Thompson ('69)
Research Associate: E.J. Barnett
Research Staff: D.A. Gwinn
Students: R. Chin ('70)
E. Heimberg ('69)
Y. Hukai ('70)
R. Sanders
J. Synan ('69)

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

Related Academic Subjects
8.541 Neutron Diffraction
22.42 Reactor and Neutron Physics Laboratory

1.8 Biomedical Applications

The Department of Nuclear Engineering is becoming increasingly interested in biomedical activities, partly resulting from the individual interest of faculty members and partly from the rapid increase in the field of nuclear medicine. Professors S. Yip and S.H. Chen, for example, are interested in the problem of atomic and molecular motions in material related to biological systems using the technique of inelastic neutron scattering.

The MIT Nuclear Research Reactor and other radiation sources provide excellent facilities for biomedical studies.
and application. These studies are carried out in cooperation with the Massachusetts General Hospital and other medical institutions in the Boston area under the general direction of Professor G.L. Brownell.

Studies on thermal neutron activation analysis have continued using a germanium solid-state detector. With this system up to 20 trace elements in biological samples can be measured without prior chemical processing. Studies are underway to determine the role of trace elements in the etiology of lung disease in man. Studies to determine the normal levels of trace elements in biological tissue are also progressing. A computer program is being prepared to automatically identify peaks in the germanium spectrum, correct for instrumental factors, and result in a table of values of trace element concentration.

Studies have commenced on the possible use of in-vivo activation analysis to determine chemical levels of substances within the body. The technique involves partial or whole-body irradiation with thermal or epithermal neutrons from the MIT Reactor to produce detectable radioisotope levels combined with subsequent measurement in a low-level counting system. Using this technique, the calcium content of the body or of a region of the body can be detected with an exposure dose of less than 1 rem. Studies included physical measurements of dose as well as observations of irradiated bone. The plan is to continue the studies with irradiations of small animals and man. This technique should be valuable in following changes in calcium content of bone during therapy for such bone diseases as osteoporosis.

The possible use of neutron capture therapy, a procedure involving administration of B-10 to a patient and subsequent irradiation with thermal neutrons from the MIT
Reactor, has been studied for some years in cooperation with the Neurosurgical Service of the Massachusetts General Hospital. Studies on the neutron spectrum and other physical aspects of this form of therapy have formed a continuing activity that will hopefully lead to renewed clinical trials of neutron capture therapy for brain tumors. Recent emphasis has been on studies of penetration of epithermal neutrons in tissue-equivalent materials and development of fast-neutron dosimetry using silicon semiconductors and tissue-equivalent ionization chambers.

**Personnel**

Professor: G.L. Brownell

Staff (Massachusetts General Hospital):

- Dr. K.M.M.S. Ayyangar ('69)
- Dr. D.M. Linekin
- Dr. H.D. Maccabee
- Dr. A.R. Reddy ('69)

Student: R. Wu

**Support**

U.S. National Institute of Health, AEC

**Related Academic Subjects**

- 22.81 Radiation and Radioisotope Application
- 22.82 Biological Effects of Nuclear Radiation
- 22.83 Physical Aspects of Nuclear Medicine

**1.9 Neutron Inelastic Scattering Spectrometer**

During the previous report period, an inelastic scattering spectrometer was 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 is by the Picatinny scientists. This brings to
six the number of neutron spectrometers currently operable on the MITR. A seventh is described in the next subsection.

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° 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 polytetrafluoroethylene (teflon) and completed early in 1969. Subsequent studies have included 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. Low temperature measurements on teflon and coherent scattering from sodium nitrate are currently underway.

Due to the recent closing down of the AMMRC Reactor at the Watertown Arsenal, the Picatinny spectrometry group there has been transferred to the National Bureau of Standards Reactor, Gaithersburg, Maryland. The remainder of the group and the above spectrometer will be transferred from MIT to NBS early in 1971.
Personnel
Design and Fabrication (MIT):

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Associate</td>
<td>E.J. Barnett</td>
</tr>
<tr>
<td>Shop Foreman</td>
<td>F.L. Woodworth</td>
</tr>
<tr>
<td>Machinists</td>
<td>F.L. Bingham, K.J. Butler, T.J. Green, J.E. Wasik</td>
</tr>
</tbody>
</table>

Operation and Research (Picatinny):

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physicist, Explosive Res. Lab.</td>
<td>H.J. Prask</td>
</tr>
<tr>
<td>Physicist, Explosive Res. Lab.</td>
<td>S.F. Trevino</td>
</tr>
<tr>
<td>Graduate Student, Boston College</td>
<td>V.E. LaGarde ('69)</td>
</tr>
<tr>
<td>Graduate Student, Boston College</td>
<td>R.D. Mical</td>
</tr>
<tr>
<td>NRC-FRL Research Associate</td>
<td>K.W. Logan ('70)</td>
</tr>
<tr>
<td>NRC-FRL Research Associate</td>
<td>J.D. Gault ('70)</td>
</tr>
<tr>
<td>Professor, Boston College</td>
<td>R.L. Becker ('70)</td>
</tr>
</tbody>
</table>

Support

U.S. Army

1.10 **Triple-Axis Spectrometer for Molecular Dynamics**

The Department of Nuclear Engineering has experimental programs underway on neutron inelastic scattering and laser light scattering, both of which are closely related to theoretical research projects within the Department. Low-energy inelastic neutron scattering can be used to measure the density fluctuations and correlations caused by atomic and molecular motions in solids and liquids.

A three-axis neutron spectrometer, fabricated in part by the MITR Machine Shop during the past year, is in the process of being installed at the 12" radial port. It will use one of the two collimators for which provisions were made in the port shield plug. Such a spectrometer is a very effective tool for investigating elementary excitations such
as phonons and magnons in solids. The immediate objective is to measure phonons in molecular crystals and alloys and also the critical scattering of neutrons from binary alloys and liquid metal mixtures.

Personnel

Professor: S.H. Chen
Research Staff: R.D. Mical ('70)
Students: S. Ayao ('70) I. Lefevre ('70)

Design and Fabrication:
Staff: E.J. Barnett V.E. LaGarde ('69) H. Massin ('69)
Students: M. Kazimi ('70)
Shop Foreman: F.L. Woodworth
Machinists: F.L. Bingham K.J. Butler T.J. Green J.E. Wasik

Support
USAEC, MIT Sloan Fund for Basic Research

Related Academic Subject:
8.541 Neutron Diffraction

1.11 Nitrogen-16 Loop

During the past two years, a small loop has been operated 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 hydrated zirconium or titanium oxide was an effective absorption agent for effecting substantial N-16 removal. It was also found that dissolved gases such as N₂, He, air
and H₂ had no effect on nitrogen chemistry at the low dose rates achievable in the facility. Various detectors were investigated including gamma scintillation, Cerenkov, N-17 neutron, and β particle, and the latter found to have the best combination of characteristics for the present application.

**Personnel**

Professor: M.J. Driscoll  
Students: S. Barnett ('70)  
F. Best  
E. Coppola ('69)  
R. Fay ('69)

**Support**

Sloan Basic Research Fund (MIT), General Funds (MIT)

**Related Academic Subjects**

- 22.29 Thermal Power Reactors  
- 22.31 Nuclear Chemical Engineering

**1.12 Proton Scattering to Measure Neutron Radiation Damage in Solids**

Another new technique for investigating radiation damage in solids is proton back scattering. When a monoenergetic, collimated beam of protons is scattered from a single crystal, the pattern of scattered protons is characteristic of the location of atoms in the crystal. By comparing the pattern of protons scattered before and after the crystal is irradiated with fast neutrons, it is possible to determine the density of interstitial atoms produced by neutron bombardment.

The scattering chamber, sample goniometer and proton detector have all been fabricated. Work is now proceeding with sample preparation, and measurements will soon be made on the 4 MeV Van de Graaff at Lincoln Laboratory. Fast neutron
radiation damage will be produced by irradiating the single crystals with fast neutrons in the MITR.

Personnel

Professors:  
N.T. Olson
T.O. Ziebold

Student:  
G. Marcus ('70)

Support

MIT Sloan Basic Research Funds

Related Academic Subject

22.721J  Radiation Damage in Crystalline Solids

1.13 MIT Reactor Core Modifications

In 1968, under the initial direction of Professor T.J. Thompson, engineering studies were initiated on modifications of the core of the MIT Reactor which would result in increasing the useful flux of thermal neutrons by a factor of three without increasing the power of the reactor above its present level of 5 megawatts. During the past year, this work has been carried forward under the direction of Professor D.D. Lanning. By the end of the report period, provisional design of the new core for the reactor was essentially completed and nearly ready to send to the Division of Reactor Licensing of the AEC for review and comment.

The proposed redesign makes use of all of the existing reactor components except the reactor tank, fuel elements, control rods and drives and top shield plugs. Parts of the present reactor to remain include the graphite reflector, thermal shield, biological shield, beam ports, heat exchangers, pumps, cooling towers, control and safety systems, containment and all building services.

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

Engineering studies and experiments on aspects of the new core have provided many opportunities for student research and participation and give unique practical training. Topics investigated by students include reactor physics calculations, neutron transport measurements in a mockup of the new beam port and reflector configuration, fluid flow measurements on a hydraulic mockup, heat transfer measurements on finned plates, safety analysis and fuel management studies. Equally valuable practical experience will be provided students during the construction, startup and checkout operation of the modified reactor.

Personnel

Professors:
J.W. Gosnell
D.D. Lanning ('70)
N.C. Rasmussen
T.J. Thompson ('69)

Staff:
E.J. Barnett
L. Clark, Jr.
K.D. Collins
D.A. Gwinn
A. Torri
Most Reactor Operations, Shop, and Maintenance Personnel shown in Tables V-la and V-lb
Students:
A. Addae
R. Chin ('70)
D. Choi ('70)
P. Furtado
E. Heimberg ('69)
Y. Hukai
A. Kadak ('70)
J. Kearney ('70)
D. Kennedy
I. Lefevre
B. Luxford ('70)
T. Rieck ('70)
R. Sanders
S. Seth
D. Spurgeon ('69)
J. Tuohy
D. Uhl ('69)
T. Yarman ('70)

Support
Reactor Depreciation Reserve Fund (MIT)

Related Academic Subjects
22.21 Nuclear Reactor Physics I
22.22 Nuclear Reactor Physics II
22.231 Nuclear Reactor Engineering
22.26 Nuclear Reactor Design
22.531T Numerical Methods of Reactor Analysis
22.54 Radiation Shielding
22.72J Nuclear Fuels

2. DEPARTMENT OF PHYSICS

A broad program of basic research in nuclear, neutron, and solid state 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 annular 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.

A number of cryostats, ovens, magnets and choppers are used in conjunction with the spectrometers. A superconducting magnet, built and tested during the past year, will be installed early in fiscal year 1971; it is capable of producing a 75,000 gauss field.

Areas of investigation during the past two fiscal years may be summarized briefly as follows. In several cases, they continue projects begun in prior years.

### 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-Gerlach 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

In passing through a magnetic field region of space, neutrons experience a magnetic refractive index which deviates from unit value in opposite direction for the two spin states. Thus a prism-shaped magnetic field region will spin-split an unpolarized neutron beam. This has been studied quantitatively using the spectrometer assembly of 2.1 above with a 60° prism-shaped magnetic field of 10,000 oersteds and good agreement is found with that calculated. With field distribution of cylindrical geometry a focussing action on a broad neutron beam is to be expected and this again was studied and compared quantitatively with what is calculated. Interestingly such a neutron magnetic-lens is also a polarizing agent, being diverging for one spin state and converging for the other spin state. With the field strength of 10,000 oersteds and the neutron wavelength of 2.4 Å used, the focal length was very long, about 1 kilometer! (Schneider, Just and Shull)
2.3 High Temperature Study of Iron Magnetic Scattering

The polarized neutron diffraction technique has been used to study the ferromagnetic scattering by iron crystals up to the Curie temperature of 770°C. A high temperature vacuum furnace with temperature control to 1°C was mounted in the vertical field magnet gap on the polarized beam spectrometer. Great care was taken to study extraneous effects that can enter into the measurements such as (a) the effect of simultaneous Bragg reflections, (b) the temperature dependence of extinction occurring in the specimen crystal and (c) the temperature dependence of neutron depolarization occurring within the crystal. Measurements on the (110) reflection, which is insensitive to changes in the spin density asymmetry, showed a temperature dependence slightly elevated above the accepted bulk magnetization. In contrast to this, previous Mossbauer measurements have fallen somewhat lower than the magnetization. This is not surprising since the three independent measurements reflect different quantities: neutron scattering senses the localized 3d electron magnetization, bulk magnetization corresponds to the total magnetization of all electron groups, and Mossbauer measurements correspond to the hyperfine field at the nuclear site produced by all electronic processes. Further measurements were performed on the (222) and (400) reflections which are very sensitive to changes in the spin density asymmetry around the nuclear site in the unit cell. These measurements indicated essentially no change in the asymmetry parameter as the temperature was elevated to $T_c$. (Maglic)

2.4 Neutron Diffraction by Crystals of InSb

Crystal slices of InSb have been examined in a double crystal spectrometer to study their intrinsic rocking curve
widths and the anomalous transmission that should occur when they are in Bragg reflection. Two matched slices with (220) planes in transmission exhibited a rocking curve width of 1.35 seconds of arc (full width half maximum intensity) for a neutron wavelength of 1.6 Å and this compares quite favorably with the calculated value of 1.18 seconds from Darwin width evaluation. Thus the crystal slices can be considered nearly perfect insofar as satisfying dynamical diffraction theory criteria. A double detecting system was arranged at the spectrometer so that the transmitted beam through the second crystal could be studied simultaneously with the Bragg beam. Traverses of the Bragg angle through the reflection showed the characteristic asymmetrical intensity distribution in the transmitted intensity with higher intensity on the smaller angle side and lower intensity on the larger angle side. Since InSb offers moderate absorption for neutrons, this demonstrates the modification of true absorption under near Bragg conditions as predicted by dynamical theory. The quantitative interpretation of the measurements is being pursued. (Just and Shull)

2.5 Single Slit Diffraction of Neutrons

The diffraction broadening of a neutron beam in passing through a fine slit has been studied at Brookhaven National Laboratory using a high angular resolution spectrometer. Long wavelength neutrons (4.4 Å) 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 gadolinium for high edge 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 dimension at least that of the largest slit opening used in the experiment. (Shull)

2.6 Neutron Diffraction by Perfect Crystals

Experiments were started at Brookhaven National Laboratory which were designed to test implications of dynamical diffraction theory (in which the intimate relationship between Bragg reflected and forward diffracted radiation within the perfect crystal volume is emphasized) for the neutron case. For silicon crystals, there is very small neutron absorption, in contrast to the x-ray case, and this permits novel testing of the theory. 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 became available from this first 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 can be used to determine with unusual precision these quantities. Further conclusions concerning the spatial longitudinal length of the neutron wave packet and the identification of the neutron wave front as being spherical or planar are also available from the experiments. These investigations are being continued actively at MIT. (Shull)

2.7 Studies of (222) Forbidden Reflections in Germanium and Silicon

This problem was directed at a quantitative determination of the (222) neutron structure factor, related to the Bragg
reflection intensity, in germanium and silicon at temperatures up to 500°C. This Bragg reflection is normally forbidden (zero intensity is expected) by the lattice symmetry, which is that of diamond. However, a number of x-ray diffraction investigations 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. Past experiments with neutrons have failed to detect any intensity at room temperature in spite of the fact that there are good arguments that model (2) should be a contributing factor. The present study was directed at improving the sensitivity of the neutron observations and elevating the crystal temperature thereby enhancing the magnitude of the effect. Perfect crystals of silicon and nearly perfect crystals of germanium were used in the study and great care was expended in removing contaminating intensity effects that can arise from higher-order wavelength components and from the presence of simultaneous reflection effects. The perfection of the crystals was studied by measuring the integrated intensity and the Darwin widths of normal Bragg reflections since this was necessary in the interpretation of the forbidden reflection intensity.

Again even at temperatures as high as 500°C the neutron experiments have failed to detect finite intensity and only an upper limit can be placed on the magnitude of the structure factor. This can be interpreted quantitatively using a formalism developed by Dawson in which each atom is considered to be an independent spherical harmonic oscillator slightly perturbed by small anharmonic potential terms. Thus
the potential $V(r)$ is taken as

$$V(r) = ar^2 + \beta xyz$$

and the anharmonic constant $\beta$ can be related to the forbidden reflection intensity. The present experiment determines $\beta$ to be smaller than $0.5 \cdot 10^{-11}$ ergs $\text{Å}^{-3}$ for silicon and $0.3 \cdot 10^{-11}$ ergs $\text{Å}^{-3}$ for germanium. These values are somewhat smaller than those expected by analogy with the values of fluorine and oxygen in CaF$_2$ and UO$_2$ determined by Dawson and Willis. In these fluorite type structures (similar to silicon and germanium) the $\alpha$ harmonic terms are quite similar to those in Si and Ge and it was thought that this would be reflected in similar $\beta$-terms. The present experimental upper limits on $\beta$ are also considerably smaller than those calculated using the Einstein model from experimental data of specific heat and thermal resistivity. This suggests the deficiency of the Einstein model in interpreting these results and further theoretical analysis is called for. (Nunes)

2.8 Study of the Kondo Effect in Cu-Fe Alloys

Polarized neutron diffraction studies are being carried out on dilute alloys of iron in copper. Attention has focused to date upon the composition 1000 parts per million Fe although other composition alloys have been prepared. For intensity reasons, the specimens must be in single crystal form and additionally they must be in random, homogeneous solution form as produced by high temperature homogenization followed by rapid quenching. It is thought that this alloy undergoes a Kondo transition at low temperature in which the atomic magnetic moment at Fe impurity sites becomes fully or
partially compensated by a cloud of conduction electrons with antiparallel spins. Through application of an external magnetic field to the crystal, polarized neutron scattering can identify the impurity atom moment and sense any modification of its alignment by the field as the temperature is changed through the Kondo temperature. Additionally if the spatial extent of the conduction electron cloud is not too large, the magnetic scattering form factor is expected to be modified. Extended neutron measurements have been made to date on the 1000 ppm crystal with 15 kOe of applied field with the following results.

a) The angular dependence of the magnetic scattering amplitude, measured at 4.22 K, was found to be of 3d character, implying that the effects measured in this experiment are solely due to the localized spin. The contribution of the localized spin to the susceptibility, determined by extrapolation to the forward direction, was found to be $2.4 \times 10^{-6}$ emu/gr at 4.22 K.

b) The temperature dependence of the magnetic scattering amplitude has been studied in the (111) reflection in the temperature region of 2-25 K. A gradual deviation from the free spin behavior with decreasing temperature has been observed providing further support for the smooth transition to a new state at low temperatures.

c) The localized susceptibility, determined by the neutron diffraction observations, was found to agree in absolute magnitude as well as in its temperature dependence with the total susceptibility measured by Professor Sellmyer on the same samples. This observation implies the absence of any large field induced polarization in the spin compensating conduction electron cloud.
d) The Kondo temperature of the system was found to be in the vicinity of 6°K corresponding to a localized spin fluctuation lifetime of $10^{-12}$ sec.

It should be mentioned that, because of the low concentration, the polarized neutron intensity effects are very small and long data collection periods are necessary. The largest value of the polarization ratio, intensity ratio upon neutron polarization inversion, differs from unity by only four parts in 10,000. The field dependence of the magnetic scattering amplitude will be investigated using a superconducting magnet. (Stassis)

2.9 Study of Pendellosung Fringe Structure in Bragg Reflections of Silicon Crystals

During the past period, one of the neutron diffraction spectrometers at MIT has been modified to permit further studies of the Pendellosung fringe structure in Bragg reflections first studied by the author a year ago at Brookhaven National Laboratory. In order to compensate for the large intensity difference between the HFBR and MITR reactors, the spectrometer is operated without a monochromating crystal and full spectrum reactor radiation is delivered through a long, narrow collimator (divergence about 3 minutes of arc) to the test crystal. The specimen crystal is in the form of a flat plate with diffracting planes perpendicular to the faces and is used in symmetrical Laue transmission. Radiation is passed into the crystal through a slit opening (0.005" generally) with tapered gadolinium edges for high slow neutron absorption. An equivalent slit opening is used on the exit face for scanning across the Bragg beam profile with its position controlled by micrometer motion. With the high collimation of the entrance beam, the perfect crystal is very selective in picking a wavelength band for Bragg
reflection. Judicious shielding is necessary between the crystal and detecting counter in discerning the Bragg reflected intensity from the flood of incoherent, white radiation being scattered by the crystal. With this system, it has been found possible to measure fringe characteristics just as before although the intensity is fairly low.

The experiments performed to date have again been with Si in (111) reflection but with significant improvements in the physical characteristics of the crystal. In order to interpret the fringe structure with high precision, it is necessary that the crystal faces be very flat and parallel and without mosaic structure. This has been accomplished using a chemical polishing technique employed in Professor Witt's laboratory. The Pendellosung fringe structure arises from interference action within the crystal of coherently split beams and their path length within the crystal must be carefully controlled. Fringe patterns have been measured for three specimen crystals of different thickness ranging up to 1 cm over the full spectrum from 0.6 to 1.6 Å in contrast to the 1.0-1.2 Å range originally studied. A preliminary study of the shift in fringe location with displacement of the exit slit opening from its normally centered position has shown without ambiguity that the neutron waves passing through the crystal are characterized by a spherical wave front rather than by a plane wave front as assumed in the original Pendellosung fringe investigation. Theory predicts a small difference in the fringe characteristics for the two cases. Very excellent consistency among five independent fringe scans has been obtained when allowance is made for the presence of a small elastic curvature existing in the crystal specimens as caused by the method of mounting the crystals. It appears from these observations
that the crystal structure factor, or the silicon coherent scattering amplitude, can be determined to a precision better than one part in 5,000. (Shull and Oberteuffer)

2.10 Testing of Neutron Velocity Selector

A mechanical velocity selector has been constructed and tested in the laboratory for later use as a neutron energy filter or as a low resolution spectrometer. It consists of 200 side-by-side passage channels which are twisted in helical fashion about the axis of a cylindrical rotor. The present system of channels are designed for relatively low resolution (30%) and high transmission (70%) operation. Extended tests of its performance and characteristics have now been carried out with monoenergetic beams of neutrons over the wavelength range 3-8 Å and these measurements agree well with those expected from the design characteristics. (DeLatour)

Personnel

Professor: C.G. Shull
Staff: W. Just
J. Oberteuffer ('70)
Graduate Students: C. DeLatour ('70)
D. Frank ('70)
R. Maglic
A. Nunes
C. Schneider
C. Stassis

Technician: 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 AND MATERIALS SCIENCE

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

Spin correlations have been observed in the antiferromagnetic materials MnO, NiO and CoO by means of magnetic neutron scattering. The objectives were somewhat different for each material, because of differences in characteristics of the magnetic ordering, but a coherent picture of the spin correlations in these antiferromagnetic materials has emerged from these studies.

3.1 MnO

This material has been investigated by Mr. Morash, who has observed the distribution of twin domains and the long range spin order at temperatures below the critical \((T_N = 122^\circ\text{K})\). He also made some preliminary measurements of the short range spin order above \(T_N\). He observed that twins occurred with equal probability along any of the four \(\langle111\rangle\) directions. The magnetic ordering produced considerable crystallographic deformation, and this caused a substantial bending of the crystallographic planes at the twin wall. This wall bending caused multiple peaks in the neutron diffraction patterns. The multiple peaks gradually disappeared as the temperature was increased toward the Neel temperature. The application of an external stress along the \([111]\) direction caused an 80% increase in the volume of the twin domains along this direction. The application of such a stress, however, did not alter either the long range or short range spin order.
Preliminary measurements of the short range order above the Neel temperature showed that there were significant correlations out to the 26-th nearest neighbor, a distance of about 16A. The local spin correlation is essentially anti-parallel for second, sixth and 10-th nearest-neighbors. The correlation for the odd shells was close to zero. This indicated that the local spin order is essentially very similar to the long range order arrangement. The interaction energies were calculated by combining the long range order and short range order data, and it was shown that the exchange parameter, $J_2/k = -3^\circ$, with $J_1/k \approx 0$. These data indicate that the next nearest neighbor exchange is predominant. (Morash and Averbach)

3.2 NiO

The antiferromagnetic ordering of single crystals of NiO was examined by Mr. Shemenski. The antiferromagnetic ordering below the Neel temperature ($T_N = 523^\circ K$), was quite similar to that observed for MnO. However, the domain arrangement was extraordinarily sensitive to stress. Finger pressure was sufficient to cause a substantial change in the domain arrangement. The relative domain population changed on heating and cooling, and on handling. The size of the magnetic domains was estimated from the scattering contours. The mean domain size was approximately 500 A just below the Neel temperature, about 80 A at a temperature $8^\circ$ above $T_N$, and 40 A at $50^\circ$ above the Neel temperature. (Shemenski and Averbach)

3.3 CoO

The spin correlation in CoO is being investigated by Mr. Rechtin. This research is still in process, but it is expected that the thesis will be finished by the end of the
contract year. CoO is different in that the contraction axis on magnetic ordering is along <100> directions, whereas the contraction axes in MnO and NiO are along <111> axis. CoO is also different in that the magnetic data suggest that there is considerable spin-orbit coupling in this material.

We have obtained quite accurate data on the long range order and on the critical scattering in the vicinity of the Neel temperature (291°K). The data are good enough to provide a sensitive test of several models of magnetic critical phenomena. It is quite clear that the Ising model will not work, and several of the more elaborate theories are now being tested. We have also obtained a three-dimensional picture of the diffuse scattering just above the Neel temperature. This has enabled us to evaluate the short range order coefficients to the 50-th nearest neighbor. In addition, we have been able to evaluate the nearest neighbor and second neighbor exchange in a preliminary fashion. It appears that $J_1/k = 5^\circ$ and $J_2/k = -20^\circ$. We believe that this is the first unambiguous determination of the exchange integrals in an antiferromagnetic material. Other measurements have been inferred indirectly. Furthermore, it is quite possible that a further analysis of the data will permit an evaluation of the higher order exchange and an evaluation of the magnetic potential function. (Rechtin and Averbach)

**Personnel**

Professor: B.L. Averbach

Students: K. Morash, M.D. Rechtin, R. Shemenski

**Support**

NSF

**Related Academic Subject**

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. 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.

4.1 Radioactive Decay and Nuclear Structure Studies

Prior to the introduction of Ge(Li) and Si(Li) detectors, the relationship between theory and experiment for radioactive decay and nuclear structure was poor. Not enough reliable data existed to allow much discrimination among a number of widely varying theoretical approaches. The initial experimental results gave indications of which theories were useful and which were not and, at the same time, revealed a multitude of new structural and decay characteristics for which no theoretical understanding existed. Now, a number of features of radioactive decay and nuclear structure have
been observed such as three-quasiparticle ladders, three- and four-phonon multiplets, strong neutron-proton interaction, phonon-hindered allowed $\beta$ decay, $0^+$ members of the second phonon multiplet, low-lying three quasiparticle $j-1$ systematics, absence of the predicted (by some theories) low-lying $5/2^+$ level in $Z = 31$ and 35 nuclides, and apparent diminished $g_{9/2} - g_{7/2}$ separation near $Z = 50$.

Summaries of the studies in progress during the past year are given below.

A. Decay of 4.2-d $^{124}$I, 60-d $^{124}$gSb and 1.2-min $^{124}$mSb to the Levels of $^{124}$Te

Studies of the levels of even-even nuclides populated by the decay of odd-odd parents are centered on nuclides near closed neutron and proton shells. The substantial advances that have been made in the theoretical understanding of closed shell nuclides have encouraged us to try to understand the decay to and structure of nuclides removed by two and four particles from closed shells. These studies of decay to $^{124}$Te were completed this year and have revealed the presence of 28 levels in $^{124}$Te below 3.1 MeV. Outstanding features observed include an apparent well organized set of vibrational levels up to 4-phonon multiplicity, a set of 2-proton quasiparticle levels near 1.8 MeV, a set of two-phonon levels with octupole-quadrupole character, and strongly hindered $\beta$ decay from 3- $^{124}$gSb contrasted to very rapid $\beta$ decay from 3+ $^{124}$mSb. (R.C. Ragaini, W.B. Walters in conjunction with R.A. Meyer of LRL, Livermore, Calif.).

B. Levels in $^{130}$Xe Populated from $^{130}$I, $^{130}$mI and $^{130}$Cs

We have decided to resume our studies of these decays in order to obtain better energies and intensities of these
lines and widen our investigation to include $^{130m}$I, as the gamma rays accompanying the decay of $^{130m}$I have not been previously reported. The 9-minute isomeric state can be reached by $^{129}$I (n,γ)$^{130m}$I with a cross-section of 19 barns. Thus we hope to determine the levels populated by these three different spin states: $^{130}$Cs(1+), $^{130m}$I(2+), and $^{130g}$I(5+). We are also interested in further characterizing the β decay properties of the $^{130g}$I. Several studies have proposed a negative parity assignment for this state although the reported log ft values of 5.7 and 5.8 to $5^+$ and $6^+$ levels in $^{130}$Xe suggest a positive parity. (P.K. Hopke, A.G. Jones, and W.B. Walters)

C. Radioactive Decay Studies of the Levels of $^{67}$Ga, $^{69}$Ga, and $^{71}$Ga

We have completed the studies of the radioactive decay of 19-min $^{67}$Ge to levels of $^{67}$Ga; 39-h $^{69}$Ge, 56-min $^{69g}$Zn, and 14-h $^{69m}$Zn to levels of $^{69}$Ga; and 2.4-min $^{71g}$Zn and 3.9-h $^{71m}$Zn to levels of $^{71}$Ga. Combined with the data from nuclear reaction studies, an excellent systematic description is obtained for the levels in $^{67}$Ga, $^{69}$Ga, and $^{71}$Ga below 2 MeV. We have found hitherto unknown β decay for $^{69m}$Zn, shown the presence of a number of hindered allowed β transitions, clearly established a 9/2+ level at 1494 keV in $^{71}$Ga, and obtained evidence for 1/2- spin and parity assignments for $^{67}$Ge. Our systematic data have shown the existence of a subshell closure at N = 38 and established a sharp drop in the 9/2+ level in $^{71}$Ga relative to the lower mass Ga isotopes. In making these studies we have developed and utilized Ge(Li) - Ge(Li) 4096- x 4096-channel coincidence spectroscopy on a highly quantitative basis. Our results have shown that the number of levels below 2 MeV in the three nuclides is consistent
with the pairing plus quadrupole theory. The results are also partially in agreement with Coriolos-coupling calculations suggesting deformed nuclear structure. 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. (W.H. Zoller, G.E. Gordon and W.B. Walters)

D. Decay of $^{95m}$Nb

Previous studies of $^{95m}$Nb have indicated that it decays entirely to the ground state by a 235.6-keV M4 isomeric transition. This isomeric state has a half-life of $86.6 \pm 0.8$ h and is assigned a spin and parity of $1/2^-$. There exists in $^{95}$Mo a level at 204 keV with a spin and parity of $3/2^+$. Thus a weak first-forbidden $\beta$ transition may compete with the isomeric transition. A careful search of the gamma-ray spectrum of an equilibrium source of $^{95}$Zr-$^{95m}$Nb-$^{95}$Nb using the Compton suppression spectrometer shows a weak peak at 204 keV. This transition indicates a $(1.6 \pm 0.6)\%$ $\beta$ branch from the isomeric state with a log $f_t$ of approximately 9. Upper limits of 0.2% are set for $\beta$ decay to other $^{95}$Mo levels below 1 MeV. (P.K. Hopke and H.N. Erten)

E. The Decay of $^{97}$Ru

The levels of $^{97}$Tc are being investigated by studying the gamma rays emitted following the decay of 2.8-day $^{97}$Ru, using a 26 cc Ge(Li) detector, the Compton suppressor and the Ge-LEPS (low-energy photon spectrometer). In particular, the nature of the 833-keV transition is being studied as this is unplaced in a decay scheme recently published by
Graeffe (Nucl. Phys. 127A, 65, 1969). Higher activities are now being obtained with long alpha-particle bombardments of enriched molybdenum targets in the MIT cyclotron, in order to identify certain very weak lines observed in the singles spectrum of the reactor-produced ruthenium samples and using the higher-efficiency 45 cc Ge(Li) detector. Ge-Ge coincidence experiments using the 26- and 45-cc detectors are also being undertaken. (P.K. Hopke and A.G. Jones)

F. **γ-γ Directional Angular Correlations of 9.6-d **125gSn

To provide a detailed description of the levels of 125 Sb, the decay scheme of 9.6-d 125gSn decay has been re-investigated and γ-γ directional angular correlations have been carried out. (E.S. Macias and W.B. Walters)

G. **Angular Correlations of 129mTe and 131gTe**

Studies of the γ-γ directional angular correlations following the β decay of 34-d 129mTe and 25-min 131gTe are continuing. Previously unreported γ rays in the decay scheme of 131gTe have been seen at 109.2, 221, 298, 353, 402, 420, 551, 568.4, 801, 804, 854.4, 1038, 1197, 1277.2, 1427.4, 1501.1, 1528.4, 1580.2. New levels fed in β-decay of 131gTe have been seen at 1298, 1347.0, 1678.4, 1730.2 keV. These may correspond to the levels reported at 1296 (ℓ = 2), 1345 (ℓ = 0), 1672, 1718 (ℓ = 0) keV seen in the 130 Te(3He,d)131 I reaction (R.L. Auble, J.B. Ball and C.B. Fulmer, Phys. Rev. 169, 1968). (E.S. Macias and W.B. Walters)

H. **Decay of 6.7 h **135I to Levels of 135Xe

The investigation of the decay of 6.7-h 135I has been completed and a paper has been submitted to Nuclear Physics. The following is the abstract from that paper:
The levels of $^{135}$Xe have been investigated by studying the $\beta$ and $\gamma$ rays from 6.7-h $^{135}$I produced in thermal-neutron fission of $^{235}$U. A decay scheme has been constructed consisting of 27 levels and fitting 63 of the 66 $\gamma$ rays attributed to 6.7-h $^{135}$I. The levels are compared with the results of nuclear reaction studies and with the levels of other odd mass Xe isotopes.

To better understand the structure of this complex nucleus we are now carrying out $\gamma$-$\gamma$ angular correlations. These experiments will allow us to determine the spins of many of the upper levels. (E.S. Macias- J.P. Op de Beeck, W.B. Walters).

I. Decay Schemes of 9.4-h $^{127}$gTe and 109-d $^{127}$mTe

The following is the abstract of an article to be submitted to Nuclear Physics:

Gamma rays emitted in the secular equilibrium decay of 109-d $^{127}$mTe and 9.4-h $^{127}$gTe and the $^{127}$gTe decay have been investigated using high resolution Ge(Li) detectors. In the secular equilibrium beta decay, five new $\gamma$ rays have been observed whose energies are: 172.1, 375.0, 618.6, 628.6, and 651.0 keV. New levels of $^{127}$I observed in beta decay of $^{127}$gTe are at 375.0 keV, and 618.6 keV, and 628.6 keV is the energy of a new level observed in $^{127}$mTe decay. Comparative gamma and beta counting of equilibrium $^{127}$Te sources with a low-background, gas-flow $2\pi$ proportional counter and Ge(Li) detectors established absolute values for beta intensities to levels of $^{127}$I. The I.T. branching of $^{127}$mTe was found to be 97.6% and ground-to-ground beta branching 98.8%. Log ft calculations disclosed severely hindered allowed $\beta$ transitions which reflect dissimilarities in parent and daughter state wave functions.
Hindered first-forbidden $\beta$ transitions were also observed, and similarities between the $\gamma$-ray decay patterns of $^{127}\text{I}$ and $^{129}\text{I}$ were noted. (K.E. Apt, W.B. Walters, and G.E. Gordon)

J. $^{127}\text{Sn}$ Decay

Investigation of the decay of 2.2-h $^{127}\text{Sn}$, extracted from fission products, to levels of $^{127}\text{Sb}$ is continuing. Gamma-ray spectra have been observed with large high-resolution Ge(Li) detectors and with a high-resolution Ge(Li) LEPS. We have tabulated the 70 $\gamma$ rays thus far attributed to the decay of $^{127}\text{gSn}$ observed from the Sn fission-product samples whose half-lives are within about 15% of 2.2 h. Coincidence studies have begun for this nucleus. Preliminary results of NaI(Tl)-Ge(Li) coincidence and Ge(Li)-Ge(Li) coincidence data are now being analyzed. (K.E. Apt and W.B. Walters)

K. Decay of $^{117}\text{In}$ Isomers

Using more sensitive detectors, another search has been made for a low-lying $9/2^-$ level in $^{117}\text{Sn}$ fed by the decay of $9/2^+ {^{117}\text{gIn}}$. Using the Compton-suppression system, the Ge(Li)-NaI(Tl) coincidence system, and the low-energy photon spectrometer, no $\gamma$ rays were observed which could be attributed to the depopulation of any low-lying $9/2^-$ level. The weak $\gamma$ ray at 861.6 keV was observed in coincidence with the 158- keV $\gamma$ ray, but no coincidences were observed with the 396.6-keV $\gamma$ ray.

The failure to find any evidence for a low-lying $9/2^-$ state is in sharp contrast to the structure observed in isotonic $^{115}\text{Cd}$ (C.D. Coryell and D.H. Hnatowich, LNS-MIT Chemistry Progress Report, 1967, p. 5) or in $^{113}\text{Cd}$ and $^{127}\text{Te}$, suggests that core participation is an important factor in the understanding of the nature of the three quasiparticle levels. (A.O. Pakkanen and W.B. Walters)
L. Decay of $^{117}$Cd Isomers to Levels of $^{117}$In

We are investigating the decay of 2.4-h $^{117m}$Cd and 3.4-h $^{117m}$Cd to levels of $^{117}$In using large-volume high-resolution Ge(Li) detectors and coincidence techniques. The level structure of $^{117}$In has taken a place of special interest as a consequence of the proposed rotational levels observed in $^{115}$In. By preparing sources both by $^{116}$Cd(n,$\gamma$) $^{117}$Cd and $^{116}$Cd(d,p) $^{117}$Cd reactions, sources richer in the low-spin and high-spin isomer respectively may be prepared. (R. Eng, A. Pakkanen, and C.D. Coryell)

M. The Decay of 3.8-min $^{134m}$I

The study of the 3.8-min isomer reported in the Chemistry Progress Report 1968, MIT 095-133, p. 14, was continued. Taking the 273-keV $\gamma$ ray as the time setting isomeric transition, the process is E3 with nearly the same hindrance as that of 2.90-h $^{134m}$Cs. We and H. Griffin (University of Michigan, private communication) have observed a 44.4-keV $\gamma$ ray with the same half-life as that of the 273 keV. Also, the relative intensities are consistent with an assignment of M1 for the 44.4 keV transition and E3 for the 273 keV transition. A tentative decay scheme has been proposed. (H.N. Erten, W.B. Walters and C.D. Coryell)

N. $^{136m}$I

The $\gamma$-ray spectrum of I samples rapidly separated from fission products has been studied. Three different intense short-lived activities were observed. A species with a 3.8-min half-life was characterized as an isomer of 53-min $^{134}$I. A number of $\gamma$ rays belonging to 83-sec $^{136}$I were observed. Another species was observed which decays with 45-sec half-life by emission of the following $\gamma$ rays (relative intensities in parenthesis): 198(25.2), 220(0.7), 114
345(1.0), 370(5.8), 383(34), and 1313(33.3) keV. These and other findings characterize the 45-sec species as an isomer of $^{136}$I. Lundan and Siivola (Annales Academiae Scientiarum Fennicae A VI 1968, 287, also private communication) also observed the 45-sec species and assigned it as $^{136m}$I. However, we are unable to confirm portions of their proposed decay scheme and are continuing our search for the one or more $\gamma$ rays needed to get down to the 1313-KeV level of $^{136}$Xe. (H.N. Erten, P.K. Hopke, W.B. Walters, and C.D. Coryell)

0. **Half-Life and Decay of $^{144m}$Pr**

We have completed our study of the decay of $^{144m}$Pr and determined its half-life to be 7.2 min. This half-life is indicative of a substantially hindered M3 transition and reflects the complex character of both the 0- ground state and 3- isomer. We also obtained evidence for a weak $\beta$ branch to the 3- state in $^{144}$Nd. A report of this work is scheduled to appear in the March 1970 issue of Physical Review C. (J.L. Fasching, C.D. Coryell, and W.B. Walters)

4.2 **Nuclear Fission Studies**

Efforts to obtain a better understanding of the fission process have been concentrated on three aspects: study of gross mass-yield relationships utilizing direct $\gamma$-ray counting, study of the detailed fractional independent chain yields of the thermal-neutron fission of $^{235}$U, and characterization of isomers formed in fission and measurement of the associated isomer ratios. From the study of the mass-yield curve of $^{229}$Th (the lightest nuclide which undergoes thermal neutron fission) we hope to better understand the transition region between asymmetric fission observed for $A \approx 225$ and symmetric fission observed for excited nuclides with $A \approx 233$. From the measurement of the isomeric ratios
of nuclides formed directly in fission, we are able to further understand the role of angular momentum in fission. The information about the fractional independent chain yields and the resultant \( Z_p \) values are important in view of recently proposed sizeable variations with mass in the shape of the fission yield curve for a mass chain. (A.A. Delucchi, A.E. Greendale, P.O. Strom, Phys. Rev. 173, 1159, 1968).

A. Mass Yields from Fission of \( {^{229}}\text{Th} \) and \( {^{233}}\text{U} \) with Thermal Neutrons

These fission studies were continued through 1969 (see M. Kay, G.E. Gordon and J.W. Harvey, LNS Chemistry Progress Report, December 1968, p. 17). The 26 cm\(^3\) and 45 cm\(^3\) Ge(Li) \( \gamma \)-ray spectrometers, acquired by the group, with their higher efficiencies have extended yield measurements to \( \gamma \)-rays in the 1-2 MeV range. The compilation of accurate \( \gamma \)-ray energies and intensities needed to utilize the advantages of these detectors have continued; it covers fission products having cumulative yields \( \sim 1\% \), major activation impurities (e.g. \( {^{24}}\text{Na} \), \( {^{56}}\text{Mn} \) and \( {^{40}}\text{Ar} \)), and natural decay species present in the samples. Data are available for most species with half-lives \( \sim 20 \) min; however, there are still some major exceptions (\( {^{84}}\text{Br} \), \( {^{92}}\text{Sr} \), \( {^{94}}\text{Y} \), \( {^{101}}\text{Mo} \), \( {^{138}}\text{Cs} \), and \( {^{142}}\text{La} \)) for which better data are needed. This compilation will be completed with a December 1969 cut-off for the literature search. Thin source targets of \( {^{229}}\text{Th} \) and \( {^{233}}\text{U} \) were irradiated. Final normalized yields for \( {^{229}}\text{Th} \) have been determined as this phase of the study nears completion. The \( {^{233}}\text{U} \) data have been analyzed, and attempts are currently being made to determine yields for mass chains not measured in a recent study published by the Idaho Nuclear Group (IN-1277, March 1969). Preliminary results indicate highly asymmetric fission
with the light peak centered about $A \approx 88$, the heavy peak centered about $A \approx 140$, and a value of $\bar{v} > 2$. The peaks are very narrow (FWHM $\approx 11$ mass units) and show fine structure around masses 85, 134 and 138. These results are in general agreement with the radiochemical work of Borisova et al. (Yadern Fiz 8, 695, 1968). (M.A. Kay and G.E. Gordon).

B. The Fractional Independent Chain Yield of 284-d $^{144}$Ce

The investigation of the fractional independent chain yields ($f_i$) of the Ce isotopes by timed extraction of fission cerium from short thermal-neutron irradiations of $^{235}$U has continued (J.L. Fasching and C.D. Coryell, MIT-LNS Chem. Prog. Reports, December 1966, p. 24; December 1967, p. 21; December 1968, p. 19; J.L. Fasching, S.M. Thesis in Chem. MIT, Aug. 1967). In one set of experiments, a half-life of $41 \pm 8$ sec for $^{144}$La was determined. On a plot of the data, zero time intercepts (counts at the end of irradiation) relate to the fractional cumulative chain yield of $^{144}$La and the fractional independent chain yield ($f_i$) of $^{144}$Ce. Assuming a value of 0.9 for $C$ in $f_i = 1/\pi \exp (Z-Z_p)^2/C$, an upper limit for $f_i$ for $^{144}$Ce has a value of $\leq 0.023$ with the most probable charge ($Z_p$) for mass chain 144 as $56.25 \pm 0.05$. (J.L. Fasching and C.D. Coryell)

C. The Fission Yields of 3-min $^{145}$Ce and 14-min $^{146}$Ce

Data obtained with the use of the above-mentioned procedure for $^{145}$Ce and $^{146}$Ce will allow the same type of yield determinations. The complete analysis of all the data is still in process, and initial results were too scattered to allow any yield determinations. (J.L. Fasching and C.D. Coryell)
D. Isomer Ratios for Fission-Product $^{134}$I and $^{136}$I Isomer

As a part of our recent discovery and study of isomerism in $^{134}$I and $^{136}$I, we are measuring the isomer ratios for these nuclides in the $^{235}$U(n,f) reaction. Preliminary values of 1.57 and 1.49 respectively are consistent with the studies of Sarantites, Gordon, and Coryell (Phys. Rev. 138, B353, 1965) on the isomer ratios for $^{131}$Te and $^{133}$Te produced in fission. (H.N. Erten and C.D. Coryell)

4.3 Physico-Chemical Studies

In this section are reported the results of our efforts in several areas in which the atomic and molecular structure or the chemical properties of the systems under study were of primary interest. These studies include investigations of the effects (or lack of effects) of physical and chemical state on $\beta$ decay rates and determinations of the behavior of various ions in solvent extraction from molten salts and in ion exchange with molten salts.

A. Effects of Physical and Chemical State on Nuclear Decay Rates

We have continued our investigation of possible physical state effects on the $\beta$ decay half-life of $^{131}$I. Reports by Bergamini et al (Phys. Rev. Lett. 18, 468, 1967) and Kemeny (Rev. Roum. Phys. 13, 485, 1968) that $^{131}$I$^-$ ion in solution has a different half-life than $^{131}$I$^-$ in crystalline form have been shown to result from a misinterpretation of the data. We have observed apparent differences under conditions which permit detection of the conversion electrons and x-rays from the internal transition decay of daughter 12-d $^{131}$mXe. In samples in which the $^{131}$mXe can escape from the sample or in which only radiations with energies greater than those of
the decay of $^{131m}$Xe are counted a half-life of 7.94 ± 0.10 days has been determined for $^{131}$I. In samples in which the radiations of $^{131m}$Xe are detected, half-life values of up to 8.12 ± 0.1 days have been determined. Kemeny has recently reported (Rev. Roum. Phys. 13, 901, 1968) variations in the half-life of $^{64}$Cu which depend upon the chemical valence of the Cu sample. As part of $^{64}$Cu decay is by electron capture, some small valence effects might be expected but they would be several orders of magnitude smaller than those reported. We are currently attempting to determine whether the data of Kemeny are correct, in error, or misinterpreted. (W.H. Zoller, P.K. Hopke and W.B. Walters)

B. Solvent Extraction from Molten Salts

The following is an abstract of the PhD thesis submitted by Z. C-H. Tan:

The distribution of perrhenate, chloride, AgCl$_2^-$ and Ag(I)-NO$_3^-$ complexes between a eutectic molten salt mixture of LiNO$_3$-KNO$_3$ and a solution of tetraoctylphosphonium nitrate (TOPN) in a polyphenyl solvent was studied at 150°C. The distribution coefficients of perrhenate and of chloride with TOPN are comparable to those obtained by Gal, Mendez, and Irvine with tetraheptylammonium nitrate (THAN), while the distribution coefficients of AgCl$_2^-$ and Ag(I$^-$)-NO$_3^-$ complexes is very efficient with TOPN (e.g. D = 1950 with 0.1 m TOPN). Distribution coefficients using 1-nitronaphthalene as organic solvent are somewhat higher for ReO$_4^-$ both with the phosphonium salt and with the ammonium salt. The TOPN has greater thermal stability than THAN.

The distribution of the anions has been interpreted in terms of a simple anion exchange equilibrium followed by polymerization of the species in the organic phase.
The equilibrium constants for the anion exchange and the dimerization constants were calculated. The dependence of the perrhenate distribution on the temperature and solute concentration was studied with both polyphenyl and 1-nitro-naphthalene as solvent.

Formation constants of AgCl and AgCl\(_2^-\) species in the nitrate melt were calculated \((K_1 = 300 \pm 20, K_2 = 117 \pm 10, \text{molality scale})\). These values are in good agreement with values previously obtained from solvent extraction, solubility, and electromotive force measurements. (Z. C-H. Tan and J.W. Irvine, Jr.)

C. The Ion Exchange Between Zeolite X and A and Neodymium Solutions in a Molten (Na,K)NO\(_3\) Eutectic

The composition of the anhydrous synthetic zeolite X, as given by the formula of the unit cell, is \(\text{Na}_{85} \text{[AlO}_2\text{]}_{85} \text{[SiO}_2\text{]}_{107}\) which is also taken as one mole of exchanger (Breck, D.W., J. Chem. Educ. 41, 678, 1964). The rather high distribution, from relatively concentrated solutions of neodymium in (Na,K) NO\(_3\) eutectic is remarkable. More so is the very high loading of neodymium in the zeolite and, assuming that no occlusion of neodymium nitrate occurred, this corresponds to an exchange of 63 alkali metal ions. Judging from the exchange isotherm, higher loading can be expected.

Exploratory experiments with zeolite A showed that this zeolite may be also a very interesting exchanger, especially for very dilute neodymium solutions. Indeed with solutions 0.09 and 0.6 molal in neodymium a very high loading of 3.0 - 3.5 mole Nd/mole anhydrous zeolite was obtained, which corresponds to an exchange of 9 - 10.5 mole of alkaline ions, again assuming that no occlusion of neodymium nitrate occurred.

The results obtained so far with neodymium shows that in molten salt media zeolites are indeed versatile exchangers,
even for the higher charged cations, and this suggests their use in the study of the chemistry of the lanthanide or perhaps even the actinides in pure ionic media.

4.4 Earth and Environmental Sciences

Increasing concern about the deterioration of our environment has been accompanied by an increasing awareness of the lack of reliable information about the current state of our surroundings or about its state in "the good old days". Instrumental neutron activation analysis (INAA), already shown to be a powerful tool in geochemical research (G. Gordon et al. Geochim. Cosmochim. Acta 32, 369 1968), contains the potential to be an equally powerful tool in the characterization of our environment, present and past. To that end we report in this section the results of our efforts to extend the utilization of INAA techniques to environmental sciences.

A. Instrumental Neutron Activation Analysis of Atmospheric Pollution Utilizing Ge(Li) γ-ray Detectors

The technique of Instrumental Neutron Activation Analysis (INAA) is being applied to the problem of air pollution. It is possible to determine up to about 20 elements, whose irradiated products have half-lives in the range from a few minutes up to several years, in any particular sample. The method is convenient and, for those products with half-lives in the range of a few minutes, very quick. The sensitivity of the method exceeds the method of emission spectrography used by the National Air Sampling Network. Other advantages are that the method involves little risk of contamination of samples and that it is non-destructive in the sense that samples are available for subsequent analysis by other techniques. A report of the above study is now in press with Analytical Chemistry. (G.E. Gordon and W.H. Zoller)
B. Air Pollutants in Boston

We have extended our general research on air pollutants in the Boston area to the possible sources of these pollutants. We have found that Boston ranks second only to New York City in the nation for vanadium content of the air, higher than any of the federal or state measurements have shown. The technique of Instrumental Neutron Activation Analysis (INAA) has been used to analyze heavy fuel oils, ash, and other materials for those elements that are observed in Boston atmospheric particulate matter.

The very large concentration of vanadium in the air is likely due to combustion of heavy fuel oils (containing 100 - 2000 ppm of vanadium) in power plants and large buildings in and around the Boston area. The high concentration of bromine previously observed is probably due to automobile exhaust. Although the combustion of ethyl fluid (tetraethyl lead and chloro-bromo ethane) in automobile engines accounts for almost all of the observed bromine, the chlorine observed is still largely from the marine environment in the Boston area. The aluminum observed in the aerosols is far too abundant to be caused solely by dust in the form of aluminum silicates and is definitely a pollutant whose source is not as yet determined. Some of the aluminum, however, does come from the heavy fuel oils, auto tires, and the burning of coal in homes of the region. As for the other elements measured, no distinct sources have yet been located.


C. Vanadium, Copper, and Aluminum in the Lower Atmosphere Between California and Hawaii

The following is the abstract of a paper appearing in Environmental Science and Technology 3, 1207 (1969):
Atmospheric particulate samples were collected from a 20-meter-high tower on the windward coast of the island of Hawaii and from a ship between California and Hawaii. The samples were analyzed for Na by flame photometry, and for V, Cu, and Al by thermal neutron activation. The Na/Cu, Na/V, and Na/Al ratios for seawater were considerably greater than those for the particulate matter, indicating a non-marine source for Cu, V, and Al. Elemental ratios suggest that Al and V probably come from the weathering of continental crustal material. The source of the high Cu concentrations is unknown, although contributions from man-made pollution on the west coast of North America is a possibility. (C.L. Hoffman, W.H. Zoller and R.A. Duce)

D. Gaseous Halogens and Trace Metals in the Boston Atmosphere

Pb and Al concentrations seem to vary rather regularly with each other which is not the case for either of these two metals with vanadium. The source of vanadium is almost entirely from the combustion of heavy fuel oils in power plants, whereas the lead is from the combustion of ethyl fluid in internal combustion engines.

The concentration of the gaseous halogens has never been reported before and has always been assumed to be relatively high. For example, the commonly used value for the concentration of gaseous iodine is approximately 100 ng/m$^3$. The measurements reported here are far below this value, ranging from 12 to 23 ng/m$^3$, and do not seem to be dependent upon relative amounts of other pollutants such as Pb or V. The majority of the gaseous iodine comes from the sea since the concentration in the unpolluted marine atmosphere is 9.5 ng/m$^3$. For particulate iodine the result is similar, although there is more particulate iodine when
other pollutants also increase. This would essentially be due to pick up of gaseous iodine by the large number of particulates in the air. The concentration of particulate iodine in the unpolluted marine atmosphere is approximately 1.5 ng/m$^3$ versus a range of from 1.5 to 15 ng/m$^3$ for Boston particulate samples. The concentration values for the unpolluted marine atmosphere were determined in Hawaii on similar samples collected during the past year.

The concentration of gaseous and particulate bromine in an unpolluted marine region are 70 and 13 ng/m$^3$ respectively. The particulate concentration in Boston is much higher, ranging from 130 to 940 ng/m$^3$. The bromine comes primarily from the combustion of leaded gasoline and is strongly correlated with lead. Gaseous bromine also shows similar results in concentration, varying from 140 to about 1,400 ng/m$^3$. The oxidation of bromide on the particles to bromine gas, or other gaseous forms of bromine, appears to go by a photochemical, and possibly ozone induced, reaction. The half period for the gaseous bromine can be estimated to be in the order of 4 hours in the polluted Boston atmosphere.

More work will be done to check on these results and their implications as to atmospheric levels of halogen and trace metal concentration. (R.A. Duce and W.H. Zoller)

E. Analysis of Ice-Core Samples by INAA

A technique to analyze ice-core samples for certain elements, such as vanadium, copper and aluminum, commonly present in the environment of modern cities, is being developed. The samples will be freeze-dried and the residue irradiated in the MIT reactor. Estimation of the elements of interest present in the samples will be done with Ge(Li) detectors, with and without chemistry being performed on the irradiated material.
For testing the reproducibility of the method, samples containing known concentrations of the elements under investigation will be irradiated. Initial results indicate poor yields with reproducibility uncertain. This will be followed by full-scale testing using three core samples, each 1 kg in weight, supplied by Dr. C.C. Langway, Jr. of the U.S. Army Terrestrial Sciences Centre, Hanover, New Hampshire. These are sections of the core drilled at Camp Century, Greenland, during 1961 and represent ages of approximately 160, 210 and 400 years old.

Eventually it is hoped to apply the technique to core samples deposited at various times up to the present day in order to correlate concentration of the elements with time. (E.S. Gladney, A.G. Jones, W.H. Zoller, and W.B. Walters)

4.5 Instrumentation

Because the work described in the four preceding sections is heavily dependent on the ability to detect and analyze the radiations emitted during the radioactive decay process, considerable effort must continually be made to improve both our hardware and software. Beta and gamma ray spectra are no more complex than in the past, but with the newer, more sensitive solid-state detectors, we are able now to observe that complexity which has always been present. Our efforts during the past year have been in three areas, purchase of a large-volume Ge(Li) detector, construction of a Compton-Suppressed Ge(Li) spectrometer, and utilization and development of computer programs to quantitatively analyze and display $\beta$ and $\gamma$ spectra.

A. Large-Volume Ge(Li) Detector

We have purchased, as proposed, a Ge(Li) detector with an active volume of $\approx 45 \text{ cm}^3$ and having a FWHM of 2.5 keV and
a relative photo-peak efficiency of 8.9% for the 1.332 MeV γ-ray of 60Co. The detector has been especially useful in studies involving high-energy γ-rays from activities with short half-lives in fission studies and activation analysis, and in Ge(Li)-Ge(Li) coincidence studies. (W.B. Walters)

B. The Compton-Suppressed Ge(Li) Spectrometer

We have completed the construction of a Compton-Suppressed Ge(Li) Spectrometer. The system has been extensively utilized in determining the energies and intensities of low-intensity γ-rays in a wide variety of experiments. (W.B. Walters and G.E. Gordon)

C. Computer Analysis of Ge(Li) Gamma Spectra

A computer code for the analysis of Ge(Li) gamma spectra has been developed by modifying "GAMANL", a core written by the MIT Nuclear Engineering Group(24). A new peak-searching routine has been added which uses the cross-correlation function technique as described by W.W. Black (Nucl. Instr. Methods, to be published). This program searches for possible peaks in gamma spectra recorded on magnetic tape by our multichannel analyzer. The strong peaks are used to calculate a quadratic function relating full-width at half-maximum of the peaks to channel number. All of the peaks are then analyzed, and the printout contains the centroid, area, background under the peak, peak height, peak height to the background, the actual FWHM, the calculated FWHM from the fitted function, the number of channels in the peak and what order multiplet to which the peak belongs. (P.K. Hopke)

Personnel

Professors: C.D. Coryell
G.E. Gordon
J.W. Irvine, Jr.
W.B. Walters
Guests:
J. Blackot (French CEA) ('70)
A. Catz (University of Massachusetts)
R. Duce (University of Hawaii)
G. Hoffman (University of Hawaii) ('69)

Research Associates:
P. Baedecker ('69)
A. Catz
J. Dran ('69)
J. Elhanan ('69)
I. Gal ('69)
P. Hopke
R. Gijbels ('69)
A. Jones
M. Liquornik
A. Pakkanen

Students:
K. Apt
R. Eng
H. Erten
J. Fasching
R. Fay ('69)
E. Gladney ('70)
S. Goldberg ('70)
C. Gowdy
C. Guttmann ('70)
S. Jackson ('70)
M. Kay
E. Macias
Z. Mester ('70)
M. Perkal
C. Pilcher ('69)
Z. C-H Tan
W. Zoller

Support
USAEC, MIT General Funds

Related Academic Subjects
5.09 Radiochemistry
5.091 Radiochemistry Laboratory
5.092 Special Topics in Nuclear Chemistry

5. DEPARTMENT OF EARTH AND PLANETARY SCIENCES

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.

Initial work with the new equipment was mainly preparatory, such as making up and checking the purity of monitor solutions and investigating flux variations within the sample container. Preliminary checks were then made on very short-lived products activated in standard rock. With improvement of the techniques, additional short-lived nuclides were identified. The high-resolution Si(Li) detector is used to look for low energy γ and/or x-rays soon after irradiation. The use of Ge(Li) - NaI(Tl) coincidence counting has proven helpful.

For analyzing the γ spectra and identifying the peaks, a computer program, written by P.A. Beadecker and others of the Nuclear Chemistry Group, searches out the photopeaks, calculates their areas, centroids and energies. A correction is made for detector efficiency,
During the past two years, the composition of a variety of rocks has been determined by this method for the purposes of the several projects described below.

5.2 Areas of Investigation

A. Rare-Earth Distribution Between Pyroxenes and Aqueous Phases

Rare earth abundances in the Lizard periodite were affected by serpentinization. Rare-earth fractionation between coexisting enstatite, diopside, and rare-earth containing aqueous phases has been investigated at 760°C and 2kb. Analyses of the separate phases have indicated that the rare-earths are preferentially incorporated into the crystalline phases. Rare-earths at a concentration range of a few parts per million are readily incorporated into these minerals. Fractionation of the rare-earths does occur between the two pyroxenes. Retention of the rare-earths in the aqueous phase is aided by the presence of sodium and fluorine ions in the initial solutions. (F.A. Frey and D.R. Wones)

B. Rare-Earths in Ultrabasic Rocks from St. Paul's Rocks

St. Paul's rocks are commonly postulated to be an exposure of the oceanic upper mantle. Rare-earth analyses have been done for 15 samples from this area and for 5 serpentinite samples from Mayaguez, Puerto Rico. The results indicate that none of the St. Paul's samples have the rare-earth distribution expected of undifferentiated mantle material. All samples are enriched in the light lanthanides relative to a chondritic rare-earth distribution. Because of this enrichment the samples do not seem to represent simple residues left after basalt magma generation. The brown hornblende mylonites are similar to alkali olivine basalts in major and trace element abundances. Overall distribution coefficients calculated between the spinel
peridotite mylonites and the brown hornblende mylonites are consistent with the hypothesis that these rock types may represent a former coexisting solid-liquid system. (F.A. Frey)

C. Elemental Abundances in Microtektites

Microtektites found in sediment cores near the Ivory Coast and Australian strewn fields have been analyzed by instrumental neutron activation analysis. Each sample analyzed consisted of several microtektites so that the sample amounted to about one milligram. Elemental abundances have been determined for Na, K, Sc, Cr, Fe, Mn, Hf, La, Ce, Sm, Eu, Dy and Th. Most of the abundances are within the ranges observed in tektites although some elements, e.g. Na, have abundances lower than in most tektites. (C.M. Spooner and P.A. Badecker)

D. Rare Earth Abundances in a High-Temperature Peridotite Intrusion

Rare-earth (RE) abundances are reported for several rocks and separated minerals of the Lizard Peridotite intrusion, Cornwall, England. The results are interpreted as providing evidence that this peridotite equilibrated with a basic magma either as a deep-seated accumulate or as a residue left after partial melting. Crustal-mantle RE mass balances indicate that the RE abundances of the primary peridotite are consistent with chondritic RE abundances for undifferentiated terrestrial material. The RE abundances of the peridotite and contact rocks are consistent with an interpretation of contact metamorphism, but other interpretations for the origin of the metamorphic country rocks cannot be eliminated on the basis of the RE data. RE analysis of unaltered minerals indicate that serpentinization has

130
removed some of the light REE from the peridotite. The data for unaltered minerals are utilized to determine RE distribution coefficients among coexisting ultramafic phases. There are some significant differences between these distribution coefficients and the values determined from phenocryst data. The applications of the Lizard data to partial melting models for basalt generation indicate that residue mineralogies which account for basaltic major element composition do not result in correct basaltic RE abundances. All partial melting models require that the basaltic source rocks have RE absolute abundances about 4 times the chondritic average. (F.A. Frey)

E. Petrologic Relations and Trace Element Abundances in Basic and Ultrabasic Rocks

Correlation of trace element abundances with major element abundances and petrology are quite useful in understanding the processes (e.g. partial melting) of deriving basic rocks from the upper mantle. Areas and rocks being studied are:

a) rocks dredged along the valley and flanks of the Mid-Atlantic Ridge at 32°N,

b) basic rocks forming the oceanic islands along the Mid-Atlantic Ridge,

c) lherzolite and pyroxenite nodules in the Honolulu volcanics, Hawaii,

d) basalt-peridotite nodule pairs from New Zealand and Australia.

(F.A. Frey, R. Zielinski, J.B. Reid, Jr.)

F. Geochemistry of Europium

Europium has anomalous abundances in most lunar rocks and also in some terrestrial rocks. These unusual abundances probably reflect a magmatic history involving feldspar. The effects of the environmental oxidation-reduction state are
unknown. The goal of this research is to study the oxidation state of Eu in glasses and various minerals under controlled oxygen fugacities. Optical spectra tracer techniques and ESR spectra techniques are being developed to quantitatively identify $\text{Eu}^{+2}$ and $\text{Eu}^{+3}$. (F.A. Frey and D. Skibo)

G. Petrologic and Trace Element Study of Basalts Cored in the JOIDES Program

The JOIDES deep sea drilling program has successfully cored basaltic crustal rock on traverses across the Mid-Atlantic Ridge. These basalts will be studied and carefully compared to the younger basalts presently forming the ridge. A variety of elemental abundances will be studied in order to separate the effects of marine weathering from any possible primary differences in basalt composition. (F.A. Frey)

H. Trace Element Abundances in Serpentized Ultrabasic Rocks

The ultrabasic rocks dredged from oceanic ridge fracture zones are dominantly serpentine. It is important to know what elements are affected when anhydrous assemblages are serpentinized. Laboratory data are being obtained for the distribution of trace elements in ultramafic mineral-aqueous phase systems. Complementing the laboratory experiments are studies of ultrabasic rocks exhibiting various degrees of serpentinization. Areas of particular interest include the fracture zones of the Mid-Atlantic Ridge and the Webster-Addie occurrence in North Carolina. (F.A. Frey, R. Zielinski, D.R. Wones)
I. Petrologic and Trace Element Studies of New England Granites and Rhyolites

The alkaline and sub-alkaline granites of New England are being studied. It is likely that these granites have had different geologic histories. Petrologic observations coupled with elemental abundance data are proving to be useful in understanding the different evolutions and origins of these granites.

Several mechanisms or combinations of processes have been proposed for the origin of rhyolites. A knowledge of Sr, Ba, and Eu abundances in rhyolites would aid in distinguishing among the proposed hypotheses. Detailed sampling and trace element analysis is being done for two extensive rhyolite areas (Mt. Rogers, North Carolina, and Traveler Mtn., Maine). (F.A. Frey, G. Buma, L. Lopez)

J. Investigation of Dusts in Diseased Lung Tissues

The MIT Environmental Medical Services is initiating a study of lung diseases caused by geologic materials such as silica, asbestos, iron oxides, and coal. Present techniques for identifying these materials in lung tissues are inadequate. It is planned to develop techniques such as x-ray diffraction and neutron activation analysis for the characterization of geologic materials in lung tissue. (F.A. Frey, H. Hardy)

K. Canadian Precambrian Iron Formations: Their Ages and Origins

A striking aspect of virtually all Precambrian shield areas is the abundance of iron-rich sediments. Despite being the most abundant and important, excepting marine carbonates, of the chemically precipitated sediments their
origins are still in doubt. Virtually no trace element work has been done on these rocks and even their time of deposition is poorly known.

The study proposed here will determine the ages of five iron formations in the Canadian Shield and establish the concentrations of certain trace elements in the various iron formation facies of the Labrador Range. A less intensive study will be made on some of the iron formations of the Michipicoten and Temagami Ranges which are believed to be of volcanic exhalative origin in order to compare them to those of the Labrador Range. It is hoped that the study of the trace elements will provide evidence bearing on the origin of Superior types of iron formations and their environments of deposition.

The trace element determinations will be done by neutron activation analysis of whole rock samples and will enable the establishment of the rare earth, Sc, As, Co, Cr, Th, K, and Na, element abundances in the oxide, carbonate, and silicate facies of the Labrador iron formation. The Algoman-type iron formation of the Michipicoten Range will then be studied to determine the similarities and differences between Algoman and Superior iron formations in the hope that this will shed some light on the origin of the vast and important iron reserves of the Superior type. (F.A. Frey and B. Fryer)

**Personnel**

Professor: F.A. Frey  
Research Staff: B. Donechaud ('70)  
Students:  
G. Buma  
R. Copeland  
B. Fryer ('70)  
J. Reid  
D. Skibo  
C. Spooner ('69)  
R. Zielinski
Support
MIT General Funds, National Science Foundation, Office of Naval Research, USAEC

Related Academic Subjects
12.066 Analysis of Geologic Materials
12.45 Geochemistry
IX. MIT 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, although 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 during fiscal year 1969 and again in 1970, covering a wide range of science and technology in the fields of both fission and applied plasma physics.
There were 130 and 128 students, respectively, all candidates for advanced 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 years 1968-69 and 1969-70. 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 8.541 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. (Alternate years)

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

139
TABLE IX-1

ENROLLMENT IN COURSES USING THE MIT REACTOR

<table>
<thead>
<tr>
<th>Subject</th>
<th>Term</th>
<th>1957-68</th>
<th>1968-69</th>
<th>1969-70</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.41</td>
<td>Fall</td>
<td>166</td>
<td>-</td>
<td>6</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>162</td>
<td>14</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>22.42</td>
<td>Fall</td>
<td>67</td>
<td>-</td>
<td>-</td>
<td>212</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>126</td>
<td>10</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>8.541</td>
<td>Alternate Years</td>
<td>66</td>
<td>8</td>
<td>(not offered)</td>
<td>74</td>
</tr>
<tr>
<td>5.091</td>
<td>Fall only</td>
<td>80</td>
<td>15</td>
<td>12</td>
<td>107</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>667</td>
<td>47</td>
<td>27</td>
<td>741</td>
</tr>
</tbody>
</table>

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 nine 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. Five present or former students are currently part of the reactor staff, listed in Tables V-1a and V-1b. Three of these - Furtado, Gwinn 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. Two others, Clark and Gosnell, have received Master's and Doctor's degrees, respectively.

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. This association with the MITR has been in addition to the normal contact which a student would have in the conduct of a thesis or a laboratory course experiment. These students and also a number of faculty and research staff, totaling about 20, who left MIT during fiscal years 1969 and 1970 after having been closely associated with the MITR in some capacity other than as a student, are listed in Table IX-2. In our previous report, MITNE-98, over 50 such people who served at the reactor between 1958 and June 30, 1968 were listed. These tables illustrate 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 either here or elsewhere 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 165 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 AND STAFF WHO WORKED AT MITR DURING FISCAL YEARS 1969 OR 1970**

<table>
<thead>
<tr>
<th>Name</th>
<th>Status at MIT</th>
<th>MITR Activity</th>
<th>Subsequent Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.J. Thompson</td>
<td>Professor of Nuclear Engineering</td>
<td>Director</td>
<td>U.S. Atomic Energy Commission, Washington, D.C.</td>
</tr>
<tr>
<td>R. Farmer</td>
<td>Student</td>
<td>Reactor Operations Assistant and Guide</td>
<td>Martin-Marietta Company, Colorado</td>
</tr>
<tr>
<td>D.F. Frech</td>
<td>Part-time Student</td>
<td>Reactor Operations Superintendent</td>
<td>Duke Power Company, Seneca, South Carolina</td>
</tr>
<tr>
<td>L. Papay</td>
<td>Part-time Student</td>
<td>Reactor Shift Supervisor and Secretary of Reactor Safeguards Committee</td>
<td>CCR Euratom, Ispra, Italy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pacific Gas and Electric Co. Los Angeles, California</td>
</tr>
<tr>
<td>E. Heimberg</td>
<td>&quot;</td>
<td>MITR-II Redesign Proj.</td>
<td>U.S. Army</td>
</tr>
<tr>
<td>D. Kennedy</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Swiss Federal Institute of Reactor Research</td>
</tr>
<tr>
<td>Y. Lefevre</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Student, MIT</td>
</tr>
<tr>
<td>B. Luxford</td>
<td>&quot;</td>
<td>&quot;</td>
<td>U.S. Navy</td>
</tr>
<tr>
<td>R. Sanders</td>
<td>&quot;</td>
<td>&quot;</td>
<td>U.S. Navy</td>
</tr>
<tr>
<td>J. Synan</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Gulf General Atomic, Inc., San Diego, California</td>
</tr>
<tr>
<td>Name</td>
<td>Status at MIT</td>
<td>MITR Activity</td>
<td>Subsequent Organization</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------------</td>
<td>-----------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>J. Tuohy</td>
<td>Student</td>
<td>MITR-II Redesign Proj.</td>
<td>Burns and Roe, New Jersey</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Manhattan College, New York</td>
</tr>
<tr>
<td>D. Uhl</td>
<td></td>
<td></td>
<td>Stanford University - student, Stanford,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>California</td>
</tr>
<tr>
<td>F.M. Clikeman</td>
<td>Associate</td>
<td>Research in Radiation Detection and</td>
<td>Purdue University, Lafayette, Indiana</td>
</tr>
<tr>
<td></td>
<td>Professor of</td>
<td>Measurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nuclear Engineering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.E. Gordon</td>
<td>Associate</td>
<td>Research in Radio-chemistry</td>
<td>University of Maryland, College Park,</td>
</tr>
<tr>
<td></td>
<td>Professor of Chemistry</td>
<td></td>
<td>Maryland</td>
</tr>
<tr>
<td>W.B. Walters</td>
<td>Assistant</td>
<td>Research in Radio-chemistry</td>
<td>University of Maryland, College Park,</td>
</tr>
<tr>
<td></td>
<td>Professor of Chemistry</td>
<td></td>
<td>Maryland</td>
</tr>
<tr>
<td>W. Just</td>
<td>Post-Doctoral</td>
<td>Research in Neutron Spectroscopy</td>
<td>University of Perugia, Perugia, Italy</td>
</tr>
<tr>
<td></td>
<td>Associate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H. Massin</td>
<td>Research Staff</td>
<td>Design of Neutron Spectrometer</td>
<td>Commonwealth Edison Company, Chicago,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Illinois</td>
</tr>
</tbody>
</table>
X. RESEARCH AND EDUCATIONAL UTILIZATION
OF THE MIT REACTOR BY OTHERS

As was mentioned in Section III, "Objectives of the
MIT Research Reactor," the University recognizes an obliga-
tion 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
these 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 irradiations which pro-
vide radioactive tracers, radiation damage specimens, radio-
isotope 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 accumu-
lated 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 de-
scribed in Section VIII, which generally have been three to

145
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.

In Table X-1 below, comparison of the totals in the three columns shows that the number of samples irradiated for outside users during fiscal years 1969 and 1970 was not far from the average of 501 for the previous ten years.

The 9 universities and research centers which have had occasion to use the MIT Reactor in connection with their own research projects during fiscal years 1969 and 1970, and materials irradiated, are listed in Appendix G. Six of these were among the 24 former users, and there were three 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 the 1 Mw reactor at the Rhode Island Nuclear Science Center, operated by the University of Rhode Island, and the 10-Kw facility at Worcester Polytechnic Institute. The U.S. Army Materials and Mechanics Research Center did operate a 2 Mw light-water reactor at Watertown, Massachusetts, but this was closed down in the Spring of 1970.

None of the universities have 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 arrangements 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
<table>
<thead>
<tr>
<th>Organization</th>
<th>Ten Fiscal Years 1959-68</th>
<th>Fiscal Year 1969</th>
<th>Fiscal Year 1970</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Organizations</td>
<td>Irradiations</td>
<td>Organizations</td>
</tr>
<tr>
<td>Universities and Research Centers</td>
<td>24</td>
<td>753</td>
<td>7</td>
</tr>
<tr>
<td>Hospitals</td>
<td>3</td>
<td>2,488</td>
<td>2</td>
</tr>
<tr>
<td>Industrial Firms</td>
<td>30</td>
<td>1,768</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>5,009</td>
<td>14</td>
</tr>
</tbody>
</table>
obtaining the substantial research funds required to pay the reactor facility rental charges MIT is obliged to make remains 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, or at least the major, 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; until recently it has not been related to the budget restrictions imposed on Government Agencies during fiscal years 1968-1970. However these recent limitations have undoubtedly aggravated the situation. (At the time of drafting this report, one local university is considering part-time use of a spectrometer beam.)

In addition to educational institutions, other organizations making use of the MIT Reactor are the local hospitals and industrial companies. The former are enumerated in Appendix H and the latter in Appendix I for fiscal years 1969 and 1970. Massachusetts General Hospital has conducted a continuing research program in neutron capture for cancer therapy and in other areas. Since MIT students are frequently involved in these studies, current MGH programs consequently are described in Sections VIII-1.8. 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 years 1969 and 1970.
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 regular academic courses conducted at MIT and described in Section IX but rather work-study programs, class visits from other schools and from special MIT summer programs, and so forth. They 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, was utilized in subsequent 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 were 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, alternating about every 13 weeks as operators. Having earned his Bachelor of Science degree in Electrical Engineering in June 1969, Rupp now works for Gulf General Atomic in California. Casey is scheduled to graduate later this year.

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**

<table>
<thead>
<tr>
<th>Academic Year</th>
<th>Educational Groups</th>
<th>Professional, Military and Other Groups</th>
<th>Total Registered Visitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 years, 1958-68</td>
<td>147 No. 2576 Indiv.</td>
<td>98 No. 1911 Indiv.</td>
<td>24,300</td>
</tr>
<tr>
<td>1968-69</td>
<td>17 No. 387 Indiv.</td>
<td>9 No. 116 Indiv.</td>
<td>1,100</td>
</tr>
<tr>
<td>1969-70</td>
<td>19 No. 306 Indiv.</td>
<td>9 No. 149 Indiv.</td>
<td>1,200</td>
</tr>
<tr>
<td>12 Years Total</td>
<td>183 No. 3269 Indiv.</td>
<td>116 No. 2176 Indiv.</td>
<td>26,600</td>
</tr>
</tbody>
</table>

MIT and the Reactor Staff have recognized the value of these tours and also the benefits accruing from the

150
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 26,600 registered visitors shown in Table X-3 should be added an estimated 11,000 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 May 3, 1969, when an estimated 900 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 1971. 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

THESSES


JOURNAL ARTICLES AND PAPERS


*Partial listing only for in progress theses.


REPORTS


APPENDIX B

DEPARTMENT OF PHYSICS PUBLICATIONS

THESSES


JOURNAL ARTICLES AND PAPERS


REPORTS


APPENDIX C

DEPARTMENT OF METALLURGY AND MATERIALS SCIENCE PUBLICATIONS

THESIS


JOURNAL ARTICLES AND PAPERS


REPORTS

APPENDIX D
DEPARTMENT OF CHEMISTRY
PUBLICATIONS AND ADDRESSES

THESES

JOURNAL ARTICLES AND PAPERS


2. Erten, H.N., C.D. Coryell and W.B. Walters, "New Iodines in Fission: 3.8-m $^{134}\text{mI}$ and 45 sec $^{135}\text{I}$," APS Division of Nuclear Physics Fall Meeting, Boulder, Colorado (October 31, 1969).


11. Zoller, W.H., G.E. Gordon, W.B. Walters, "Radioactive Decay Studies of the Levels of $^{67}\text{Ga}$, $^{69}\text{Ga}$, and $^{71}\text{Ga}$," APS Division of Nuclear Physics Fall Meeting in Boulder, Colorado (October 30, 1969); Radiochemistry Division, Lawrence Radiation Laboratory, Livermore, Calif.


REPORTS


APPENDIX E

DEPARTMENT OF EARTH AND PLANETARY SCIENCES PUBLICATIONS

THESSES


JOURNAL ARTICLES


ADDRESSES


REPORTS

In 1964 a computer program 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, as originally written, 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 may be produced in order to obtain copies of the plot.

12. In fiscal 1969, a subprogram was written which prints out the entire reactor fuel inventory in a form useful for preparation of the semiannual AEC Material Status Reports (Form AEC-578). The inventory is divided into three parts: fresh fuel, fuel in or at the reactor, and spent fuel in the storage tank. The code arranges the elements in order by groups, lists the initial and the current U and U-235, and totals the columns. It also lists the elements which have sustained burnup during the reporting period and gives the total. Elements received and shipped are likewise listed. Since some elements are purchased with a few plates unassembled and separate, provision is made in the program for listing these "loose" plates separately.
## APPENDIX G

### IRRADIATIONS FOR OTHER UNIVERSITIES AND RESEARCH CENTERS

<table>
<thead>
<tr>
<th>Institution</th>
<th>Fiscal Year 1969</th>
<th>Fiscal Year 1970</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argonne National Laboratory* Argonne, Illinois</td>
<td></td>
<td>Spectrometer</td>
</tr>
<tr>
<td>Boston College* Chestnut Hill, Massachusetts</td>
<td>$^{235}U_3$</td>
<td></td>
</tr>
<tr>
<td>Boston University Boston, Massachusetts</td>
<td>Biotite</td>
<td></td>
</tr>
<tr>
<td>Brandeis University Waltham, Massachusetts</td>
<td>Cu</td>
<td>Cu foils in Al foils</td>
</tr>
<tr>
<td>Harvard University Cambridge, Massachusetts</td>
<td></td>
<td>Tissue culture, H$_2$O and Poly Vial</td>
</tr>
<tr>
<td>Hawaii, University of Honolulu, Hawaii</td>
<td>KCl, rainwater, charcoal, filter paper, distilled H$_2$O, Al, SiO$_2$, dust in H$_2$O</td>
<td>Rainwater, charcoal</td>
</tr>
<tr>
<td>U.S. Air Force Electronic Systems Division Bedford, Massachusetts</td>
<td>Transistors, Al$_2$O$_3$, SiO$_2$, Li$_2$, PT, FeS, Sb, In, Sn, CaF$_2$, SiC</td>
<td>Al$_2$O$_3$, Nd$_2$O$_3$, GeO$_2$, H$_2$O$_3$, Li$_2$O, graphite, SiO$_2$, GeO$_2$, Al$_2$O$_3$ (ruby)</td>
</tr>
<tr>
<td>Wellesley College* Wellesley, Massachusetts</td>
<td>Tadpole</td>
<td></td>
</tr>
<tr>
<td>Woods Hole Oceanographic Institute Woods Hole, Massachusetts</td>
<td>Coral</td>
<td>SrNO$_3$, Millipore HA filter</td>
</tr>
</tbody>
</table>

*New user of MITR
<table>
<thead>
<tr>
<th>Hospital</th>
<th>Fiscal Year 1969</th>
<th>Fiscal Year 1970</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massachusetts General Hospital, Boston, Massachusetts</td>
<td>Tissue ash, tissue culture, LiF, Au, CuSO₄, chromatography paper, cellulose, Ni, NH₄Br</td>
<td>Tissue ash, Au liquid chromatograph paper, Cd, Polyethylene, P₃l, CS (liq) cellulose, Co, Au, Sc, Sb, Cr, Co</td>
</tr>
<tr>
<td>New England Deaconess Hospital, Boston, Massachusetts</td>
<td>Scalpel blade, poly vials, Al-Co wire tissue, dried tissue, dried serum, Bn</td>
<td>Insulin, scalpel blade, Mn, CaAl, MnSO₄, Zn, Cl₂, dried tissue, freeze dried tissues live rat, millipore filter, GeO₂, human nail, KB₇ crystal, millipore HA filter, polystyrene, poly vials, KTO₃ standard</td>
</tr>
<tr>
<td>Veterans Administration Hospital*, Boston, Massachusetts</td>
<td></td>
<td>KIO₃</td>
</tr>
</tbody>
</table>

*New user of MITR
# APPENDIX I

## IRRADIATIONS FOR INDUSTRIAL FIRMS

<table>
<thead>
<tr>
<th>Firm</th>
<th>Fiscal Year 1969</th>
<th>Fiscal Year 1970</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cambridge Nuclear Corporation</td>
<td>Na$_2$CO$_3$, CuSO$_4$, K$_2$CO$_3$,</td>
<td>NaCO$_3$, K$_2$CO$_3$, NH$_4$Br, MnCO$_2$,</td>
</tr>
<tr>
<td>Cambridge, Massachusetts</td>
<td>NH$_4$Br, U$_2$CO$_3$, Na$_2$CO$_3$</td>
<td>NnCO$_3$</td>
</tr>
<tr>
<td>Fram Corporation</td>
<td>Auto bearings</td>
<td></td>
</tr>
<tr>
<td>Providence, Rhode Island</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GCA Corporation*</td>
<td>Semiconductors</td>
<td></td>
</tr>
<tr>
<td>Bedford, Massachusetts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plymouth Rubber Company*</td>
<td>Special purpose tapes</td>
<td></td>
</tr>
<tr>
<td>Canton, Massachusetts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tech Operations, Inc.</td>
<td>Foils and wires</td>
<td></td>
</tr>
<tr>
<td>Burlington, Massachusetts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracerlab, Incorporated</td>
<td>Tantalum wire, Au cellulose acetate,</td>
<td>Fe needles, cellulose acetate</td>
</tr>
<tr>
<td>Waltham, Massachusetts</td>
<td>Ac</td>
<td>Eu in lung tissue, tantalum</td>
</tr>
<tr>
<td>Westwood Research Laboratory*</td>
<td>Tooth enamel</td>
<td>Tooth enamel, thionalid</td>
</tr>
<tr>
<td>Westwood, Massachusetts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yankee Atomic Electric Co.*</td>
<td>Flux wire</td>
<td></td>
</tr>
<tr>
<td>Boston, Massachusetts</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*New user of MITR
## APPENDIX J

**NON-MIT EDUCATIONAL TOURS, FY 1969**

(Groups of four or less not tabulated)

<table>
<thead>
<tr>
<th>School</th>
<th>Visits</th>
<th>Number of Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belmont Junior High School, Belmont, Mass.</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Boston College, Chestnut Hill, Mass.</td>
<td>1</td>
<td>27</td>
</tr>
<tr>
<td>Bristol Community College</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Canadian Student Group</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Dennis-Yarmouth Regional High School, S. Yarmouth, Mass.</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Lowell Technological Institute, Lowell, Mass.</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>Massachusetts General Hospital, Boston, Mass.</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special Summer Course 2.16s</td>
<td>2</td>
<td>27</td>
</tr>
<tr>
<td>Special Summer Course 22.94s</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>Upward Bound Program</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>North Smithfield High School, Rhode Island</td>
<td>1</td>
<td>47</td>
</tr>
<tr>
<td>Northeastern American Nuclear Society Student Conference</td>
<td>1</td>
<td>38</td>
</tr>
<tr>
<td>Northeastern University, Boston, Mass.</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>University of Connecticut, Storrs, Conn.</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Wellesley Junior High School, Wellesley, Mass.</td>
<td>1</td>
<td>38</td>
</tr>
<tr>
<td>Wentworth Institute, Boston, Mass.</td>
<td>1</td>
<td>28</td>
</tr>
</tbody>
</table>

Sum: 17

387
## APPENDIX J

### NON-MIT EDUCATIONAL TOURS, FY 1970

(Groups of four or less not tabulated)

<table>
<thead>
<tr>
<th>School</th>
<th>Visits</th>
<th>Number of Visitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston College, Chestnut Hill, Mass.</td>
<td>3</td>
<td>40</td>
</tr>
<tr>
<td>Brennan School, Attleboro, Mass.</td>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>Bristol Community College</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td>Dennis-Yarmouth Regional High School, S. Yarmouth, Mass.</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Exeter Academy, New Hampshire</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Harvard School of Public Health, Cambridge, Mass.</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Lincoln School, Melrose, Mass.</td>
<td>1</td>
<td>31</td>
</tr>
<tr>
<td>Massachusetts General Hospital, Boston, Mass.</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special Summer Course 2.15s</td>
<td>2</td>
<td>33</td>
</tr>
<tr>
<td>Special Summer Course 2.26s</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>Special Summer Course 22.94s</td>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td>Medford High School, Medford, Mass.</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Northeastern University, Boston, Mass.</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Norwood High School, Norwood, Mass.</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>U.S. Information Agency with Associated Producers, Inc.</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

Total: 19 visits and 306 visitors
## APPENDIX K

### NON-MIT PROFESSIONAL AND MISCELLANEOUS TOURS, FY 1969

(Groups of four or less not tabulated)

<table>
<thead>
<tr>
<th>Company</th>
<th>Visits</th>
<th>Number of Visitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Science and Engineering, Inc., Cambridge, Mass.</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Budweiser Company, Cambridge, Mass.</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Electronics Corporation of America, Cambridge, Mass.</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>FRAM Corporation, Providence, R.I.</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>I.A.E.A. Student Tour</td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>Japanese Industrial Metallurgists</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>Japanese University Professors</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Medical Program Directors, American Hospitals</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>USAEC, Division of Biology and Medicine, Program Directors</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>116</td>
</tr>
</tbody>
</table>
## APPENDIX K

**NON-MIT PROFESSIONAL AND MISCELLANEOUS TOUGHS, FY 1970**

(Groups of four or less not tabulated)

<table>
<thead>
<tr>
<th>Company</th>
<th>Visits</th>
<th>Number of Visitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Science and Engineering, Inc., Cambridge, Mass.</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Cambridge Fire Department, Cambridge, Mass.</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Neurosurgeons from an International Conference on Surgery</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>Royal Netherlands Navy</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Second International Conference on Medical Physics</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>University-Industry Relations Meeting, sponsored by Atomic Industrial Forum</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Western Electric, N. Andover, Mass.</td>
<td>1</td>
<td>14</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9</td>
<td>149</td>
</tr>
</tbody>
</table>
APPENDIX L

REFERENCES


