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# Capabilities for Nonnuclear Applications with Nuclear Facilities at NRL

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# PREFACE

In recognition of the fact that many nuclear facilities and techniques are not being applied to maximum advantage toward solving DOD and Navy research and development problems, a Nuclear Applications Committee was established in the Nuclear Physics Division of NRL on Oct. 27, 1966. Members of the committee were:

Chairman
Dr. E. A. Wolicki - Consultant on Nuclear Applications

Dr. C. R. Gossett - Cyclotron Branch
Dr. K. W. Marlow - Reactors Branch
Miss M. E. Toms - Linac Branch

The function of the committee was to prepare a report which would inform scientists at NRL and elsewhere of the potential advantages of nuclear techniques and which would thereby contribute toward solution of problems through the use of such techniques. A preliminary report containing a list of the nuclear facilities at NRL and the capabilities of these facilities for applications to nonnuclear problems was published on Feb. 27, 1967. The present document incorporates that report and in addition includes a comprehensive list of references, an index, and several additional examples of interesting applications.

Inquiries are invited regarding the utilization of the facilities described herein and, if originating outside of NRL, should be addressed to the Director, Naval Research Laboratory, Washington, D.C., 20390.

## ABSTRACT

A number of the techniques used in nuclear-physics research can be applied to problems in nonnuclear areas. In order to promote the utilization of nuclear techniques for problems for which they may have an advantage, descriptions have been written about the seven major facilities in the NRL Nuclear Physics Division. These facilities are a 75-MeV cyclotron, a 5-MV positive ion Van de Graaff accelerator, a 60-MeV linear electron accelerator (linac), a 2-MV electron Van de Graaff, a 1-MW nuclear reactor, a 14-MeV neutron source, and a 13-kCi $Co^{60}$ irradiation facility.

To inform potential users of the range of possible applications, and to facilitate extensions of applications into new areas, a list of the capabilities of these facilities has been compiled. The applications are listed under eleven main categories, according to technique or function. Whenever possible, examples are discussed in terms of the specific nonnuclear areas to which they apply. These examples and the accompanying discussion allow the reader to evaluate the potential benefits of a given technique for his own work.

For the benefit of readers not familiar with basic nuclear techniques, additional information has been incorporated in appendixes on the interaction of radiation with matter and radiation detection, and on more detailed descriptions of each of the major facilities.

# CAPABILITIES FOR NONNUCLEAR APPLICATIONS WITH NUCLEAR FACILITIES AT NRL

## I. INTRODUCTION

Communication between different disciplines in scientific research is difficult, and many potential benefits which might result from the use, by one discipline, of techniques and results of another may not be realized. In many instances the interdisciplinary approach has proven most important not only for solving a given problem but also for opening up entire new areas of research. In the case of research in nuclear physics, effective communication exists with many nonnuclear areas, and the results and developments which are taking place in nuclear research are being applied promptly in these areas. However, many other nonnuclear areas exist where potentially useful nuclear techniques are neither well known nor being applied to best advantage.

Nuclear power and nuclear weapons have affected the world so profoundly that any elaboration here is unnecessary. It is worth noting that in areas other than these two, a great many nuclear techniques and results have received important application to other problems. The list of such applications is most impressive but far too long to recount here. An excellent discussion and list of examples illustrating the impact of nuclear physics on other fields may be found in the NAS-NRC Report on Subfields of Physics (1). Mention here of a few of the more outstanding of such applications should suffice to put the present situation in proper perspective.

Radioisotope tracer techniques and activation analysis are being used in virtually all sciences and industries. Nuclear magnetic resonance techniques are routinely used in many sciences and have proven especially important in chemistry. Research on nuclear moments led to the development of the atomic hydrogen maser, and to an atomic clock which appears to be the most accurate clock thus far developed. The long half-lives for decay of some radioactive nuclei provide the most accurate and reliable "clocks" for dating events which occurred a few thousand or more years ago. Scintillation-counting techniques developed for detection of nuclear radiations are being used in measurements ranging from the location of cancers to geological prospecting for oil. Similarly, the development of solid-state detectors for nuclear radiations has produced important benefits for a variety of applications. The Mössbauer effect, that is, the recoilless emission or absorption of a gamma ray by a nucleus, has provided an important tool for solid-state physics.

These examples illustrate that nuclear research has been fertile in producing important applications. Moreover, the rate at which new discoveries and new measuring techniques are being applied to other areas remains high. In fact, any consideration of the applications which may be found at the present time in nuclear research leads to the conviction that many opportunities for research and applications in nonnuclear areas exist which are not receiving adequate attention.

It is the purpose of this report to promote the utilization of nuclear techniques at NRL for those problems for which they have an advantage and where potentially important benefits may result. This report describes the facilities which exist in the Nuclear Physics Division which can be utilized for research in nonnuclear areas, and it provides an extensive list of realized or potential applications which illustrate the capabilities of these facilities. An attempt has been made to insure that sufficient information has been included and put into a convenient form so that the reader can evaluate the potential benefits of a given technique for his own work.

## II. NUCLEAR FACILITIES

Nearly all nuclear techniques involve radiation, in one way or another. This radiation can be electromagnetic, such as x-rays and gamma rays, or corpuscular, such as electrons, neutrons, and high-velocity atomic nuclei. Such radiations may be used to produce nuclear reactions, or they may be emitted from unstable nuclei produced by nuclear reactions. When a technique depends on radiations emitted from unstable nuclei, at least a part of the instrumentation will necessarily consist of radiation detectors. A discussion of the operation of radiation detectors and the interaction of radiation with matter may be found in Appendix A.

Radiations which are used to produce nuclear reactions usually require nuclear reactors (for neutrons) or high-energy charged-particle accelerators for their production. Neutrons, having no charge, can penetrate into a nucleus at all energies; atomic nuclei, since they must overcome Coulomb repulsion to interact with a target nucleus, must usually have relatively high energies. Electrons and gamma rays must have energies in excess of nuclear binding energies before they can produce nuclear transmutations (binding energies are most commonly in the range from a few million electron volts (MeV) to 10 MeV).

An important fact which is sometimes overlooked is that beams of radiation from an accelerator or a reactor can be used to produce not only nuclear reactions but many effects besides. Thus, all irradiations can produce varying degrees of ionization in the target material, with possible consequences to the chemical bonds in the material. Beams of atomic nuclei or neutrons can produce dislocations of the atoms of the target material and can introduce chemical elements into the target material which are different from the original material. The radiation impinging on a target also deposits energy and charge (except for neutrons) in the target material. Finally, if the radiation is intense enough and if the sample is irradiated for a long enough time, sufficient transmutation can take place by means of nuclear reactions to introduce a significant quantity of trace elements into the host material.

NRL operates seven facilities which can be used to produce radiation, nuclear reactions, and radioactive isotopes. These are a 75-MeV cyclotron, a 5-million volt (MV). Positive ion Van de Graaff accelerator, a 60-MeV linear electron accelerator (linac), a 2-MV electron Van de Graaff, a 1-megawatt (MW) nuclear reactor, a 14-MeV neutron source, and a 13-kilocurie (kCi) $Co^{60}$ irradiation facility. In addition, there is a 2-MV Van de Graaff accelerator which is one of the few in this country equipped to accelerate ions of radioactive gases such as tritium. This accelerator is no longer operating, but it will be kept intact for a time and will be easy to use again should a need develop. A brief description of each operating facility is given in the following sections.

### 1. 75-MeV Cyclotron

The cyclotron is an electromagnetic device which uses a potential changing at radio frequency to accelerate charged particles contained by strong magnetic fields. The NRL cyclotron is capable of producing external beams over a wide range of energies; these include protons with energies up to 75 MeV, deuterons up to 39 MeV, $He^3$ up to 100 MeV, alpha particles up to 78 MeV, and various heavier ions, the energy depending upon the mass and the degree of ionization. Beam currents varying from nanoamperes to 100 microamperes may be produced for many ion species. The ion beam has an inherent energy spread of about 0.3 percent. An extensive beam-handling system allows the transport of the beam into heavily shielded rooms, where it may strike sample materials; the spatial distribution and position of the beam are adjustable. Experimental measurements and manipulation of samples during bombardment must be remotely controlled. The cyclotron beam may also be used to produce large quantities of fast (high-energy)

neutrons, with either a narrow or a widely spread energy distribution, or monoenergetic fast neutrons from selected low-energy reactions. The high-energy ion beams are capable of producing radioistopes throughout the periodic table, especially proton-rich isotopes not available from reactor irradiation. Compact high-intensity beams also have capabilities for depositing large amounts of mass, charge or energy in small samples. A more detailed description of the cyclotron facility appears as Appendix B.

2. 5-MV Van de Graaff Accelerator

The Van de Graaff accelerator uses a static high voltage directly to accelerate charged particles. The NRL 5-MV Van de Graaff accelerator produces beams of atomic nuclei such as protons, deuterons, helium-3, helium-4, and when required also carbon, nitrogen, oxygen, and heavier ions. These beams are usually steady currents with well-defined energy, and accurately controllable position and direction. Analyzed beam currents range up to a maximum of 100 $\mu$A. The maximum energy available is equal to about 5.5 MeV for singly ionized particles and 11.0 MeV for doubly ionized ones. Monoenergetic neutrons can be produced as secondary particles from nuclear reactions such as $D(d,n)He^3$. While the flux of neutrons which can be produced ($10^9$ $sec^{-1}$ $cm^{-2}$) is much lower than that available from a reactor, the energy is accurately known and can be easily varied. A beam scanner is in operation which can produce a uniform integrated beam flux for irradiations over a four-square-inch area. A high-resolution electrostatic analyzer is available for defining the beam energy, and a magnetic spectrometer is available for analyzing charged particles emitted from nuclear reactions. A more detailed description of the 5-MV accelerator may be found in Appendix C.

3. 60-MeV Electron Linac

The NRL linear electron accelerator (linac) uses radio-frequency power to accelerate electrons in pulses with variable repetition rates up to 360 pulses per second. The energy of the electrons as they leave the linac can be varied from 5 to 60 MeV. Pulses of neutrons can be produced when the electron beam impinges on a suitable target. The beam of electrons can be used directly or to produce a broad spectrum of high-energy x-rays (bremsstrahlung), the maximum energy in the spectrum being equal to the energy of the electrons. Positrons can be produced and accelerated in the linac to energies from 10 to 40 MeV and are used primarily to produce nearly monoenergetic gamma rays by the process of annihilation in flight. Beam-handling systems deflect the electron or positron beams magnetically and analyze the energy. Any of the linac beams can be used for exciting or activating nuclei, which then can be studied directly or can be used in investigating other phenomena. A detailed description of the linac facility is given in Appendix D.

4. 2-MV Van de Graaff Accelerator

The 2-MV Van de Graaff is used to accelerate electrons. The energy of the electrons is variable from 0.5 to 2.0 MeV. The maximum beam current which can be produced is 80 microamperes, at which current the dose rate in the electron beam is approximately $4 \times 10^8$ rad/hr (1 rad equals 100 ergs/g) at a distance of 20 cm from the exit window. While this radiation can produce intense ionization and may affect many atomic or molecular properties of samples irradiated, it does not in general induce transmutations and does not, therefore, result in radioactivity in the sample.

5. 1-MW Nuclear Reactor

A nuclear reactor produces intense fluxes of neutrons from the fission process. The neutrons have a continuous energy spectrum ranging from less than one millielectron volt

(meV) to greater than 10 MeV. The neutron flux of all energies near the NRL reactor core is approximately $10^{13}$ neutrons $cm^{-2}$ $sec^{-1}$. It is in this region that samples are normally exposed. Beams of neutrons (at lower intensity) may be extracted through holes in the reactor shield for those experiments which require it, such as neutron diffraction. The reactor has a "thermal" column which slows down the fast neutrons to obtain a neutron flux which consists primarily of slow neutrons. The thermal neutron flux is characterized by the fact that the velocity spectrum is that of a gas at the same temperature. Unlike accelerators, the reactor can furnish various beams simultaneously while irradiating many samples near the core. The production of radioactive isotopes by neutron capture is a major activity of the reactor. For more information on neutron fluxes, gamma radiation, and other characteristics of the reactor, see Appendix E.

### 6. 14-MeV Neutron Source

The 14-MeV neutron source consists of a high-voltage power supply (180 kV), a deuterium ion source, an accelerating tube, and a tritium target. Variable intensities of neutrons up to a maximum of $10^{11}$ neutrons/sec are produced through the $T(d,n)He^4$ reaction. If a deuterium target is used, the neutron energy is approximately 4 MeV and the maximum intensity which can be produced is $10^9$ neutrons/sec.

### 7. 13-kCi $Co^{60}$ Irradiation Facility

The 13-kCi $Co^{60}$ irradiation facility consists of a $Co^{60}$ source housed in a pool of water, 6 ft square and 12 ft deep. The energy of the gamma radiation is nominally 1.25 MeV. Maximum dose rate available is $5 \times 10^6$ rad/hr; the minimum is approximately $10^4$ rad/hr. As in the case of the 2-MV electron Van de Graaff, irradiation with this source does not result in radioactivity in the sample.

## III. NUCLEAR APPLICATIONS

A list of applications of nuclear techniques to nonnuclear areas has been compiled to cover specifically those capabilities which NRL possesses. Only those applications are listed which are known to be technically feasible. Although speculation upon ideas and applications which appear promising but have not yet been tried is both fascinating and tempting, it has been excluded from the present report. The list also does not include applications which, although feasible, would require major development or equipment procurement. In the listing of items, no consideration was given to the availability of personnel or equipment operating time, since these factors are not essentially related to the potential usefulness or importance of an application.

Applications are listed under eleven major categories, with examples for each category. Some types of applications, for example, activation analysis or radioisotope tracer techniques, are well known and possess an extensive published literature. For completeness, these applications have nevertheless been listed, although the examples given here represent only a minute fraction of all those which have been used. For most categories, the examples given are not to be taken as exhaustive. Wherever possible, an attempt has been made however to include a sufficient variety of examples so that the full power of a technique is well illustrated. The understanding implicit throughout the entire listing is that the reader may from the examples given be led to discover new applications and that, therefore, the list of examples should be such as to enhance this possibility. Many, but not all, of the techniques have been applied at NRL; a parenthetical note after each example gives the nuclear facility at NRL which was used or may possibly be used.

## 1. Production and Uses of Radioisotopes

Radioisotope tracers are in routine use in hundreds of different applications and in virtually every technical field. A few of the references which were found to be particularly useful are the following. A short introduction to this field is given in a booklet entitled "Radioisotopes in Industry" (2). The AEC Division of Technical Information publishes a quarterly journal entitled "Isotopes and Radiation Technology" which contains excellent and comprehensive reviews of the technical progress in the field. Many interesting and unusual applications to aerospace and military problems were discussed at a Symposium on Radioisotopes Applications for Aerospace (3). NRL possesses the capability for producing various radioisotopes, handling radioactive materials, and making measurements on the radiations which are emitted. Radioisotopes can be produced by reactor neutron irradiation, bremsstrahlung, or high-energy electron irradiation, and charged-particle bombardment. Production of radioisotopes by irradiation in a nuclear reactor generally proceeds through neutron capture, so the isotopes produced are neutron rich. Irradiations by cyclotron or linac beams, on the other hand, in general produce proton-rich radioisotopes.

The choice of means for producing a radioisotope will depend on the specific isotope desired, and on requirements that the radiation should not produce some particular isotope which would interfere with the measurements. For example, production of a single radioisotope in carrier-free form is sometimes desirable. Often a given radioisotope produced by a nuclear reaction is subjected to chemical or physical processes, following irradiation, to introduce it into materials for experimentation. It is sometimes possible, however, to cause the production of a radioisotope directly in the material to be studied. The requirements of the particular experiment may be such that activation of a radioisotope is required throughout the volume, in which case the radiation would be performed by longer-range radiations such as neutrons or high-energy bremsstrahlung. On the other hand, it may be desirable only to activate the surface of some particular material. In this case short-range charged-particle bombardment from either the Van de Graaff accelerator or the cyclotron could be used to produce the desired radioisotope, although the higher-energy beams from the cyclotron are sufficiently penetrating to produce limited volume irradiation. Since the choice of the facility to be used for producing a radioisotope depends so greatly on the specific application, a listing for each example of the NRL facility best suited for it has been omitted in this section. A few representative examples of the uses of radioisotope tracers should suffice to show how the techniques can be used in other applications.

a. Wear measurement can be made on irradiated machine parts by monitoring the lubricant carrying radioactive wear particles. Similarly, corrosion processes can be studied by introducing radioisotope tracers into the material which will be subjected to corrosion (2).

b. Radioisotopes can be used in instruments which measure such quantities as densities, liquid levels, and thickness of materials (2).

c. Radioisotopes are being used to measure flow rates and transport and distribution patterns of various materials. They can be used, for example, to measure wastes and effluent flowing into rivers, lakes, and oceans. As another example, they can be used to determine the rate of gas discharge from various devices (2).

d. Mössbauer effect, that is, the recoilless emission or absorption of a gamma ray by a nucleus, has been used to study magnetic and electric field strengths and gradients in crystals. This effect has been shown also to depend on temperature and pressure (4,5,6).

e. Various specialized radiation-detector calibration sources can be produced at NRL. In particular, short-half-life sources or sources which are difficult to obtain commercially may be produced.

f. $Na^{24}$ and $K^{42}$ have been used by NIH in studies of ionic transport through membranes.

g. Radioactive $Be^{10}$, whose half-life is $2.5 \times 10^6$ years, has been found to be present in ocean sediment cores. This nuclide is produced by high-energy neutrons in the cosmic-ray flux reacting with oxygen and nitrogen in the atmosphere. Assuming constancy in time of the cosmic-ray flux allows a determination to be made of the sedimentation rate in the ocean (7).

h. Radiosotope tracers can be used to measure water currents too slow to activate standard transducers. A tracer is released at a central point, and its rate and direction of movement are measured through peripheral detectors. These measurements are being used, for example, in studies of nutrient upwelling in the ocean (8).

i. Chemical analyses or assays can frequently be performed most simply by mixing a known amount of a radioisotope into the original ingredients and then detecting the amount present in the final product. This method is known as isotope dilution analysis (2).

j. Radioactive sources of gamma rays have been used to induce the emission of characteristic fluorescent x-rays from a sample. Measurements of the fluorescent x-rays with high-resolution semiconductor detectors permit a rapid qualitative elemental chemical analysis to be made on a sample even for elements (atomic number $Z \geq 20$) which differ by only one unit in atomic number (9).

## 2. Activation Analysis

In activation analysis, a stable element present in a sample is detected by inducing characteristic radioactivity through a nuclear reaction with that element. The sensitivity of the measurement is such that it is most commonly used for measuring elements which are present only in trace quantities. The trace elements which are to be measured by activation analysis may be present in the sample as extraneous impurities, or they may be purposely introduced. The latter situation occurs, for example, when stable isotopes are used as tracers. This technique, closely similar to that of using radioisotope tracers, is most important, since it can be used in many cases where the use of radioactive materials is precluded prior to analysis. The type of radiation which is used for activation will depend on the trace elements which are being measured and on the material in which they are present. Most commonly, the sample to be analyzed is placed in the high-intensity neutron radiation which is present in a nuclear reactor. It is also possible, however, to produce a desired radioactivity by subjecting the sample to electron or bremsstrahlung bombardment from a linac or to charged-particle bombardment from either a Van de Graaff accelerator or a cyclotron. In the latter case, activation by $He^3$ particles is worthy of special note, since this technique is effective for the very lightest elements, including Be, B, C, N, O, F, and S, where neutron activation is not adequately sensitive. A review of the methods and applications of activation analysis has been given by Sayre (10). An interesting list of applications and a compilation of over 200 references may be found in U.S. Air Force Report No. TR 66-10 (Ref. 11).

After irradiation, the sample containing the activated elements is placed in a low-background detector, and the emitted radiations, usually gamma rays, are measured. In some cases, a chemical separation may be performed to increase the sensitivity. The energies of the emitted gamma rays are characteristic of the radioactive isotopes emitting them, just as optical radiation is characteristic of the emitting atom. In addition,

a particular activity will have a characteristic half-life for decay. By measuring the energies of the various gamma rays which are being emitted, and in some cases determining the half-lives, it is possible to identify the radioactive isotope or isotopes which have been produced in the sample and from these to determine which elements are present. An additional important advantage of this technique is that it is usually nondestructive.

The sensitivity of the technique is such that quantities as small as one part per billion can frequently be measured with ease. In certain cases, extreme sensitivity can be achieved by measuring gamma rays from the desired radioisotope in a coincidence arrangement. In this method, not only are the energies of the gamma rays used to characterize a particular radioisotope but also the decay scheme for that isotope is used. Listed in the following paragraphs are a few of the many ways in which activation analysis is being applied to various problems.

a. An important aid in the investigation of illegal drug traffic is the determination of the place of origin of drugs which are confiscated by law-enforcement officials. In the case of opium, the quantities and proportions of trace elements such as gold and rare earths vary with the origin of the opium. Neutron-activation analysis can be used to determine the quantities of these elements in opium samples. The technique is being used by the Internal Revenue Service (NRL Nuclear reactor) (12).

b. In the development of new and improved rocket propellants, it is necessary to be able to analyze the propellant materials nondestructively. The Naval Ordnance Station, Indian Head, Md., has used neutron-activation analysis as a means to determine various constituents of rocket propellants including trace elements (NRL nuclear reactor).

c. The motions of air masses in clouds have been studied through neutron activation of stable isotope tracers in the following way. An aircraft disperses into a cloud an aerosol containing a stable isotope which is rare in the atmosphere. At a later time, the aircraft, flying through various portions of the cloud, collects samples of the dispersed aerosol. Neutron activation of the rare isotope in these samples then yields data on dispersal and air currents (NRL nuclear reactor) (13).

d. Bombardment of sea water by bremsstrahlung of about 20 MeV makes it possible to detect the presence of trace quantities of fluorine. In this case, the radioisotope $F^{18}$ is produced by the $(\gamma,n)$ reaction on $F^{19}$. It may be possible to study the bromine and the iodine content of sea water by a similar method (NRL linac).

e. The oxide layers formed on p-type silicon during etching and quenching and the oxidation rate of etched silicon on subsequent exposure to oxygen have been measured using proton-activation analysis. The nuclear reaction used was $O^{18}(p,n)F^{18}$; after irradiation, the radioactivity corresponding to $F^{18}$ was measured. The oxidation rate as a function of time for the etched silicon was measured by exposing the silicon to an atmosphere which was enriched to contain 20 percent of molecular $O^{18}$. The sensitivity of the method was such that oxide layers as thin as 0.01 monolayers were measurable (NRL 5-M Van de Graaff) (14).

f. One of the most frequent applications of activation analysis has been the testing of highly purified materials such as semiconductor materials, particularly silicon and germanium, which are used in electronic devices. For example, protons of approximately 18 MeV have been used to measure traces of boron in silicon down to a level of three parts in $10^9$, by means of the reaction $B^{11}(p,n)C^{11}$. The technique consisted, in outline, of irradiating doped silicon samples in the beam of a cyclotron and then processing them by a quick, chemical method to isolate the $C^{11}$ in a source which was then counted by a gamma-ray scintillation counter (possibly NRL cyclotron) (15).

g. Fossil marine invertebrates have been irradiated in a reactor, and the resultant radioactivity has been analyzed to yield a measurement for the ratio of $Sr^{86}$ to $Ca^{48}$. A comparison of this ratio in the fossil to the ratio found in the same marine invertebrate existing today gives information on whether or not the chemical composition of the ocean is changing as a function of geological time. (Isotope ratio measurements are important also for nuclear geochemical dating techniques and for studying isotopic differentiation in chemical processes) (NRL nuclear reactor (16,17).

h. Silicon diffusion coefficients in silicon and in some silicon compounds were measured using activation of a stable tracer in the following way: a thin film (about 0.1 micron) of 89.1-percent enriched elemental $Si^{30}$ isotope was evaporated on to one side of a single crystal silicon specimen. Following evaporation, the samples were annealed in an argon atmosphere and then sectioned chemically. The sections were then irradiated in a reactor, where radioactive $Si^{31}$ was produced by the $Si^{30}(n,\gamma)Si^{31}$ reaction. Each section was subjected to measurements with a gamma-ray scintillation spectrometer. Prior to these measurements, a suitable experimental technique for measuring self-diffusivity in silicon was not available (possibly NRL nuclear reactor)(18).

i. The microscopic distribution of oxygen and carbon has been observed by bombardment of metallographically polished samples with $He^3$ ions and autoradiography of the activated areas. Positional resolution of 0.0005 in. has been obtained in samples having bulk carbon concentrations of about 250 ppm (19).

## 3. Analysis by Nuclear Reactions

Just as measurements of the radioactivity produced in a sample material by an irradiation can be used to determine the chemical constituents of the sample material, so measurements of the prompt radiation can be used (20,21). In this case, the emitted radiations are not restricted to beta or gamma rays, as is usual in activation analysis, and the detected radiations may frequently be emitted as charged particles. Analysis by nuclear reaction is most commonly performed using charged-particle beams produced by Van de Graaff accelerators or cyclotrons and using particles such as protons, deutrons, helium-3 particles, or alpha particles to produce the nuclear reactions. This method of analysis often requires that the sample of material be in the form of a thin film, thus these charged-particle beams are best applied to studies of surfaces. For low-energy beams, however, this limitation turns out to be an advantage, since only the surface is activated and not the entire volume of the sample. The method is especially useful for measuring chemical composition of thin films formed on solid host materials.

Just as is the case for activation analysis, the chemical constituents being measured can be present in the sample as extraneous impurities, or they may be purposely introduced into the sample as stable isotope tracers. The sensitivity which can be achieved depends on the amount of background which the detecting system measures in the region in which the characteristic radiation occurs. The possibility of analysis by nuclear reactions should always be considered when more common techniques do not appear completely satisfactory. It may be the case that no suitable radioactive species can be produced from a particular trace element which is being looked for, but that a nuclear-reaction analysis on the same trace element may be relatively simple. Two representative examples of analysis by nuclear reactions are given in the following paragraphs.

a. The $S^{32}(d,p)S^{33}$ nuclear reaction has been used to measure the presence and the amount of sulphur in thin films which had been formed on five-cent coins. In this particular case, other analytical methods, including chemical, spectrographic, and microprobe analyses had not proved successful, but the analysis by nuclear reaction turned out to be straightforward and had a high sensitivity. Estimates based on the measurements showed that films with surface densities of $10^{-7}$ g/cm$^2$ could be measured quite easily (20).

b. Because the incident beam begins to lose energy as soon as it enters the target material, sharp nuclear resonances can be used to measure the amount of a given isotope as a function of the distance from the surface. This fact, combined with the use of stable isotopes as tracers, produces a very powerful technique. Thus, for example, the ion-transport mechanism in the growth of oxide films during anodic oxidation of aluminum has been studied by using $O^{18}$ as a stable tracer. The position of the $O^{18}$ and Al atoms was determined by measurements near sharp resonances for the $O^{18}(p,\alpha)N^{15}$ and $Al^{27}(p,\gamma)Si^{28}$ nuclear reactions. The studies indicated that the oxygen sublattice remains stationary and that the metal atoms move by vacancy diffusion and by interstitial exchange capture (22).

4. Radiation Damage

Radiation damage will here be taken to mean all those effects produced by the interaction of radiation with matter which are deleterious to the sample being irradiated. Examples of damage to various materials and devices will be given; damage to biological systems is excluded from consideration here. Radiation damage to matter can be the result of a number of physical changes. If the radiation is intense enough and if the sample is irradiated for a long enough period, sufficient transmutation can take place by means of nuclear reactions that a significant quantity of trace elements is introduced into the host material. Also, all irradiations can produce varying degrees of ionization in the host material, with consequences to the chemical bonds in the material. Irradiations can in addition produce dislocations of the atoms of the host material and, in the case of ion beams, also can introduce extraneous elements into the host material.

Gamma-ray, electron, and neutron radiations can produce damage through relatively large volumes of the sample being irradiated. For heavier charged particles, damage produced by beams from the Van de Graaff accelerator would be limited to very thin surface layers, while that produced using beams from the cyclotron would be produced in relatively deeper layers of the host material. Even for the cyclotron, however, particularly if particles heavier than protons are being used for the beam, the radiation damage will be limited to a surface layer of the host material.

a. The radiation damage to electronic components, including transistors and diodes, has been investigated in situ by irradiating the devices with neutrons (NRL nuclear reactor).

b. Accelerometers and strain gauges were tested for use on naval propulsion reactors by irradiating them with neutrons (NRL nuclear reactor).

c. Electronic equipment and components, such as xenon flash lamps, silicon solar cells, and various crystalline laser materials, have been irradiated by pulse beams of high-energy electrons or x-rays to study the transient radiation effects produced (NRL linac).

d. The most damaging space-radiation environment for solar cells is comprised of the geomagnetically trapped electrons and protons in the magnetosphere, or the so-called Van Allen radiation. Radiation-damage measurements have been made for solar cells which have been irradiated with both electrons and protons (NRL 2-MV and 5-MV Van de Graaffs) (23).

e. Thermal control coatings for earth-orbiting satellites have been irradiated with protons in the energy range from 50 to 400 keV. In this range, the entire energy exchange occurs within the paint film, so that all incident energy is absorbed. The resulting damage is observed as a decrease in spectral reflectance. The amount of degradation was found to be nearly linear with absorbed energy (24).

## 5. Radiation Effects

Radiation effects will be taken here to mean all those physical changes which are desired in a particular experiment or which improve the properties of the material which is being irradiated in some way that is desired.

a. High-energy electron beams and bremsstrahlung radiation have been used to produce cross linking in numerous organic compounds. Among many applications of this effect are: curing of various paints and polyester epoxy varnishes; increasing the impact strength (by 100 percent) of polyethylene film; production of extreme plastic memory, a property utilized in heat-shrinkable films and tubings (possibly NRL $Co^{60}$ source, 2-MV Van de Graaff, or linac).

b. Some synthetic fibers in use today are so dye resistant and so given to electrostatic charging that some treatment is needed to make them useful in fabrics. Slight degradation of the synthetic materials by irradiation with high-energy electrons renders them able to absorb dyes and some moisture from the atmosphere to reduce electrical charging (possibly NRL 2-MV Van de Graaff)(25).

c. Alkali halide crystals have been irradiated with single or low-rate repetitive pulses of high-energy electrons, and transient optical effects produced by these irradiations have been measured (NRL linac).

d. The formation of chemical compounds has been investigated with the aid of intense ionization produced by fission products. A uranium compound is intimately mixed with other materials of interest and irradiated by neutrons (NRL nuclear reactor) (26).

e. Bombardment of thin magnetic films with beams of high-energy $He^3$ particles, while the films are suspended in a magnetic field, has produced films with improved magnetic hysteresis properties (NRL 5-MV Van de Graaff) (27).

f. It has been found that damage trails made by moving charged particles in a material can be chemically attacked much more rapidly than the normal undamaged regions of the sample. A few illustrations of this important effect, which promises to be useful in many diverse areas, are the following. It has been used to determine geological age of minerals with high sensitivity. Examinations of tracks in meteorites have yielded information on the abundance of heavy primary radiations in cosmic rays. Uranium fission tracks produced in a sample which was irradiated by neutrons have been used to obtain a dose measurement for the irradiation. Also, a new filter has been developed by bombarding a material with energetic heavy ions and etching the resulting tracks. The filter has holes so small that it can be used to separate biological cells of different sizes. Holes with uniform diameters ranging from approximately 50 Å up to many microns are easily obtainable (28).

## 6. Ion Implantation

An ion which has been accelerated to a given energy and directed against the surface of a solid will penetrate into the solid to a depth determined by the incident energy of the ion and the stopping power of the solid (range straggling is, in general, smaller than 5 percent of the range). If, in addition, the mobility of the atom implanted in the host material is sufficiently low, it will be effectively trapped at its penetration depth. This process is termed ion implantation. While this field is relatively new, the work performed thus far has demonstrated that the diversity of the areas in which ion implantation may be expected to have important applications is large. The NRL accelerators have excellent capabilities in this area in terms of beam production and handling. Available energies

range up to 5.5 MeV for the large Van de Graaff and up to 75 MeV for the cyclotron. Both accelerators are capable of accelerating heavy ions.

Ion implantation can be used either to introduce a tracer element with no appreciable change in the properties of the host material, or to introduce an element for the specific purpose of affecting the properties of the host material. A brief comparison of ion implantation and thermal diffusion, as alternative ways of introducing impurity atoms into a host lattice, will serve to illustrate the principal advantages of ion implantation. They are the following.

- The impurity-concentration profile, that is, the impurity concentration versus the distance from the surface, can be controlled to almost any desired shape by appropriately varying the energy of the incident ions during bombardment. Results obtained thus far have shown that the radiation damage produced in the crystal by the ion implantation can usually be successfully removed by annealment at temperatures below those at which thermal diffusion of the implanted atoms is appreciable.
- The quantity of implanted ions can be measured quite accurately over a range which starts with quantities too small to produce detectable changes in the properties of the host solid and ends at the other extreme with supersaturation of impurity atoms; the latter is a condition which cannot be attained through thermal diffusion. The measurement accuracy is due to the fact that the quantity of ions implanted is measured as an electric current integrated over the bombardment time.
- The purity of the implanted ions can be very high. Prior to striking the surface which is being irradiated, the ions can be subjected to deflection through a magnetic field which removes impurities in the beam to a high degree.
- The location of the implanted ions can be controlled presently through masking techniques similar to those used for microelectronic circuit fabrication; eventually this control may also be achieved through accurate positioning of a small beam spot.
- Any type of ion can be implanted in any host material, provided that a suitable source can be developed for the ion in question. Diffusion characteristics will be important only for determining whether the implanted ion remains close to where it stopped, and not for the implantation process itself.

Ion implantation has not yet been performed at NRL. The available facilities are such, however, that this type of research could easily be started. Listed in the following paragraphs are representative examples of applications which have thus far been found.

a. Solar cells with efficiencies greater than 13 percent have been produced using ion implantation. This efficiency is as good as or better than the best cells which can be produced by conventional diffusion techniques (29).

b. Multi-element solid-state detectors, with a minimum of dead space between detectors, have been produced by bombarding a silicon wafer through a mask (30).

c. Boron and phosphorous ions at energies ranging from 100 keV to 1.5 MeV have been implanted in bulk silicon to produce controlled p- and n-type layers at junction depths of 0.35 to 2.3 microns (29).

d. Small area mesa and planar diodes have been produced by ion implantation (29).

e. Using low-energy ions, shallow implantations have been achieved. Shallow thermal diffusions are very difficult to produce (31).

f. Supersaturation of sodium atoms in silicon has been achieved. With thermal diffusion, an upper limit of sodium concentration in silicon is about $10^{15}$ atoms per cubic centimeter. With ion implantation, concentrations of $10^{21}$ atoms per cubic centimeter have been achieved (31).

g. Implantation of sodium in silicon has produced sheet resistivities $10^3$ times lower than can be achieved by thermal diffusion (31).

h. Implanted radioactive krypton-85 has been used to study the onset of corrosion processes. The measurement is based on the fact that the implanted krypton escapes as a metal surface oxidizes. The reduction in radioactivity of the metal sample can then be correlated with the amount of surface oxidation (32,33).

i. Radioactive krypton-85-implanted solids (Kryptonates*) have been shown to be highly accurate end-point indicators for chemical titrations, where previous indicators were not satisfactory. The Kryptonate reacts with the titrant but not with the solution being titrated; the release of radioactive krypton produced by the reaction and detected with a radiation detector is used as the end-point indicator (33).

j. Kryptonates which release radioactive krypton upon reaction with a chemical have been used for detecting the presence of corrosive or hazardous gases such as ozone, fluorine, chlorine trifluoride, oxygen difluoride, hydrogen sulfide, sulfur dioxide, and others (33).

## 7. Energy Loss in Materials and Related Ionization Phenomena

Energy loss of charged particles in matter has been a relatively neglected area for many years. In the past few years, however, significant advances have been made in understanding energy-loss mechanisms because of high-resolution studies of narrow nuclear reaction resonances. NRL has played a key role in these studies and is exceptionally well equipped to continue work in this area. In a related field, that of utilizing energy loss in matter to produce highly excited and ionized atoms, NRL is also well qualified. The two examples given here illustrate how energy-loss processes have been applied.

a. A beam of high-velocity atomic ions (such as $N^+$ or $O^+$) from an accelerator such as a Van de Graaff or a cyclotron can be turned into a unique source of optical radiation. The principle used is basically simple. The beam of atoms is passed through a thin foil of carbon. These atoms are excited by passage through the foil and subsequently de-excite by emitting optical radiation which may be viewed by a spectrograph. Since the beam of atomic ions is analyzed magnetically before it reaches the foil, it is free to a high degree from any contaminants. The method permits fairly direct measurements of atomic-state lifetimes. In addition, after the beam has passed through the foil, it is possible by means of electrostatic deflection to sort out the various charge states and to identify the observed spectral lines definitively with the charge state from which they were emitted. High states of ionization can be produced by this technique more conveniently than by the usual methods used in atomic spectroscopy (NRL 5-MV Van de Graaff, possibly cyclotron) (34).

b. Some nuclear resonances are so narrow that if the energy of the incident beam is off resonance by as much as 100 eV, the yield from the reaction will drop by more than a factor of ten. High-resolution studies of such nuclear-resonance reactions, together with energy-loss calculations, can be used as a sensitive test for the uniformity of thin foils or films; deviations from uniformity as small as 5 percent can be detected. Uniformity here means both microscopic and macroscopic uniformity of surface density. Thus,

*Krypton-implanted solids have been termed "Kryptonates," and the name has been registered as a trademark by Parametrics, Inc., Waltham, Massachusetts.

if the film consists of clusters or microscopic globules of atoms uniformly distributed, the test will still show it to be nonuniform (NRL 5-MV Van de Graaff) (35)

c. Relatively pure sources of low-energy characteristic x-rays ($\lambda > 10$ Å) can be produced by bombarding targets with beams of protons or alpha particles. Since these nuclei at energies of a few MeV are nonrelativistic, they do not produce interfering bremsstrahlung along with the characteristic x-rays, as do electrons (36,37).

8. Energy or Charge Deposition

The capability of accelerator beams to deposit energy or charge or to affect the properties of a sample material by such deposition have not to date been specifically utilized with the NRL facilities. However, these facilities have a considerable potential in this area, as may be illustrated by the following examples.

a. Electrons of a given energy have a much longer range in matter than atomic nuclei of the same energy, so that effects with high-energy electron beams can be produced through a relatively large volume of sample material. Atomic nuclei such as alpha particles, having much shorter ranges, can deposit relatively large power densities. Average available beam powers for the 5-MV Van de Graff, cyclotron, and linac, respectively, are 0.5 kW, 7.5 kW, and 3.5 kW. Beam-spot sizes for all three accelerators can be adjusted to be as small as a few square millimeters. The power densities deposited by these beams can be applied to such problems as sputtering and melting, and to studies on thermal shocks.

b. One interesting technique may depend on deposition of charge; the mechanism for it has not yet been clearly established. In this technique, a beam of heavy atomic nuclei from a Van de Graaff accelerator has been used to effect a uniform removal of material from a surface of fused silica upon which the beam impinged. This process, termed "ionic polishing," appears to be capable of producing a higher degree of polish than previous mechanical techniques. It is being studied commercially at present in connection with the final figuring of lenses, with the figuring being done simultaneously with lens testing. This process works also on other glass-like materials. (Ionically polished surfaces may also be important for ceramic bearings) (38).

9. Radiography

X-ray radiography is an old and established technique currently in use in many areas of NRL. The NRL facilities in this area are distinguished by the relatively higher energy (and thus more penetrating) x-rays which they can produce. For the newer technique of neutron radiography, suitable sources of neutrons at NRL are generally available only with the Nuclear Physics Division facilities.

a. NRL possesses two electron accelerators, a 2-MV Van de Graaff and a 60-MeV Linac, which could be used for radiography. The high-intensity, high-energy bremsstrahlung from these accelerators makes them particularly well suited for some applications.

b. Neutron radiography is still in a developmental stage. Neutrons are scattered more strongly from hydrogen than from a heavy element such as lead, thus enabling neutron radiography to complement x-ray radiography. Neutrons will show up masses of hydrogenous material, while x-rays, of course, show up heavy elements best. It is possible with neutron radiography, for example, to detect, through a lead wall, a stream of water flowing on the other side (possibly NRL nuclear reactor).

## 10. Neutron Diffraction

The wave nature of neutrons permits them to be diffracted from materials, such as crystals, which possess some regularity in their atomic structure. In addition, the magnetic moment of the neutron enables information to be obtained on magnetic structure of materials. The following two examples, performed at the NRL nuclear reactor, illustrate the utility of neutron-diffraction measurements.

a. An anomalous behavior in the resistivity (and other properties) had been noted for PdH near 50°K, but no complete explanation of the effect had been proposed. Neutron-diffraction measurements have been able to show that the crystalline structure is different above and below this transition temperature. Since deuterium has a lower incoherent scattering cross section than hydrogen, PdD has also been used in the measurements and has permitted assignment of the crystalline structure in the two temperature regions. In this experiment, the approximate equality of the scattering amplitude of hydrogen and palladium allows the neutron-diffraction experiment to be performed; on the other hand, the analogous experiment with x-rays would be impractical (39).

b. The magnetic structure of materials such as yttrium iron garnet, magnetite, and $CoCl_2 \cdot 6H_2O$ has been studied. In these cases, the magnetic moment of the neutron interacts with the magnetic structure and allows a determination of the arrangement of the magnetic atoms in the crystalline structure. In some cases, different arrangements of atoms of a given element may produce different magnetic properties, such as ferro- and ferrimagnetism, and neutron diffraction can reveal these differences (40,41,42,43).

## 11. Detector Calibrations

The calibration of radiation detectors, while basically a nuclear activity, may be of importance to many nonnuclear applications which involve the detection of radiation. The NRL facilities provide a very wide range of types of radiation, energies, and intensities, and are well suited to provide radiations for such calibrations. A few examples of calibrations using these facilities are listed in the following paragraphs.

a. Various charged-particle detectors intended for use in earth-orbiting satellites can have their energy and efficiency characteristics measured by subjecting them to irradiations with charged particles, such as protons, deutrons, and alpha particles of known intensity and known energy, produced either by the 5-MV Van de Graaff accelerator of the cyclotron, and to electrons produced by the linac or the 2-MV Van de Graaff accelerator (44).

b. Experiments involving the calibration, efficiency measurement, and electronic testing of multielement gamma-ray telescopes of the type designed to be carried on earth-orbiting satellites have been performed with extremely low beam intensities of high-energy electrons from the linac.

c. Various detectors have been irradiated with monoenergetic neutrons produced at the 5-MV Van de Graaff accelerator. The cyclotron is able to produce monoenergetic neutrons at higher energies than those available at the 5-MV Van de Graaff.

d. Neutron monitors have been calibrated using neutrons produced by the linac.

e. Thermal neutron dosimeters have been calibrated using the thermal column of the NRL nuclear reactor.

f. High-energy electrons from the NRL linac have been used to produce pulses of intense radiation which have been used to study the characteristics of thermoluminescent dosimeters.

g. Radioactive sources produced in the reactor have been used by many investigators to provide gamma and beta-ray energy calibration for detectors. The cyclotron will also be capable of producing a wide variety of radioactive sources.

## IV. AREAS DESERVING SPECIAL ATTENTION

An attempt has been made throughout this report to present the material in such a way that the reader will be able to evaluate the importance of the various techniques described to his own work. In addition, in order to enhance the possibility that completely new applications might be discovered, examples have been chosen so that the advantages and the power of each technique would be illustrated. With these objectives in mind, it may nevertheless prove useful to speculate upon those areas which appear most promising for future effort at NRL.

Radioisotope tracer techniques are so widely applicable in such a variety of ways that it seems likely that there exist many problems for which these techniques could be used to advantage. NRL, moreover, has a range of capabilities in this area which are not commonly found in one laboratory. The NRL nuclear reactor facility is fully equipped for producing and handling a wide variety of radioactive nuclei. Also, the potentialities of the cyclotron and the linac for producing unusual radioisotopes should be noted; it may be that some applications will be possible with these radioisotopes which are not possible with those more commonly used. In particular, the availability of the NRL facilities permits the utilization of shorter half-life activities. Finally, the capabilities of the NRL facilities to activate radioisotopes in existing samples may provide an advantage over the use of radioisotopes from commercial sources which must be introduced into the sample. In particular, the ability of the cyclotron and the 5-MV Van de Graaff accelerator to produce radioisotopes directly in the surface of a given sample may facilitate needed measurements.

Although the technique of activation analysis has seen a rapid development in the past few years, it has only begun to be used at NRL. A few groups are equipped or are now equipping themselves to carry out a program in activation analysis, and it may be beneficial for others to do so. In particular, since the need for highly purified and exotic materials is expected to increase in the future, it appears likely that the high sensitivity of activation analysis will be not only useful but necessary for measuring the purity of such materials. New developments continue to affect this technique: for example, the recent development of the lithium-drifted germanium detector, with its high energy resolution, has greatly increased the power of activation analysis. Although the nuclear reactor is useful for most applications, the linac, cyclotron, or 5-MV Van de Graaff can be useful or even necessary for the detection of certain elements. Activation analysis also can be used in conjunction with stable-isotope tracers to make measurements possible in cases where radioactive tracers cannot be used. The use of stable isotope tracers is a technique which shows great promise for the future.

A relatively new and promising area is that of analyzing surfaces for trace quantities of elements by using nuclear reactions induced by charged-particle bombardment. This technique may have advantages over others, particularly for detecting the light elements. It may also be combined with the use of stable-isotope tracers to study various surface phenomena. Additionally, if a nuclear reaction possessing a sharp resonance is used, it is even possible to measure the quantity of a trace element as a function of the distance from the surface.

Improvements due to radiation-induced cross-linking in organic compounds have already been reported for such characteristics as impact strength, bonding strength, and plastic memory. Since some organic compounds show promise in the search for new materials and new fabrication processes, it may be that radiation-induced effects

should receive increased attention at NRL. The transient responses of materials to bursts of radiation, under carefully controlled laboratory conditions, have proved to be quite useful in some cases for studying properties of materials.

Preferential chemical etching of damaged trails made by moving charged particles in a material is an effect which promises to have many interesting applications, ranging from radiation dosimetry to the production of holes as small as 50 Å in diameter.

Ion implantation is another area which appears particularly promising. This technique lends itself to a great variety of potential applications, yet only a relatively few laboratories are presently engaged in this type of research. From results already obtained elsewhere, it appears likely that this technique will make important contributions to solid-state problems, particularly to the field of semiconductors. Also, Kryptonates, that is, solids in which radioactive krypton-85 has been implanted, appear promising for a variety of applications involving chemical reactions.

## V. CONCLUSIONS

Past experience has shown that an interdisciplinary approach to a problem frequently provides a solution otherwise unobtainable and sometimes opens up entire new areas of research. It is also true that an all-too-rare combination of skills, interests, and facilities must be present before effective interdisciplinary research can be pursued. The present report resulted from an attempt to assist the solution of difficult research problems at NRL by examining the potential advantages of applying nuclear techniques to nonnuclear areas.

During the preparation of this report, the following conclusions were reached by the Nuclear Applications Committee:

1. Powerful nuclear techniques exist which may have important advantages over other methods but, in many cases, are not being adequately exploited either at NRL or elsewhere. For example, analysis by nuclear reactions and activation analysis by nuclear charged particles and gamma rays should be considered for specific problems, along with the more common technique of neutron-activation analysis. Also, ion-implantation and radiation-induced materials effects hold promise of important advances in producing new solid-state devices and in materials preparation. These and other promising areas have been discussed more fully in Section IV.

2. The NRL nuclear facilities are highly instrumented and can handle numerous applied problems; together they cover an exceptionally wide range of nuclear applications. These facilities, since they are presently not operating on a three-shift basis, can accommodate additional work through an increased operating schedule.

3. The scientific competence, excellent facilities, and broad spectrum of research in the physical sciences combine to put NRL in an advantageous position for applying an interdisciplinary approach to the solution of research problems. In particular, an increased utilization of nuclear techniques and facilities in nonnuclear areas is recommended as highly promising.

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## Appendix A

## INTERACTION OF RADIATION WITH MATTER AND RADIATION DETECTION

### INTRODUCTION

Nuclei can, depending on the specific nucleus and its state of excitation, emit gamma rays, electrons, positrons, neutrons, protons, deuterons, alpha particles, etc. These radiations can be emitted spontaneously from radioactive nuclei, or they can be the product of induced nuclear reactions. The distinction between these two cases is arbitrary. In practice, the term radioactive is applied to nuclei whose decay half-life is sufficiently long that measurements on the emitted radiations can be made after the production of the unstable nuclei has ceased. The half-lives of radioactive nuclei range from more than billions of years to less than one millisecond.

It is convenient to divide radiation-detection measurements into time ranges. For activities with half-lives of about one minute and longer, the sample can be taken from the place in which it was irradiated to a separate detection facility (usually one which has low radiation background). In many of these cases, there is adequate time for chemical or other processing which may be required to obtain high sensitivity for detection of some specific result. For half-lives in the approximate range from one-tenth of a second to one minute, the sample can be moved to a separate detection facility, but there is usually not sufficient time for additional processing. For half-lives in the range from a fraction of a microsecond ($\mu$sec) to about one-tenth of a second, there is time to stop the irradiation, but the sample is left in place for counting. For half lives shorter than a fraction of a microsecond, radiation detection is performed concurrently with irradiation.

The ideal radiation detector is one that can identify the type of radiation which is incident on it, measure its energy with high resolution, have 100-percent efficiency for detection, and have a response time as short as possible. Some of these characteristics tend to be mutually exclusive, and the best detector for a given purpose usually represents some compromise of the ideal properties. The properties and operating characteristics of detectors are basically due to the various ways in which radiation interacts with matter. For most purposes, a general discussion of radiation interactions should suffice to show how detectors operate.

### GAMMA RAYS

Gamma rays interact with matter in three ways: through the photoelectric effect, the Compton effect, and, if there is sufficient energy, through pair production.

In the photoelectric effect, essentially all of the energy of the gamma ray is imparted to an electron. Since electrons are stopped in matter because they lose energy by ionization and excitation processes, there is then a good probability that all of the energy will be deposited in the detector. The spectrum of energies deposited by monoenergetic gamma rays will show a single peak corresponding to the energy of the gamma rays.

In the Compton effect, a gamma ray is scattered from an electron and loses a fraction of its energy to the electron. If the scattered gamma ray escapes from the detector, the spectrum of energies deposited in the detector is very broad.

In pair production, a gamma ray is converted into an electron-positron pair; both the electron and the positron are stopped, but the positron then annihilates with an electron to produce two 511-keV gamma rays. If both annihilation gamma rays are absorbed in the detector, then all of the initial gamma-ray energy will have been deposited in the detector. Depending on the size of the detector, the escape of one or both annihilation gamma rays may occur. In the case of pair production, therefore, the spectrum of energies deposited in the detector may show three peaks, one corresponding to total absorption, one to single escape, and the lowest to escape of both annihilation gamma rays.

At the present time, the two most commonly used types of gamma-ray detectors are scintillation detectors and semiconductor detectors. A scintillation detector consists of a photomultiplier tube optically coupled to a scintillator such as a NaI(Tl) crystal. Scintillators have the property that a fraction of the energy deposited is converted to fluorescent radiation which is essentially proportional to the energy transferred to the electrons by the incident radiation. Voltage pulses from the photomultiplier system are usually amplified and sent into a multichannel pulse-height analyzer, where they are accumulated to form a pulse-height spectrum. For monoenergetic gamma rays, the more nearly a detector is ideal, the more nearly will all output pulses be of the same size, and the sharper will be the peak in the pulse-height spectrum. A typical pulse-height spectrum produced by gamma rays, with energy below the pair-production threshold, incident on a scintillation detector is shown in Fig. A1. The energy resolution of a peak is usually defined as the full width at half maximum divided by the pulse height at the peak. For best resolution in measuring the energy of a gamma ray, it is clearly desirable to obtain total absorption of its energy in the scintillator and efficient collection of the fluorescent radiation at the photomultiplier cathode. Absorption increases with increasing crystal size and with increasing crystal density and average atomic number. Thus, for example, NaI(Tl) is to be preferred on the last two counts to a crystal such as anthracene. Light-collection efficiency, however, goes down as crystal size goes up, so the optimum crystal size is usually chosen according to the range of gamma-ray energies which is of interest. For gamma rays with energies up to a few MeV, detectors with 3-in.-diameter and 3-in.-long crystals of NaI(Tl) are widely used.

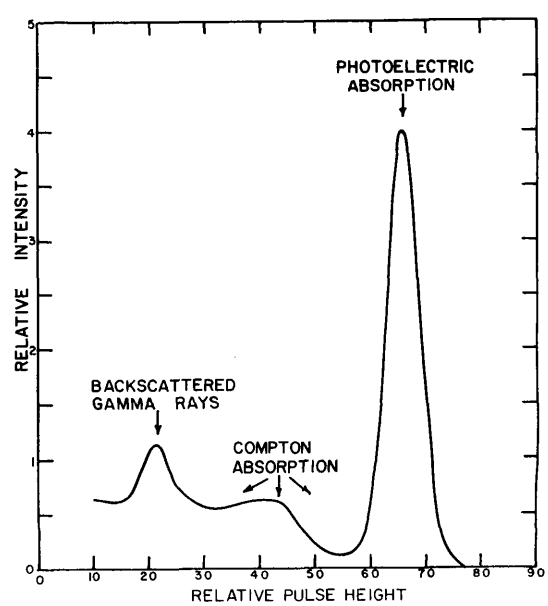


Fig. A1 - Pulse-height spectrum obtained for monoenergetic gamma rays incident on a NaI(Tl) scintillation detector

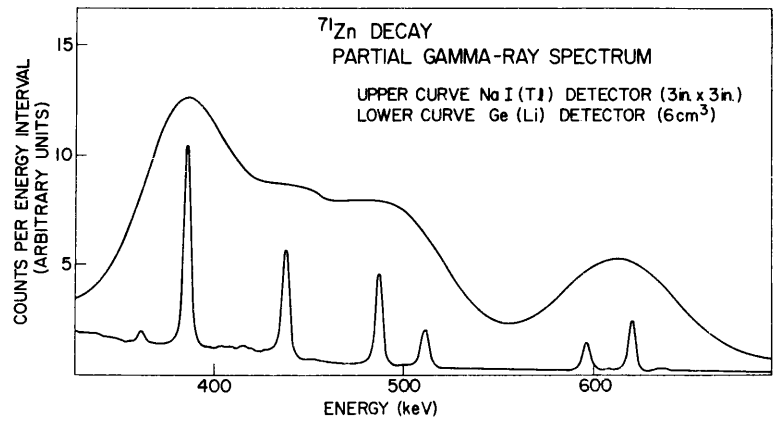


Fig. A2 - A comparison between the pulse-height spectrum obtained with a sodium iodide scintillation detector and that obtained with a lithium-drifted germanium detector

Semiconductor detectors for gamma rays, at present, are of the PIN type, consisting of a crystal of either lithium-drifted silicon or lithium-drifted germanium. The latter, because of its higher atomic number, is preferred in most cases. These detectors are usually cooled to the temperature of liquid nitrogen for best resolution; the lithium-drifted germanium detectors must be kept at low temperature even when they are not in use. The action of a semiconductor detector is analogous to that of an ordinary ionization chamber; the electron-hole pairs created in the crystal by the electrons from the gamma-ray interactions are collected, and the resulting voltage pulse is amplified and analyzed according to pulse height, just as is done with a scintillation detector. Because the number of electron-hole pairs deposited in the crystal is relatively large, semiconductor detectors have excellent energy resolution; resolutions as low as 0.1 percent have been obtained in some cases. For gamma-ray detection, however, these detectors have the disadvantage of relatively small volume. Whereas NaI(Tl) crystals with volumes of several hundred and even one or two thousand cubic centimeters are common, the largest commercially available semiconductor detector to date has a volume of only 40 cu cm. A comparison between the pulse-height spectrum obtained with a NaI(Tl) scintillation detector and that obtained with a lithium-drifted germanium detector is shown in Fig. A2.

## CHARGED PARTICLES

Charged particles are more easily stopped in matter than gamma rays or neutrons of the same energy, since they lose energy directly by excitation and ionization of the atoms in the material through which they are moving. If the detector thickness is greater than the range of an incident particle, there is a relatively high probability that all of the energy of the particle will be deposited in the detector. Thus, usually, the pulse-height spectrum produced by monoenergetic charged particles incident on a detector will consist of a single peak whose pulse height is proportional to the energy of the particle. Spectra from charged-particle measurements are thus inherently simpler than for gamma rays, where the pulse-height spectrum usually has a structure as shown in Fig. A1. For charged particles, as for gamma rays, detector energy resolution is given in terms of the full width at half maximum of the total absorption peak.

The advent of semiconductor detectors, during the past few years, has so revolutionized the field of charged-particle detection that semiconductor detectors are used wherever possible. The principal exceptions to such usage are those cases for which the charged-particle range is large compared to the dimensions of the detector, or for

which the energy resolution required by the measurements exceeds that which can be obtained with semiconductor detectors.

It is useful to distinguish between the detection of electrons or positrons and the detection of heavier particles, such as protons, deuterons, and alpha particles. Electrons (or positrons) have, for a given energy, a much longer range than the nuclear particles; for example, 5.0-MeV electrons in silicon have a range of 1.02 cm, whereas 5.0-MeV protons in silicon have a range of 0.02 cm. Therefore, if good resolution is to be obtained, electron detectors should have relatively large volumes. For electron ranges in silicon greater than 1 mm or so, lithium-drifted silicon detectors are most commonly used.

For the heavier charged particles, whose ranges in the detector are approximately equal to 1 mm or less, the most commonly used semiconductor detectors are of the PN-junction type, with silicon as the host crystal. These detectors may be operated at room temperatures, have a fast response time, and can have energy resolution as good as 0.25 percent. For longer-range particles, as for gamma rays, the PIN detectors, with their relatively greater volume, are used.

In cases where several types of charged particles are present (as in many nuclear reactions), a very thin detector may be placed in front of a detector thick enough to stop the particles. Relationships between the energy loss in the thin detector and the sum of those lost in both detectors (total energy) may be used to identify most of the common lighter reaction products.

Magnetic analyzers with a detection system located in the image plane are used for both electrons and heavier charged particles in a number of situations where semiconductor detectors alone are not satisfactory. Such situations are encountered, for example, when resolutions better than 0.25 percent are required. Also, the intensity of background radiation may in some cases be so high relative to the radiation of interest that measurements with a semiconductor detector alone are not practical; a magnetic analyzer set to accept a particular energy may reject the interfering background and make measurements possible. A third situation which may arise is that a magnetic analyzer is required to distinguish between charged-particle species with small relative mass differences. Distinguishing between $Li^6$ and $Li^7$ ions, for example, can be achieved with magnetic analysis but not with solid-state detectors alone. Resolutions of 0.1 percent are readily obtained with magnetic analyzers but the acceptance solid angles are generally smaller than those of semiconductor detectors used directly.

## NEUTRONS

A neutron deposits energy in a detector by first imparting energy to a charged particle, which then produces ionization in the detector. Neutrons can do this in two ways: through elastic scattering from atomic nuclei, and through absorption in atomic nuclei, thereby causing nuclear reactions. In the latter case, charged particles and gamma rays may be emitted. The types of radiation affect the way in which energy is deposited in the detector. Because neutron interactions have relatively small cross sections, neutrons are not easily stopped in matter. Thus, apart from problems of energy resolution, neutron detectors inherently have low efficiency for detection. The relatively long mean free path of neutrons in matter also means that, in general, when neutrons are being detected, there is a background of neutrons present which must be taken into account.

The central problem in neutron detection remains, however, to obtain good energy resolution. In the elastic-scattering process, a neutron loses a fraction of its energy; for a head-on collision with a proton, it loses all of its energy. If the detector utilizes absorption of the radiation emitted from neutron-induced reactions, energy resolution

may still be a problem, because there may be a number of alternative modes through which a reaction can proceed, or the energy release in the reaction may be large compared to the neutron energy.

No one or two techniques for neutron detection are predominant to the extent that is true for charged-particle and gamma-ray detection. Among the more common detectors in use are: scintillation detectors which have scintillating liquids, or crystals with high hydrogen content or with a high content of an isotope which, upon neutron capture, will give rise to a desired nuclear reaction; proportional counters filled with $BF_3$ or $He^3$ gas; and detecting systems which measure a neutron's energy by measuring its time of flight over a known distance. The latter technique is becoming more widely used, and, as electronic pulse techniques improve, it shows improvement in energy resolution. Semiconductor detectors are beginning to be used for certain applications, but at the present time they have too low an efficiency for most experiments.

## Appendix B

## CYCLOTRON FACILITY

### CYCLOTRON

The cyclotron is an electromagnetic device for the acceleration of positive ions to medium high energies. Groups of ions originating from an ion source near the center of the cyclotron magnet are constrained by means of steady magnetic fields to move in roughly circular orbits. Acceleration of these groups of ions is accomplished by incremental increases in energy on successive passes through a gap across which an electric potential is imposed, varying sinusoidally at a fixed frequency in the range from 7.5 to 22.5 Mc/sec. Appropriate relationship of the magnetic-field configuration and the frequency permit the ions to cross the gap at the peak of the varying potential so that the ions are accelerated to orbits of increasing radius and energy. At an appropriate radius, guiding electrostatic and magnetic fields extract the ions from their orbits to produce an external ion beam of fairly compact proportions. These beams are conducted in vacuum through successive magnetic focusing lenses to impinge upon targets of sample materials. The ion beams may be transmitted over sufficient distances to carry the beam through penetrations in the shielding walls, permitting experiments to be performed in areas relatively free of the considerable background radiation from the vicinity of the accelerator itself. The floor plan of the experimental areas is shown in Fig. B1, with the NRL cyclotron and various guiding magnets shown in room 4.

### PROPERTIES OF THE ION BEAMS

In the case of modern cyclotrons, such as the one at NRL, the capability of adjustment over a range of both accelerating frequency and magnetic-field configuration permits the acceleration of a wide variety of ion species over a range from about 10 to 100 percent of the maximum energy available. The maximum energy depends upon the mass and charge state of the ion; some representative values (energies in MeV) are $^{1}H^{+}$, 75; $^{2}H^{+}$, 39; $^{3}He^{+2}$, 100; $^{4}He^{+2}$, 78; $12C^{+4}$, 115; $^{14}N^{+4}$, 100; $^{16}O^{+4}$, 88; $^{20}Ne^{+5}$, 108; $^{40}A^{+7}$, 103; $^{84}Kr^{+12}$, 145. The initial ion-source configuration will provide primarily beams of the hydrogen and helium isotopes. Some modifications of this type of source may be required for heavier ions. Available ions will generally be limited to elements available in gaseous form until, in the course of development of the facility, a proposed axial injection system is developed which will permit the use of the external ion sources necessary for other less readily ionizable elements. The acceleration of any radioactive ion species such as $^{3}H$ or $^{85}Kr$ is not contemplated with this facility.

The energy homogeneity of the external beam from the cyclotron is expected to be about 0.3 percent, which is quite adequate for most user experiments. Where greater homogeneity is required, a beam-analyzing magnet is available which will produce an ultimate homogeneity of about 0.02 percent, at the expense of a loss of about 90 percent of the beam intensity. This loss should produce little difficulty from background, because the energy-defining slits, upon which the excess beam is dumped, are within the cyclotron vault and shielded from the experimental areas. The cyclotron is designed to handle a circulating beam of up to 100 $\mu$A of 75-MeV protons. Extraction efficiencies of 50 percent and better are anticipated. It is thus expected that the accelerator can be run stably over a very large range of external beam intensities, from a few nanoamperes to at least tens of microamperes. It should be noted, however, that currents at the high end of this

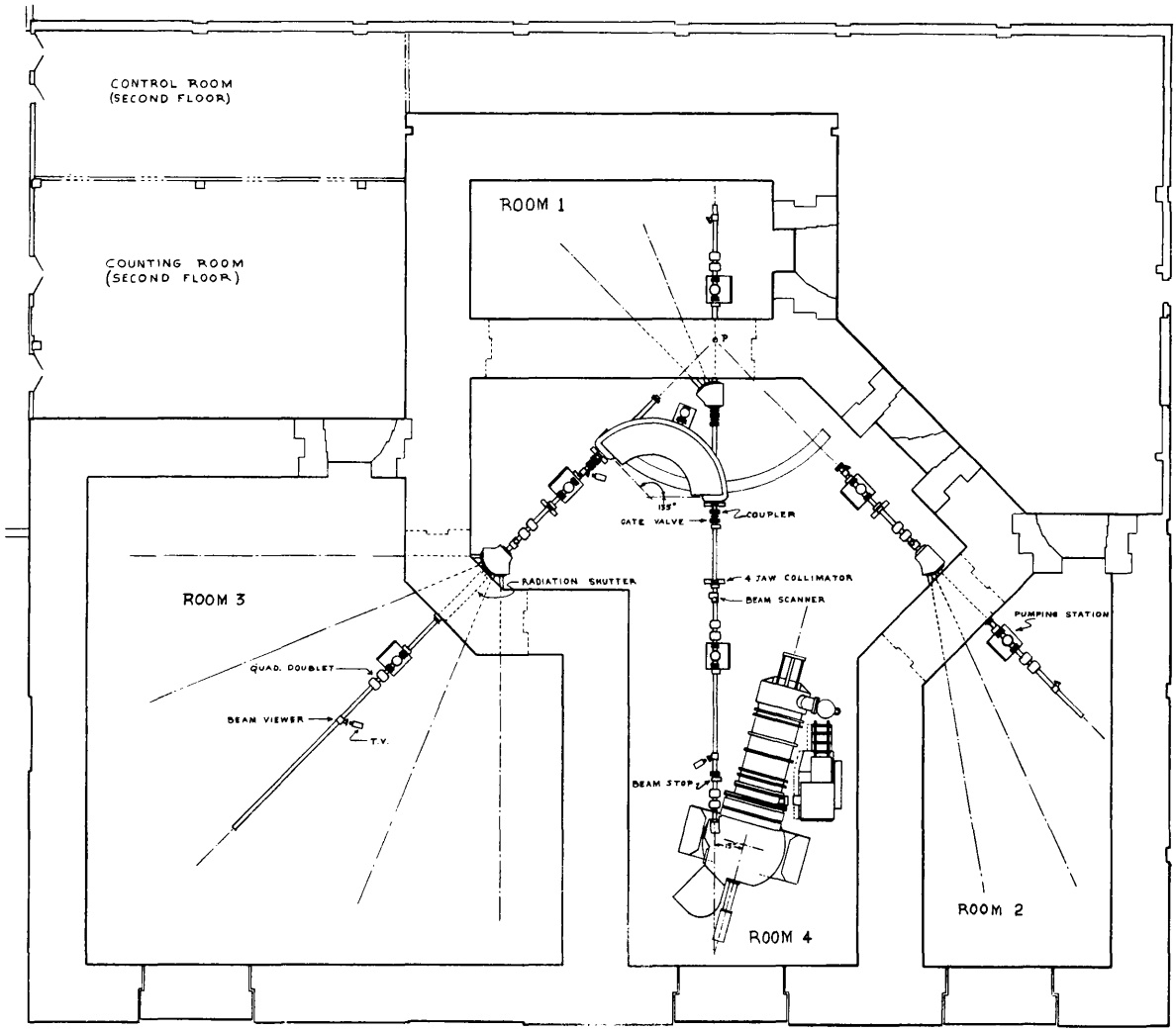


Fig. B1 - Floor plan of the cyclotron facility experimental area, showing the present and future beam paths

scale will probably not be attempted until a later stage of the development of the facility, because of the problem of induced radioactivity in the accelerator. It is hoped that larger external beams will eventually be possible.

The properties of the virtual source for the particles in the ion beam are such that it should be possible to focus 90 percent of the output beam through a one-millimeter-square aperture, although with somewhat more angular divergence (about one degree half angle for the smallest image size) than common to Van de Graaff-type accelerators. Various combinations of beam size and angular divergence are obtainable from the ion-optics system, depending upon the requirements for a particular experiment, including that in which the beam is allowed to diverge to provide reasonable uniformity over regions several square centimeters in area. However, in common with Van de Graaff beams, it is generally not possible to irradiate bulk samples with very good uniformity without the use of scanning devices. The problems of beam scanning are somewhat more difficult with cyclotron beams than with Van de Graaff beams, due to the greater rigidity of the beams and the larger divergences. However, the same effect may usually be obtained by mechanical motion of the sample, if the required scanning rate does not exceed mechanical limitations. At present, no scanning devices are being provided for the cyclotron, although such development may be necessary as interest in bulk irradiation develops.

The output beam, which for most user experiments may be regarded as continuous, actually has a microstructure consisting of beam bursts spaced in time at the period of the radio-frequency accelerating potential. The duty cycle is on the order of 15 percent providing typical bursts about 5 nsec long with a period, depending on the frequency, of 44 to 133 nsec (or several times longer when subharmonics are used to achieve lower energies). If very rapidly occurring phenomena are being studied, this microstructure may be of importance. It is anticipated that cases will arise in which the transmission of only one burst in every n (an arbitrary number) bursts would be experimentally useful, particularly for experiments involving time of flight (for neutron energy measurement) or measurement of very short half-lived activities. It should also be possible to provide beam pulses of longer pulse widths and periods by other techniques, including pulsing of the radio-frequency system, sweeping the beam through an aperture, or mechanical interruption of the beam. Devices providing such pulse selection (or even single pulse selection) will be developed if sufficient interest arises.

## EFFECTS OF THE ION BEAMS

The principal differences between Van de Graaff and cyclotron beams stem from the different energy ranges of each, that of the cyclotron starting from or somewhat above the maximum of the NRL 5-MV Van de Graaff and extending to more than an order of magnitude above it for most ions. In addition to the different specifically nuclear aspects in the two energy regions, an important distinction arises in the atomic interactions of the ion beams with matter. That is, the energy loss per unit length decreases as the energy of the ion increases. As a consequence, for a very thin sample, a higher energy beam will deposit less energy per particle in the sample than a lower energy beam. Because of this effect and the presence of an initially greater energy, the higher energy beam obviously has a much greater range in matter than a lower energy beam. Thus, while Van de Graaff proton beams may penetrate most materials for only a fraction of a millimeter, cyclotron proton beams may penetrate for more than a centimeter in many lighter materials. It should be noted, however, that the range decreases rapidly with increasing nuclear charge and mass of the impinging ion, so the heavier ions have ranges greatly reduced from those of protons of comparable energy. In any event, the range of ions in material is always significantly shorter than the ranges of comparable energy neutrons, gamma rays, or electrons, and this effect may be of importance where uniform irradiation of thick bulk samples is important. On the other hand, the shorter range effects may be used in some cases to irradiate selectively only portions of a sample, particularly the surface layers.

For samples thick enough to stop the beam, the greater initial energy and the potentially greater beam intensity available with cyclotron beams may permit the deposition of larger amounts of energy in the sample than are possible with the Van de Graaff, a factor which could be important in the study of thermal shock or other nonequilibrium processes. However, this same effect provides a limitation of the beam intensity per unit area which may strike a given target without destructive evaporation of material, fracture, rupture, or other deleterious effects, according to the various physical properties of the material in question. In instances where beams may be spaced over a larger area (particularly for scanned beams) the problem may be alleviated, but in those instances where the beam cross section must be kept compact, this effect may frequently provide a limitation on the maximum beam intensity usable, although this maximum may vary greatly from material to material.

The cross sections for nuclear reactions induced by cyclotron beams of course depend in detail upon the material bombarded and the energy and species of the bombarding ions. However, some generalizations are possible. For elements beyond the "light" elements, and for most energies in the cyclotron range, the cross sections for a given reaction do not vary rapidly with either the charge or mass of target nucleus, or the

bombarding energy. Furthermore, for a given bombarding ion, in general a number of competing reactions occur, each leading to different residual nuclei. It is, therefore, not generally possible, as is sometimes the case at lower energies, to produce predominantly one specific reaction or one specific residual nucleus without the concurrent presence of others. Thus, in radioisotope production, for instance, physical or chemical separation techniques are most often necessary to produce a pure sample of a given radioisotope, even if only a single isotope was present as the target material. Of course, varying half-lives and other factors may aid in such separations, but in general the production of single activity is less likely with a cyclotron than with thermal neutron activation or more selective reactions induced by lower-energy ion bombardment. On the other hand, because of the multiplicity of reaction products which generally accompany cyclotron bombardment, a very large range of radioisotopes can be produced in this way, many of which, because they tend to lie on the proton-rich side of the stability curve, cannot be produced by neutron bombardment; or, in the case of medium to heavier nuclei, cannot be produced by lower-energy ion bombardment due to Coulomb repulsive effects.

## SECONDARY PRODUCTS OF ION BEAMS

In the nuclear reactions resulting from the impingement of an ion beam on a target material, large quantities of charged particles, gamma rays, and neutrons are emitted. The former two are chiefly useful in the study of the nuclear reaction itself or of the structure of the nuclei involved in the reaction. The neutrons produced, however, may additionally be useful as bombarding particles or probes of other properties of matter. Unlike the neutrons emerging from a reactor, which are preponderantly at or near thermal energies, the neutrons from cyclotron-induced reactions are almost wholly fast (high-energy) neutrons. Of course, some of the neutrons produced are moderated in collisions with the shielding walls and surrounding materials to produce lower-energy components in the neutron spectrum, but experimental arrangements are feasible which preserve a large fraction of the high-energy neutrons. These high-energy neutrons may then themselves be used to induce nuclear reactions in sample materials. In general, the modes of reaction and the cross sections for interaction are quite different from those of thermal neutrons. Thus for some elements, activation-analysis techniques may be much more selectively sensitive with high-energy neutrons than with thermal neutrons, and vice versa. It should be noted, however, that fast-neutron cross sections are in general lower than thermal cross sections, which may be very high for certain elements. The non-nuclear interactions of neutrons with matter may also be quite different from those of thermal neutrons, due to the possibilities of the transfer of a relatively much larger momentum in collision processes.

Unlike the primary ion beam, which is essentially monoenergetic, the secondary neutron spectrum generally covers a very wide range, with the shape of the spectrum depending upon the particular reaction producing the neutrons. Because of the large velocity possessed by the high-energy neutrons, mechanical methods of energy selection such as choppers or diffractometers, which are appropriate to very-low-energy neutrons, are not applicable. For those phenomena in which a prompt indication of an interaction is present, the techniques of time-of-flight selection of events to relate to neutron energy may be applicable. However, time of flight is not appropriate to any cumulative phenomena such as radioisotope production or radiation-damage studies. In cases where such phenomena must be studied as a function of neutron energy, very-light-element lower-energy positive-ion reactions (such as deuterons on deuterium) may be utilized to produce nearly monoenergetic neutrons. Certain regions of neutron energy may be reached only through ion bombardments at energies above the range of the NRL 5-MV Van de Graaff but accessible to the cyclotron. It should also be noted that certain selected reactions such as the $Be^9(p,n)B^9$ at forward angles may produce neutrons with a rather narrow range of energy up to very high neutron energies.

Although gamma rays are normally produced as secondary products of the interaction of the cyclotron ion beam with matter, the presence of large numbers of neutrons generally negates their usefulness for irradiation or physical-property measurements. Those users requiring gamma irradiation will probably find their needs better served by either the linac or one of the large source facilities.

## USER FACILITIES

While the cyclotron facility at NRL was primarily designed for the purpose of basic studies of nuclear-reaction mechanisms and nuclear structure, a realization of the great capabilities of the cyclotron as a tool in other areas of physical research has led to the incorporation of features which may be principally useful to users from outside the Cyclotron Branch. Experimental room 1 (Fig. B1) is expected to provide services for most outside users. This room is located to permit the transmission into the room of the full unanalyzed output beam of the cyclotron. Initially one beam path will be provided into the room, although the later addition of a switching magnet inside the cyclotron vault will ultimately permit three paths. The beam path will be fully instrumented to provide the magnetic quadrupole lenses, viewers, beam stops, vacuum pumping station, etc. (all remotely controllable), to produce a beam of the required characteristics for impingement on the user's target or sample.

The user will normally be expected to provide his own target chamber to hold his target or sample, and this chamber must conform to certain established standards. Certain routine irradiations can be accommodated with equipment furnished. Advice may be available on special arrangements to be provided by the user to handle special materials for irradiation. The user will also normally supply all necessary apparatus and instrumentation necessary to his measurements, if they are to be made in situ. However, measurements of beam current and total charge deposited may be provided by the operators, and some information on the strengths of sources produced may be supplied by the Health Physics staff.

The radiation hazards associated with the cyclotron beam prohibit the occupation of the experimental room whenever the beam is present; consequently, all manipulations or measurements must be controlled remotely. The experimental room is supplied with shielded signal and control wires which terminate at a panel in the counting room adjacent to the cyclotron control room (Fig. B1). A closed-circuit TV system is also provided to assist in remote operations. Penetrations for the later installation of a fast pneumatic sample transport system (rabbit) have been provided, should demand arise. However, no provision for radioactive chemistry has been provided within the cyclotron building, and any chemical separations or manipulations of items irradiated with the cyclotron beam must be conducted in hot labs available elsewhere at NRL. Shielded isotope storage vaults in the floor and an overhead crane for removal of the lids are provided in experimental room 1. The production of isotopes and their removal from the facility are performed only with the approval of the Radiological Safety Committee and with monitoring by the Health Physics staff.

Services provided include: space on the beam line for the users' apparatus and instrumentation, with necessary power, water, and compressed-air service; space in the counting room for remote instrumentation and control circuitry; the cooperation of the operating staff in providing an ion beam of the required characteristics, and information thereon; and advice and information on the nuclear aspects of the problem, including expected interactions with the target materials and the amounts and type of background radiation expected to be present.

It is expected that bombardment time with the cyclotron will normally be rented by the hour. The scheduling of time for outside users must, of course, remain the

prerogative of the Cyclotron Branch. The arrangement of three separately shielded experimental rooms allows experiments to be performed in one room while the other rooms are occupied. This arrangement permits the user at least one shift of set-up and check-out time (without beam) in his experimental room prior to his bombardment shift. In addition, preliminary assemblies may be accomplished in set-up areas external to the vault and experimental rooms at any time.

The experience of members of the Cyclotron Branch may be available in some cases to offer advice and information on problems of the remote control of experimental apparatus, on techniques for mounting target samples of various types, and on methods of radiation measurement. Inquiries for possible use of the cyclotron facility are always welcome, and will be considered in the light of the feasibility of use of the facility.

## Appendix C

## VAN DE GRAAFF FACILITY

### VAN DE GRAAFF ACCELERATOR

A Van de Graaff accelerator uses a static high voltage directly to accelerate charged particles down an evacuated tube which extends from a high-voltage terminal to the ground end of the machine. The terminal is made of metal and is supported by an insulating structure. Voltage is developed on it by means of a belt, made of an insulating material such as cotton which has been impregnated with rubber, which carries electrical charge from the ground end to the inside of the terminal. Once inside the terminal, charge is collected from the belt, thereby producing a voltage on the terminal. In order to make the voltage at which the terminal will discharge through the surrounding gas as high as possible, the terminal is free from points and projections and is usually either spherical or has a rounded shape. In addition, since breakdown voltage in a gas is dependent on both the type of gas and the pressure, the entire structure is housed in a tank which permits pressures many times atmospheric to be used and which also allows the gas mixture to be controlled.

The accelerating tube consists of a series of flat annular metal electrodes separated from each other by cylindrical ceramic insulators. A uniform voltage gradient is maintained in the accelerator between the high-voltage terminal and the ground end by means of a series of resistors. The metal electrodes of the accelerating tube are then connected to this string of resistors, so that a constant voltage gradient exists also down the accelerating tube. A source of ions (only positive-ion acceleration will be discussed, since the NRL 5-MV Van de Graaff accelerator is of this type) is connected to the accelerating tube and is located inside the high-voltage terminal. Ions from this source are injected into the accelerating tube and are accelerated toward the ground end of the machine, which they reach with an energy given by $zV$, where $z$ is the charge on the ion and $V$ is the voltage on the high-voltage terminal. The NRL large Van de Graaff accelerator, nominally called the 5-MV Van de Graaff, actually can reach a voltage somewhat in excess of 5.5 MV. Thus, for doubly ionized particles such as helium-3 or helium-4 nuclei, the maximum energy which can be produced by the accelerator is approximately 11.0 MeV. The metal electrodes of the accelerating tube are so shaped that they exert a focusing action on the beam of ions which is travelling down the accelerating tube. It is convenient to speak of the ion beam in optical terms; thus, an aperture in the ion source may be considered as the object, and the accelerating tube as a compound lens which forms an image of that object.

### ION SOURCE

The ion source usually consists of a glass bottle which has a cathode at one end and an anode electrode at the other. A small hole, typically about 0.03 in. in diameter, is located in the center of the cathode and leads to the evacuated accelerating tube. A coil which is part of the plate circuit of a radio-frequency oscillator is located just outside the bottle and is coaxial with it. When gas is admitted at low pressure into the bottle, the high field from this coil ionizes the gas. Positive ions are repelled by the anode and, after some focusing, are driven through the small hole in the cathode. They then enter a set of focusing and accelerating lenses and are injected finally into the accelerating tube. The small hole in the cathode forms the object of the system referred to earlier. For

the NRL 5-MV Van de Graaff, the magnification of the accelerating tube, together with the lens system just in front of the ion source, is approximately 1.5.

The type of gas which is admitted into the bottle determines the type of ions which will be injected into the accelerating tube. Thus, if hydrogen gas is admitted into the bottle, the ions which will be injected will consist mainly of singly ionized hydrogen atoms, that is, protons, and singly ionized hydrogen molecules. In addition, due mostly to outgassing from the walls of the ion-source bottle, trace amounts of gases such as oxygen, nitrogen, and water vapor may also be present in the bottle. Thus, various ions formed from these gases will also be injected into the accelerating tube. In order to insure that the beam which strikes the target consists of only a single type of ion, it is necessary to subject the beam to magnetic analysis. Such a magnet is situated along the beam path just after the beam exits from the accelerating tube. The NRL 5-MV Van de Graaff accelerator produces beams of atomic nuclei such as protons, deuterons, helium-3, helium-4, and when required carbon, nitrogen, oxygen, and heavier ions.

## BEAM PORTS

The 5-MV Van de Graaff is a horizontal machine, and the beam-analyzing magnet deflects the beam in a horizontal plane. Since magnetic deflection depends on the charge and the momentum of the traversing particle as well as magnetic field intensity, the magnet can be used to regulate and to define the energy of the beam which is incident on the target. A signal from the output end of the magnetic analyzer is used to adjust the voltage on the accelerator high-voltage terminal. The energy homogeneity of the analyzed beam is usually 0.2 percent or better. For protons and deuterons, beam currents in excess of 50 $\mu$A can be obtained. For other ions the amount of beam which can be obtained depends on the ion-source properties and in part on the energy at which the accelerator is being run. Usually, beam currents of several microamperes can be obtained. The output beam is a continuous steady current of ions. Mechanical beam stops can be used to start and stop an irradiation or, if very short beam pulses are required, an electrostatic deflection system may be used. The beam, which must always be conducted through evacuated tubes or chambers, may be focused and steered by electromagnetic means to produce a desired spot size on the target which is being bombarded.

When the beam strikes the target material, the majority of the ions will undergo collisions with the atomic electrons of the target material and will lose energy. A small fraction of the beam will undergo interactions with the atomic nuclei of the target material, to produce various types of nuclear reactions; the ratio of atomic cross sections to nuclear cross sections is approximately $10^9$. As an example of how rapidly ions lose energy in matter, 5.0-MeV protons have a range in silicon of about 0.2 mm. For a given ion, the rate of energy loss in matter decreases as its ion energy increases; thus, the range of a 75-MeV proton, from the NRL cyclotron, is approximately 100 times as large as that for a 5-MeV proton, namely 2.0 cm.

The energy of a beam from the 5-MV Van de Graaff can be varied easily and with increments as small as may be desired. By adjusting the magnitude and polarity of the deflecting magnetic field, the analyzed beam can be sent to any one of four separate beam ports. A diagram of the experimental facilities associated with the 5-MV Van de Graaff is shown in Fig. C1. Beam spot sizes on targets smaller than 1 $mm^2$ are easily obtainable, and the axis of the beam in space can be defined and held constant to better than 0.25 mm in most cases. The various uses to which a Van de Graaff beam can be put will be discussed in terms of the four beam ports which are available. All of the beam ports may be used for either basic research on nuclear structure or for applications.

The beam port labeled as "solar cell irradiation" in Fig. C1 is a general-purpose port which is available for various types of irradiations which may be required by users

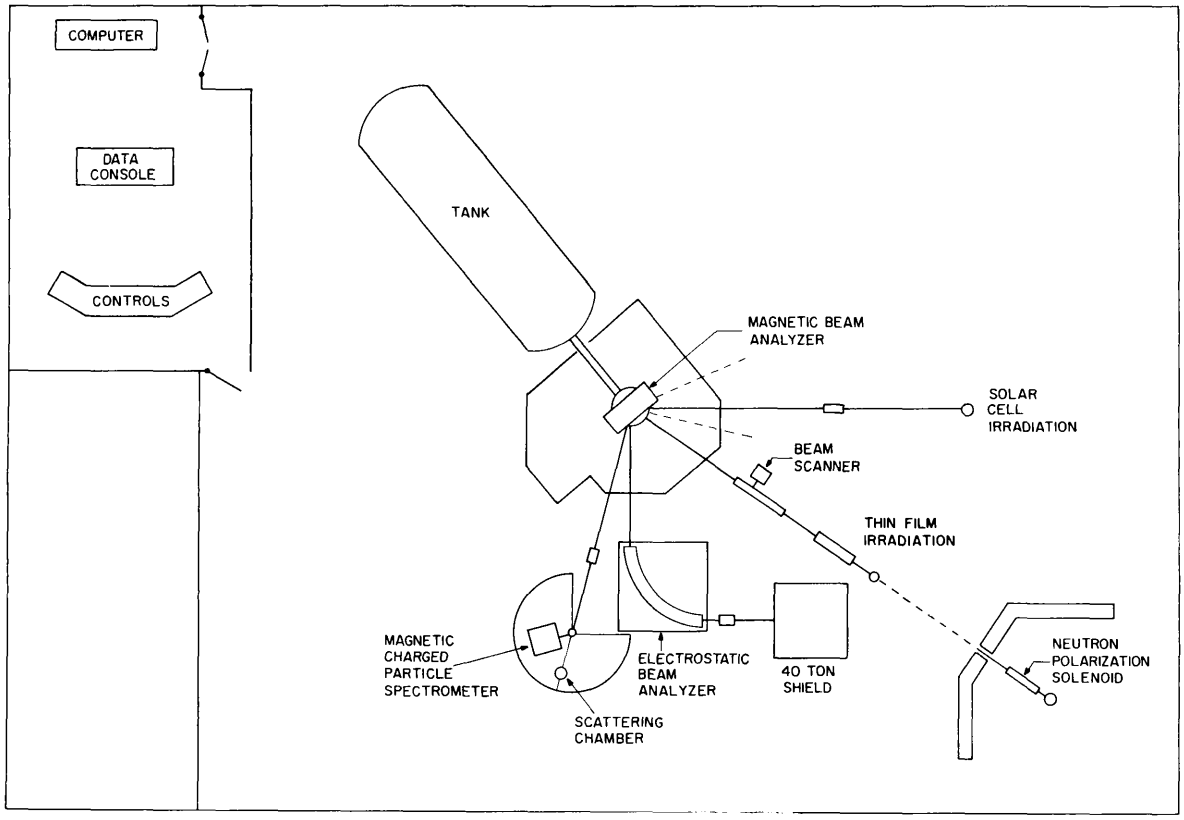


Fig. C1 - Diagram of the 5-MV Van de Graaff accelerator experimental facilities

from outside the Van de Graaff Branch. This port has been used, for example, by the Applications Research Division for radiation-damage studies on solar cells. It has also been used for studies of the rate of oxidation of silicon by means of the $O^{18}(p,n)F^{18}$ reaction.

The port next to the one discussed in the preceding paragraph contains along its path an electrostatic beam scanner which may be used to provide a uniform flux for irradiating samples. The uniformity is better than 10 percent over an area of approximately four square inches. This beam scanner, possibly unique, was developed in connection with irradiations of thin films which were required by the Metallurgy Division. The same port contains at its end a gas target assembly which may be used for producing large fluxes of neutrons. If the $D(d,n)He^3$ reaction is used, neutron-flux densities of $10^9$ $sec^{-1}$ $cm^{-2}$ may be achieved, and the energy of the neutrons is accurately defined and adjustable in the energy range from 1.6 to 8.5 MeV.

The third port contains, along its path, an electrostatic beam analyzer and a 40-ton radiation shield. The electrostatic analyzer has a two-meter radius and has been constructed with high mechanical precision. It can measure the energy of the beam absolutely and define the homogeneity of the energy to better than three parts in ten thousand. This instrument is used to study the characteristics of narrow nuclear-reaction resonances and also has been used to establish an absolute energy scale for nuclear reactions. One interesting by-product of the high-resolution study of nuclear resonances is a technique which allows measurement of nonuniformity of very thin films. The 40-ton radiation shield reduces the amount of background radiation which reaches the detectors and thus permits experiments to be made on low-yield nuclear reactions.

A double-focusing magnetic spectrometer and a scattering chamber are located at the fourth port. Both instruments are used for measuring the yields and angular distributions of charged particles which are emitted from nuclear reactions. The scattering chamber is used with solid-state detectors and has four independently movable arms on which the detectors may be mounted. The magnetic spectrometer is used for those measurements for which solid-state detectors alone are inadequate. At input solid angles of 0.005 steradians or smaller, the momentum resolution of the spectrometer is better than 0.1 percent. In conjunction with various nuclear reactions, some of which release more than 15 MeV of energy, the magnetic spectrometer has been used to calibrate the energy response of space satellite detectors in the range from 0.3 to over 15 MeV.

Van de Graaff Branch scientists are available for consultation with regard to proposed experiments.

## Appendix D

## LINAC FACILITY

### ELECTRON AND POSITRON ACCELERATION

The NRL linac produces a beam of electrons having an energy adjustable from 5 to 60 MeV. The maximum electron beam current at 40 MeV is 72 $\mu$A average. Electrons from the injector pass through a prebuncher and travel in bunches through three six-foot sections of waveguide. Each section contains 50 cavities tuned to the resonant radio frequency and is powered by a 10-MW S-band klystron amplifier. The electron bunches are accelerated as they travel in synchronism with the crest of the travelling rf field. The power required is such that the duty cycle of the klystrons limits the obtainable combinations of beam-pulse length and repetition rate. The pulse length is variable from 0.02 to 0.6 $\mu$sec, and the repetition rate is variable from a single pulse to 360 pulses per second (pps), in nine steps. The maximum average power in the beam is now 3 kw. Modifications are underway to increase the repetition rate to 480 pps and the pulse length to 1.0 $\mu$sec.

A short section between the first and second waveguide sections houses a retractable heavy-element target, the positron converter, in which positrons are produced by a two-step process. Electrons, accelerated to about 12 MeV in the first section, produce x-rays in the target, some of which create "pairs" (an electron and a positron constitute a pair). The phases of the rf fields in the second and third sections can be varied with respect to the phase in the first section. To be accelerated, the positrons need the field to be phased 180 degrees from that for electrons. The positron beam is of low intensity, being in the order of $10^7$ positrons per pulse compared with the maximum electron intensity in the order of $10^{12}$ electrons per pulse. The maximum energy of the positron beam is 45 MeV.

### X-RAY AND NEUTRON PRODUCTION

High-intensity x-rays are produced by electrons impinging on a water-cooled heavy-element target after leaving the vacuum beam path through a water-cooled aluminum window. The continuous spectrum of x-rays (bremsstrahlung) has its maximum energy equal to the energy of the incident electrons. The target is of sufficient thickness so that most of the electrons are stopped; however, neutrons from photoproduction in the target are present in the x-ray beam. The maximum average dose rate at 10 cm from the target is $4 \times 10^6$ rad/min for the x-rays. The neutron production is essentially isotropic, and the intensity into $4\pi$ steradians can be as high as $4 \times 10^{12}$ neutrons/sec, or $10^{10}$ neutrons/pulse. These maximum values are for production by electrons which are undeflected after they leave the linac.

### BEAM HANDLING AND MONITORING

Figure D1 shows schematically the linac and the magnet-deflecting and energy-analyzing systems. Various beam paths are indicated; however, the actual beam can traverse only one of these paths at a time. Beam 1 indicates the path of the full-power undeflected beam when the high-power aluminum window is in place. When a deflection path is used for a high-current, long-pulse beam the intensity is reduced substantially in passing through the analyzing system. Such a beam may have an energy spread as large as 20 percent (full

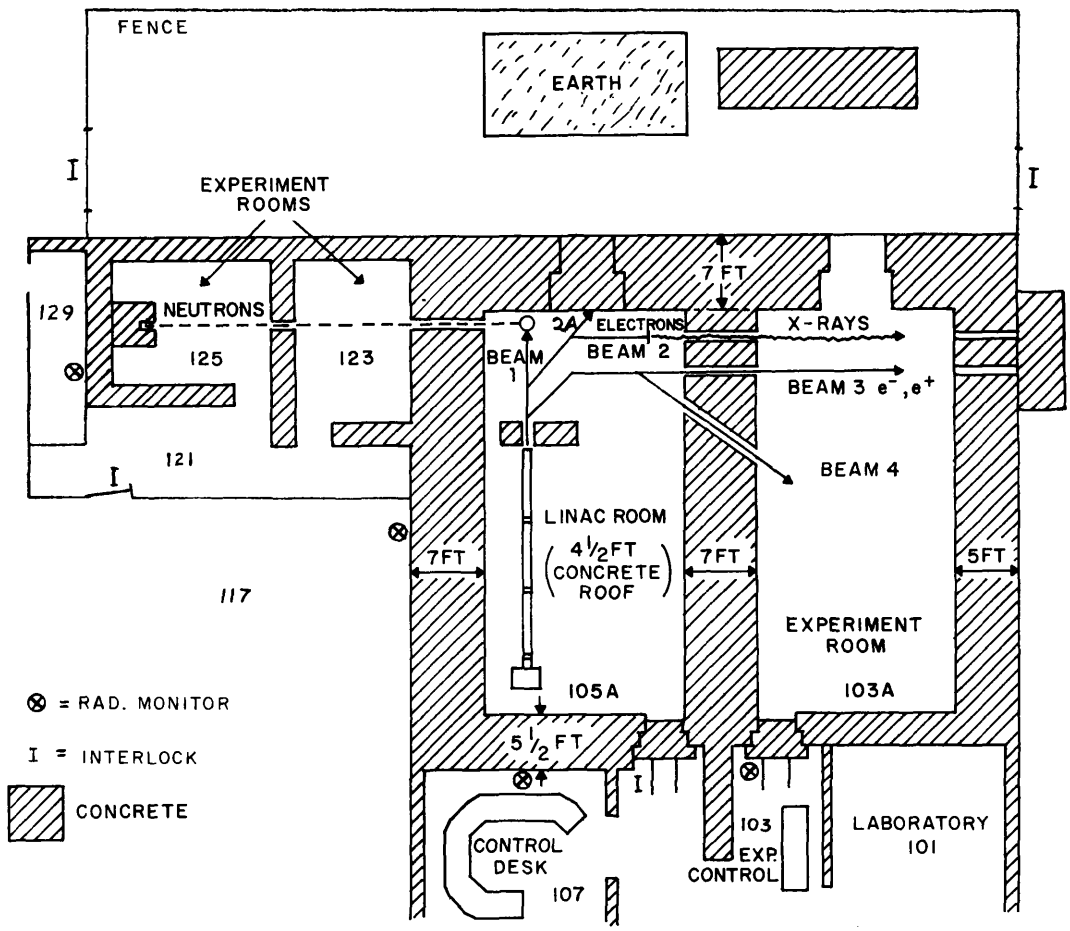


Fig. D1 - Floor plan of the NRL linac facility, showing shielded rooms for the accelerator and for experiments. The various beam paths are indicated.

width at half maximum), while 8 percent energy spread is the maximum passed by the slit system. With lower current and shorter pulse lengths, the energy spread decreases, so that this type of beam is used when energy definition is important. The beam labeled 2A is a high-power beam which has better energy definition than that obtained in beam 1. It exits into air through a specially designed aluminum window and can be used for either x-ray or neutron production. Beams 1 and 2A are available for producing radioactivation by photonuclear or neutron-induced reactions.

The energy-analyzing slit systems are located at the common focal point between two 45-degree magnets which deflect the beam 90 degrees into paths labeled beam 2 and beam 3. The range of energy analysis is from 8 to 0.08 percent of the electron or positron energy for which the deflecting magnets are set. At the exit of the linac and just beyond the 90-degree systems are located pulse-current transformers. These are used to monitor the current pulses in the "main" beam and the deflected beams by the display of their outputs on an oscilloscope. The smallest peak current which can be monitored is about one milliampere ($3 \times 10^9$ electrons/pulse). Beam 2 is the path used for electrons which impinge on a water-cooled aluminum target to produce a low-background, well-collimated x-ray beam primarily for photonuclear research. This x-ray beam can be used for non-nuclear investigations such as radiation-damage effects. Along the beam 3 path in the linac room is located a 35-degree magnet which deflects electrons into

beam 4 for use in the electron-scattering equipment. A very-low-intensity beam may pass through this apparatus with an additional 15-degree deflection to be used for instrument calibration.

When the 35-degree magnet is off, the electrons or positrons continue along the beam 3 path. In room 103A, the adjacent experiment room, a removable section of beam pipe is provided so that the beam can be brought through a foil (window) into air for experimental use. With the pipe in place, the electrons or positrons continue in the vacuum to a thin beryllium target (annihilation target) where electrons produce bremsstrahlung and positrons produce both bremsstrahlung and a higher-energy peak of monoenergetic photons due to annihilation in flight. By use of both photon beams to produce nuclear reactions, the effects due to the monoenergetic photons can be determined. Just beyond the annihilation target there is placed a magnet for removing the excess particles from the photon beam. When the magnet is off and the annihilation target is retracted, electrons or positrons leave the vacuum through the foil, which otherwise serves as the photon-exit window. This location is available for other experiments which need medium- to low-intensity electrons with good energy resolution. A low-intensity, uncollimated (hence, large diameter) x-ray beam can be produced here by electrons incident on a sheet of lead.

The path labeled beam 3 is intended for use exclusively by groups from outside the Linac Branch. It has been proposed that an additional 35-degree magnet be installed along beam 3 just inside room 103A. The beam deflected by this magnet would be developed as a monoenergetic-photon facility.

## BEAM SIZE AND POSITIONING

Magnetic fields are used to focus and steer the electron and positron beams as well as to deflect them. Solenoid coils placed around the waveguide sections are used for focusing the beam inside the linac while quadrupole magnets focus the beam in the various beam paths. The amount of current in these magnets determines, at a given location, the size and shape of the beam, which can vary in shape from circular, with a diameter from 0.2 to 1.0 cm, to elliptical. Extra-large-diameter particle beams can be produced by scattering from a foil. Beam positioning is accomplished by fields produced by currents in sets of wire loops along the waveguide sections and along segments of the beam pipes. Some steering is needed just to cancel the effect of the earth's magnetic field. In the same range of beam intensity for which the pulse current transformers can be used, the beam size and position can be monitored by viewing, with closed-circuit TV, the light from a piece of pilot B plastic scintillator situated just outside a beam window or from a retractable quartz probe viewed through a glass port on the vacuum pipe.

## LOW-INTENSITY BEAMS

Beams of electrons of low average intensity, obtained either by low intensity per pulse or by a low repetition rate, are available and useful for a variety of applications. Such beams require special detectors for monitoring their intensities and for adjusting the focusing and steering. Such detectors are a Faraday cup, an ionization chamber and a sodium iodide scintillation detector. In the extreme limit of an average of one electron per pulse, only the NaI scintillation detector is sufficiently sensitive. Fine adjustments to the focusing and steering, and the measurement of the beam size and shape, have been accomplished by exposing a Polaroid film to such a beam.

## CAPABILITIES AND USES

The primary output of electrons from the linac can be varied over wide limits of intensity, energy, energy definition, and repetition rate of the pulses. This output can be used directly for excitation of atoms, and is useful for studying transient effects in crystals, for calibration of detectors, or for radiation-damage studies. The positron beam, although low in intensity, is variable in energy and energy definition. It can be used directly or to produce the high-energy annihilation-in-flight photo peak; both outputs have been used for instrument-calibration studies. Neutrons can be produced as secondary particles in short pulses of high intensity, with some variation of the energy distribution by means of the selection of the neutron-source target and the amount of moderation used. Any of these beams can be used for exciting or activating nuclei, which can be studied directly or used to investigate other phenomena. With the exception of the neutrons, the linac beams can deposit energy by producing ionization without adding mass to the system being investigated.

One of the most useful capabilities of the linac is the production of high-energy x rays from electron bremsstrahlung. The very intense x-ray beam has been used and is being used to produce activation by photonuclear reactions, primarily those in which a neutron is ejected. Of considerable interest are activations produced by the photo-ejection of more than one particle. Although the same residual radioactive nucleus may be produced by particle reactions, a different target nucleus is involved. Activation-analysis studies of trace elements can be conducted by utilizing the photoproduction of radioactivity; the bremsstrahlung energy and the specific nuclear reaction used should be carefully selected. For example, if the bremsstrahlung energy is kept below the threshold for the $Na^{23}(\gamma,n\alpha)F^{18}$ reaction, the $F^{18}$ activity produced by the $F^{19}(\gamma,n)F^{18}$ reaction can be used to detect traces of fluorine in sea water.

## CONSULTATION WITH THE LINAC BRANCH

The head of the Linac Branch and various members of the branch have furnished and will furnish consultation with users and prospective users. The head of the Accelerator Section is in charge of the linac and of scheduling time for its use. Consultation in the early planning stages of a prospective experiment is highly desirable.

## Appendix E

## NUCLEAR REACTOR FACILITY

### INTRODUCTION

The NRL nuclear reactor and its associated facilities for research were designed to meet the needs of a wide variety of investigations in the physical sciences. Its principal function is to provide a powerful source of neutrons and gamma rays required in many aspects of NRL research programs in such fields as nuclear physics, solid-state physics, metallurgy, chemistry, mechanics, electronics, and reactor technology. The neutrons which are emitted when the reactor is operated are extremely useful in physical investigations. They may be used to produce new substances, to make substances radioactive for study, and to produce chemical and biological changes. They may be used to study the structure of matter, including such practical applications as the structure of new alloys.

Gamma rays are also given off from the reactor. The gamma-ray dose rate near the reactor core operating at its licensed power of one megawatt is approximately $4 \times 10^7$ rad/hr. This intense source of gamma rays can be useful in radiation-damage studies, but frequently is an undesirable condition associated with the neutron exposures.

The pool-type reactor design was chosen because of its flexibility for research and its inherent safety characteristics. This reactor and others of this general type have been operated safely for many years.

The pool is located approximately in the center of a structure 60 ft wide and 210 ft long. The pool itself is 40 ft long, 26 ft wide, and 20-1/2 ft deep. One end of the pool consists of a heavy concrete-radiation shield, pierced by a number of openings, or "beam ports," which provide access to neutrons. Laboratories, offices, and a machine shop occupy the remainder of the building. A "hot lab," where work can be done by remote control on highly radioactive materials, a radiochemistry laboratory, and a shielded counting room for accurate measurement of radioactive materials are among the facilities available.

The fissionable material in which the nuclear chain reaction occurs is $U^{235}$. The fuel is contained in assemblies which are supported in the water on an aluminum grid plate suspended at the middle of a movable bridge which spans the pool. The array of fuel assemblies is called the "core" of the reactor. The bridge rides on rails, making it possible to locate the core at any point on the center line of the pool. Normally, however, the core is operated at one end of the pool in the recess, or niche, of a heavy shield consisting of concrete and lead (Fig. E1).

### THE REACTOR CORE

The fuel of the NRL reactor is 93 percent enriched in the uranium-235 isotope, the remainder being uranium-238. The uranium is contained in plates 0.060 in. thick. The center, 0.020 in., is a uranium-aluminum alloy, and the outside is aluminum cladding 0.020 in. thick bonded to each side of the uranium center section. The cladding serves two purposes: it prevents contamination of the pool and air by sealing in the radioactive products of uranium fission, and it prevents corrosion of the uranium by the water. A

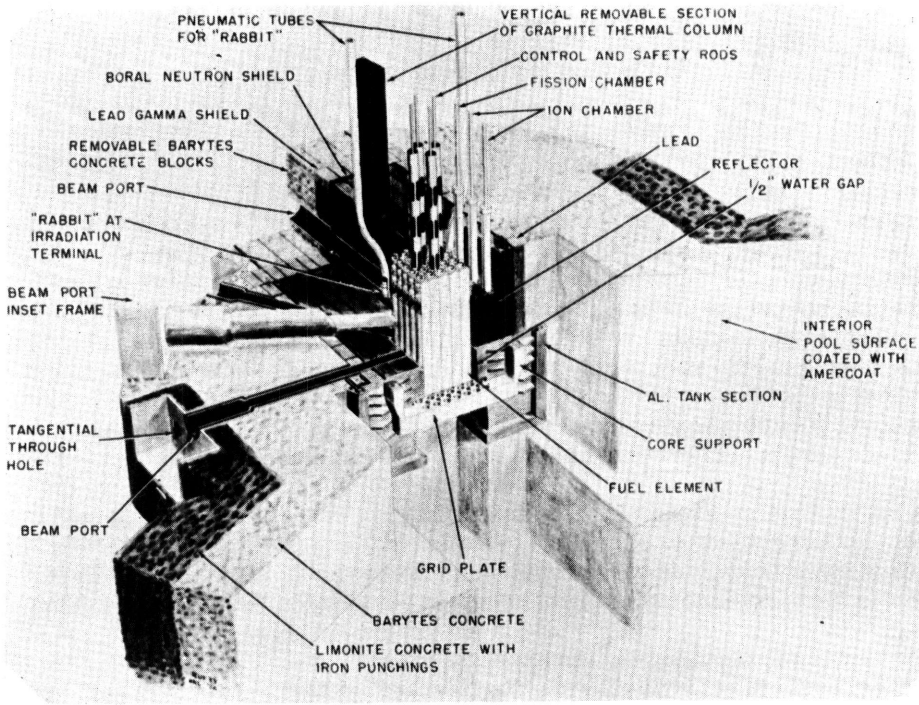


Fig. E1 - Cutaway diagram of the NRL nuclear reactor, showing the reactor core, control and safety rods, lead and concrete shielding, several beam ports, pneumatic rapid-transfer sample tubes (rabbits), and thermal column

fuel assembly consists of 18 of these plates spaced about 0.117 in. apart, and contains a total of 140 grams of $U^{235}$. Each assembly is open at the top and bottom. Water flowing down through the assembly by forced convection passes between the fuel plates, removing the heat produced during operation. A neutron-free source of high-energy gamma radiation can be obtained from the $N^{16}$ activity in the coolant water.

In several special fuel assemblies, the nine central plates have been omitted to provide an open channel for insertion of control and safety rods. The control rod, made of stainless steel, is moved up and down in one of these channels to regulate the reactivity, and hence to control the power of the reactor. Four other rods containing boron carbide, a highly absorbing material for neutrons, are inserted in the remaining such fuel assemblies as a safety measure to provide for rapid quenching of the nuclear reaction if needed. These safety rods are also called shim rods, since they are used to compensate for the effect of the uranium in the core in excess of that required for criticality.

The core of the reactor consists of a group of fuel assemblies arranged, generally, in a square array. As few as 17 or as many as 30 fuel assemblies may be required to sustain a chain reaction, the exact number depending on the configuration used and the materials immediately adjacent to the fuel.

## THE MAIN REACTOR SHIELD AND THERMAL COLUMN

In the center of the main reactor shield, just behind the reactor core recess, is a stack of graphite blocks called a thermal column, roughly 3-1/2 ft by 4 ft horizontally and 9-1/2 ft high. Graphite, being a dense form of carbon, is a good material for slowing

down neutrons to thermal velocities. Two openings near the top of this column provide sources of thermal neutrons when these are required in particular experiments.

Seven horizontal beam ports penetrate the concrete and carbon to provide sources of fast or fission-energy neutrons and thermal neutrons. In addition to these openings, there is a "through-hole" passing alongside the core, which is convenient for certain types of experiments. These holes penetrate the graphite blocks at various angles.

The graphite region extends into the shield on each side of the core recess, or niche. The graphite immediately surrounding the core is called the "reflector," because many of the neutrons which are slowed down in this region are reflected back into the core. When the core is in the niche, it is graphite-reflected on three sides and water-reflected on the remaining three sides. Since graphite is a better reflector than water, less fuel is required to constitute a critical mass in the niche than in the pool. Because the neutron flux for a given power is greater around a smaller core, this arrangement also increases the available neutron flux at the ends of the beam ports.

## THE POOL

High-purity water is used in the pool to minimize corrosion of aluminum cladding on the fuel elements and to prevent activation of the water contaminants. City water is demineralized by passing it through a special treatment plant in the reactor building.

The pool may be divided in half by positioning a movable water gate across its center, making it possible to drain half the pool while the reactor is being operated or stored in the other half. This arrangement increases flexibility of operation. The half of the pool farthest from the shield may be used for investigations aimed at improving methods of calculating radiation shielding requirements, optimizing shield arrangements and materials, etc. It may also be used as a gamma-ray irradiation facility using radioactive fuel elements as a gamma source.

## THE HOT CELL

A room shielded by heavy concrete, called a "hot cell," adjoins the pool at the end opposite the shield. A number of metallurgical, chemical, or mechanical operations can be conducted on highly radioactive specimens in the kilocurie range in this room by scientists working with special manipulators from an adjoining room. Objects made radioactive by suspending them close to the reactor core in the pool may be transferred directly into the hot cell through a lock-type underwater transfer chamber.

The cell is equipped with three windows for direct viewing of operations. Each of these consists of two sheets of one-inch-thick plate glass, with the intervening three-foot space filled with a saturated solution of zinc bromide, a dense liquid with good optical properties and excellent shielding properties against radiation. In front of each window is a pair of master-slave hand manipulators, and the cell also has a heavy-duty powered manipulator operated electrically from a console.

## NEUTRON EXPOSURE FACILITIES

### The Pneumatic Rabbit

With this system, small sample holders may be transported by compressed air to a region near the reactor, where the thermal neutron flux is approximately $10^{12}$ n cm$^{-2}$ sec$^{-1}$. After activation for a few seconds, or longer, the compressed air is used to send

the sample holder to any one of several receiving stations within the building. The sample holder (or rabbit) interior is 13/16 in. in diameter and 3-1/8 in. long.

### The High-Flux Exposure Tubes

Several aluminum tubes extend from the surface of the reactor pool to one face of the reactor core. Samples in these tubes near the core are exposed to a thermal neutron flux of approximately $10^{13}$n $cm^{-2}$ $sec^{-1}$ and a fast (or epi-cadmium) flux of approximately $10^{13}$n $cm^{-2}$ $sec^{-1}$. These exposure tubes are normally air filled, but one water-filled tube is available for those experiments for which it is important to keep the temperature near ambient. The inside diameter of the largest such tube presently limits the diameter of a sample and its encapsulation to 1.75 in.

### The Thermal-Column Exposure Tube

As of the time of this writing (August 1967), an exposure tube is being installed into the thermal column, where samples may be exposed to a neutron flux for which the proportion of slow-to-fast neutrons is greatly enhanced over that obtainable in the high-flux or pneumatic-rabbit exposure tubes. The total flux in this exposure tube will be lower, however. After installation is complete, the flux and the proportion of slow-to-fast flux will be determined at various positions in the tube. Samples up to three inches in diameter can be exposed in this facility.

## NUCLEAR REACTIONS WHICH MAY OCCUR

In general, nuclei have a much higher neutron interaction cross section for neutrons at thermal energy than at higher energy. Consequently, the reactor is most useful as a means of activation by thermal neutrons. The substantial fast flux, however, can result in (n,p), (n,$\alpha$), and (n,2n) reactions. These reactions are sometimes undesirable side effects in an experiment, but they may also be used to produce desired activities which cannot be produced by other means. Samples may be covered by cadmium to reduce drastically the effect of thermal-neutron activation when the fast neutron reactions are of principal interest.

For example, $F^{18}$ and $Mg^{28}$ may be produced by indirect methods. Energetic tritons are produced by the neutron absorption of $Li^6$. A compound or intimate mixture of other elements with $Li^6$ can, when irradiated, result in (t,n) or (t,p) reactions producing radioactive isotopes. Even though these end products are sometimes attainable by other means, the reactor can usually produce them in larger quantities. Carbon-11 has been produced in a similar way by $\alpha$-particle bombardment resulting from the neutron irradiation of boron in an aqueous slurry of $B_4C$.

## ARRANGEMENTS FOR REACTOR UTILIZATION

Requests for reactor utilization originating outside of NRL should be addressed to the Director, Naval Research Laboratory, Washington, D.C., 20390. Within NRL, requests should be in the form of a written memorandum containing pertinent details and should be addressed to the Reactor Utilization Committee, Code 7650. This committee has been set up to consider proposed experiments with regard to safety, the desirability of performing the experiment in the reactor, and priority for use. Members of the committee and other members of the Reactors Branch are available for consultation on proposed experiments. Activation of samples is a routine action and usually is

approved with little delay. Requests which require more deliberation may take several days for approval.

Once an experiment is approved by the Reactor Utilization Committee, it may be scheduled for reactor time by contacting the Reactor Supervisor.

## SUBJECT INDEX

This index is intended to make it easier for the reader to discover applications of nuclear techniques to problems which are not specifically discussed in this report. The parentheses which follow page numbers contain the section number used to label the Nuclear Applications category and a letter designating the particular example in that category which is being referenced.


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13. ABSTRACT

A number of the techniques used in nuclear-physics research can be applied to problems in nonnuclear areas. In order to promote the utilization of nuclear techniques for problems for which they may have an advantage, descriptions have been written about the seven major facilities in the NRL Nuclear Physics Division. These facilities are a 75-MeV cyclotron, a 5-MV positive ion Van de Graaff accelerator, a 60-MeV linear electron accelerator (linac), a 2-MV electron Van de Graaff, a 1-MW nuclear reactor, a 14-MeV neutron source, and a 13-kCi $Co^{60}$ irradiation facility.

To inform potential users of the range of possible applications, and to facilitate extensions of applications into new areas, a list of the capabilities of these facilities has been compiled. The applications are listed under eleven main categories, according to technique or function. Whenever possible, examples are discussed in terms of the specific nonnuclear areas to which they apply. These examples and the accompanying discussion allow the reader to evaluate the potential benefits of a given technique for his own work.

For the benefit of readers not familiar with basic nuclear techniques, additional information has been incorporated in appendixes on the interaction of radiation with matter and radiation detection, and on more detailed descriptions of each of the major facilities.

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| Van de Graaff accelerator | | | | | | |
| Nuclear reactor | | | | | | |
| Neutron source | | | | | | |
| Cobalt-60 irradiation facility | | | | | | |
| Radioisotope applications | | | | | | |
| Activation analysis | | | | | | |
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| Radiation damage | | | | | | |
| Radiation effects | | | | | | |
| Ion implantation | | | | | | |
| Detector calibrations | | | | | | |
| Linac | | | | | | |