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RADIOLOGICAL SAFETY ASPECTS OF THE OPERATION OF NEUTRON GENERATORS

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INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

This manual is a contribution to the International Atomic Energy Agency's programme on the protection of man against possible damage resulting from the use of radiation. Dr. Richard F. Boggs, of the Department of Health, Education and Welfare, Maryland, USA, was engaged as a consultant to write it, and the work was undertaken with the co-operation of the staff of the Agency.

A draft of the manual was sent to certain experts in various countries and the Agency gratefully acknowledges the helpful comments received from Messrs D.H. Sykes (Canada), W. Eyrich (Federal Republic of Germany), H. Kawai, R. Miki (Japan), R. Burkhart, W.E. Gundaker, E. Moss, A.C. Tapert and W.E. Thompson (United States of America), which have been taken into account in the final text.

The publication is aimed at advising and assisting those who, with little or no experience of the subject, wish to gain knowledge of the radiological safety aspects of neutron generators. Comments from readers for possible inclusion in a later edition of the manual would be welcome; they should be addressed to the Director, Division of Nuclear Safety and Environmental Protection, International Atomic Energy Agency, Kärntner Ring 11, P.O. Box 590, A-1011 Vienna, Austria.

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INTRODUCTION

The number of neutron generators has increased at a rapid rate during the past 15 years. The uses for neutron generators in the many fields of education, research, industry and medicine are still expanding [1].

Two aspects are of particular importance for the evaluation of the potential hazards of newly installed neutron generators:

(i) neutron generators are relatively inexpensive machines and it could be overlooked that an additional amount of money is necessary for their safe operation, including shielding materials and radiation surveillance services.

(ii) neutron generators are easy to operate and highly trained personnel are not required. They could be operated in areas where little or no health physics capability is available.

Most of the machines now in use use the Cockcroft-Walton type of voltage multiplying circuitry. The neutrons result from the deuteron-tritium interaction, that is, deuterons are accelerated onto a tritium target with the subsequent release of 14 MeV neutrons. Until recently, very little information concerning the associated health hazards has been available. This manual attempts to present additional and current information related to the production and/or release of tritium, X-rays, neutrons, and the resultant need for adequate shielding and radiation monitoring.

PURPOSE

The purpose of this manual is to provide some basic guidelines to persons with a minimum of training in radiological health or health physics, on some safety aspects of the operation of sealed-tube and Cockcroft-Walton type neutron generators. The manual does not state rules and regulations, but presents a description of hazards which are most likely to exist around such devices.
Because of the relatively low cost of these small neutron generators, they are frequently obtained by organizations with little or no competency in the area of radiation safety. The purpose is to present in basic terms some of the problems which must be anticipated when operating these neutron generators.

SCOPE

The concepts and ideas presented are intended to cover radiological health aspects for those relatively compact neutron generators which usually operate at less than 150-200 kV for the purpose of producing 14 MeV neutrons. The scope is limited to basic discussions of hazards and measurement techniques and the reader must refer to more detailed technical literature to obtain specific information on the concepts presented.

1. CHARACTERISTICS AND USE OF NEUTRON GENERATORS

The neutron generator design characteristics are such that high current beams of protons and/or deuterons are used for the production of fast neutrons by the following reactions:

\[ ^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + ^1\text{n} + 17.6 \text{ MeV} \quad \text{T(d,n)} \]
\[ ^2\text{H} + ^1\text{H} \rightarrow ^2\text{He} + ^1\text{n} + 3.25 \text{ MeV} \quad \text{D(d,n)} \]

In the T(d,n) reaction, the energy released is about 17.6 MeV. By applying the basic energy and momentum theory, which requires that the lighter particle acquires the greater amount of energy, it can be determined that the resultant neutron will have an energy of approximately 14.6 MeV.

By applying the same calculations to the D(d,n) reaction, the neutron energy can be determined to be about 2.6 MeV.

The neutron yield from the T(d,n) reaction at the typical target bombarding energy of 100 keV is about 100 times greater than that from the D(d,n) reaction and is therefore of greater interest.

1.1. Sealed-tube type neutron generators

The sealed-tube type of neutron generator provides a source of 14 MeV neutrons with typical yields of up to around \(10^9\) n-s\(^{-1}\).
with maximum outputs of about $10^{11} \text{n}\cdot\text{s}^{-1}$. The systems are relatively compact to allow for a degree of portability and can be operated in either a continuous or pulsed mode. Because of their degree of simplicity, they require less monitoring and supervision than the larger Cockcroft-Walton type neutron generator.

The tubes contain an ion source, an accelerator system (usually 100 - 200 kV), a replenisher to maintain a constant pressure within the tube and a self-replenishing tritium gaseous or metallic target. The tubes are frequently 30 to 65 cm in length and interconnected to the required power supplies and control consoles.

The metallic targets are usually tritium loaded titanium targets containing 10 to 20 Ci (370 to 740 GBq) of tritium. The target areas are usually water or oil cooled.

Tube life for continuous operation for neutron outputs of $10^{10} \text{n}\cdot\text{s}^{-1}$ can be expected to exceed 500 hours, while under pulsed conditions the lifetime can be reduced by as much as 50%.

1.2. Cockcroft-Walton type neutron generators

Of more importance to the health physicist are the extremely high yield machines (up to $10^{13} \text{n}\cdot\text{s}^{-1}$) that have been developed from the early experimentation of the two English physicists Cockcroft and Walton in 1932. These machines are suitable as electron accelerators or as ion accelerators and usually operate at voltages of about 150 keV and currents of up to 2.5 mA. Most of the Cockcroft-Walton type neutron generators now in use accelerate deuterium ions onto a metallic-backed tritium target to produce 14 MeV neutrons by the T(d,n) reaction. Detailed information on the operation of these machines is available in the literature [2-4].

The operation of Cockcroft-Walton type neutron generators involves the formation of positive ions (deuterons), acceleration, flow through a drift tube and finally collision with the target.

The major component sections in a neutron generator are:
(i) High voltage power supply; (ii) Ion source; (iii) Acceleration tube; (iv) Drift tube, target assembly and target; and (v) Vacuum system.

An outline drawing of a Cockcroft-Walton type neutron generator is shown in Fig.1.

1.2.1. High voltage power supply

The high voltage power supply is usually contained in a separate oil or gas-filled tank that may or may not be physically
FIG. 1. Outline drawing of a Crockcroft-Walton type neutron generator equipped with an oil diffusion pumping system and post acceleration pulsing [2].
removed from the immediate area of the neutron generator. A good external ground must be present during operation of the power supply.

1.2.2. Ion source

The ion source is usually one of two different types. The first uses a radio-frequency (RF) field operating between 30 to 80 MHz to produce an intense ionization of deuterium gas. The RF field passes through the quartz envelope into the gas, causing electrons to move back and forth rapidly. As they move, collisions with atoms in the gas cause additional electrons to be produced, thus generating a plasma consisting of many free electrons and free deuterium ions. A d.c. electric field applied by means of the extraction electrode will force the ions toward the exit canal and those ions which leave the exit canal are then focused by gap lenses and accelerated in the main beam [4].

The other ion source is the Penning ion gauge. This ion source operates on direct current (thus eliminating any RF interference with health physics monitoring equipment). Electric and magnetic fields are used to focus and align the ion beam toward the accelerating tube.

With each of these systems a palladium or nickel leak (a membrane of palladium between the deuterium and the vacuum in the ion source) is usually employed to introduce the deuterium or hydrogen gas into the ion source (at times a mechanical leak is used). Palladium becomes more porous to hydrogen atoms when heated. Therefore, the flow of gas is regulated by controlling the temperature of the palladium. Since palladium is not porous to atoms other than hydrogen, it acts as a filter, preventing ingress of other ions or foreign materials.

1.2.3. Acceleration tube

After leaving the ion source and gap lens, the beam enters the acceleration tube. This tube usually consists of a series of electrodes used to accelerate the beam. Each electrode is at an increasing potential so that when passing through the electrodes, the ions of the beam acquire a potential of 150 kV or more.

1.2.4. Drift tube and target assembly

After being accelerated to the desired velocity, the ion beam enters a potential-free drift tube. The purpose of this drift tube is
to provide a vacuum link between the target and accelerating section where accessory equipment can be located. Some items that may be located in or on the drift tube include:

(a) vacuum pumps,
(b) target isolation valves,
(c) beam deflectors,
(d) beam dumps,
(e) beam viewers, and
(f) electron suppressors.

The target isolation valves are located so that the vacuum in the drift tube can be maintained during target changes, thus permitting shorter 'pump-down' times and minimizing contamination of the vacuum system components or the air.

Some Cockcroft-Walton neutron generators are capable of providing a pulsed beam in which the ion beam can be interrupted before or after acceleration by diverting it out of its normal path. The beam may be diverted after acceleration by electrostatic deflectors. In such cases, beam catchers are installed on the drift tube to absorb and dissipate the energy of the deflected beam.

Before allowing the beam to reach the target, a beam viewer is frequently used to determine the size and location of the beam spot on the beam catcher.

An electron beam suppressor may be installed in the drift tube to reduce the reverse flow of secondary electrons back through the tube and into the accelerating section.

Various other accessories may be added to the drift tube section depending on the particular type of neutron generator being used.

The target assembly consists of a target holder and a cooling system (water, oil or freon is usually employed as the coolant). The target and holder have a vacuum- or gas-tight seal at the end of the drift tube.

The targets are usually about 3 cm diameter disks consisting of tritium gas occluded in a thin layer of titanium (about 1 mg·cm⁻²). The titanium is then evaporated onto a thin copper backing material. Usually about 1 Ci·cm⁻² (37 GBq·cm⁻²) of tritium is used; however, this can be increased to about 10 Ci·cm⁻². Replenishing systems are sometimes available where up to 100 Ci (3.7 TBq) can be deposited over a period of time. The 'half-life' for such targets in continuous operation varies depending on the beam currents used. The average lifetime of a standard target is approximately 4 mA·h. Therefore target life can be as low as one hour for high current accelerators.
In order to increase the length of operation before the target must be disassembled, neutron generators have been manufactured with rotating targets (the tritium being plated out on the side of a cylindrical target) and multiple target assemblies (several targets placed on a larger disk). This enables the operator to move the target such that a fresh area of tritium is in the beam.

1.2.5. Vacuum system

A high vacuum must be produced within the accelerator for the particle beam to be effectively accelerated. The most common arrangement of pumping apparatus consists of a forepump to rough out the system, and an additional pump which is turned on after the roughing out, thus producing the high vacuum required. This additional pump may be a turbomolecular pump, a diffusion pump, or an ion pump. If an ion pump is used on the system, the forepump (or backing pump) is isolated from the system by a valve after the ion pump is started. The other pumps discharge directly into the forepump.

Forepumps used with most systems are of the mechanical oil-filled rotary type. The air passing through the pump comes in direct contact with the oil during the pumping cycle and bubbles through a layer of oil before reaching the exhaust port.

Diffusion pumps containing either oil or mercury are used between the accelerator and the forepump to obtain vacuums in the region below about $10^{-3}$ mmHg. The diffusion pump is started after the pressure in the system has been lowered to approximately $10^{-2}$ mmHg by the forepump.

In place of oil or mercury diffusion pumps, ion pumps (often called sputter ion pumps or getter ion pumps) are frequently used to produce the high vacuum required for accelerator operation. Ion pumps trap gas molecules in the pump elements, and once the pump has started its pumping action the valve between it and the forepump is closed. Basically, ion pumps consist of a stainless steel container housing one or more elements, often referred to as Penning cells. These cells consist of two titanium cathodes with a honeybomb-like stainless steel anode between the cathodes. The design of the Penning cell is such that a large number of electrons move back and forth through the anode where they ionize gas molecules that are present. The gas ions thus produced are accelerated toward the cathode, striking with several thousands of volts of energy, and sputtering fresh titanium over the surface of the cathode. Gases like nitrogen and oxygen form stable low vapour pressure
compounds with the titanium cathode, while the light gases, such as hydrogen, diffuse into the cathode forming what is considered to be a solid solution of hydrogen in titanium.

The use of ion pumps on accelerators containing tritium can create a health hazard since the tritium is trapped within the pump elements themselves. Several hundred curies of tritium can accumulate during several years of operation.

1.3. Fields of application of neutron generators

The high yields and relative low cost of neutron generators make it possible to use these devices on a wide scale in education, research, industry and medicine [1].

In education, the neutron generator is being used to demonstrate the basic principles of atomic and nuclear physics, to demonstrate and develop methods for neutron production and measurement, and to demonstrate the principles and applications of activation analysis. Extensive use of neutron generators is being made in basic and applied research. Included are the study of nuclear reactions, new developmental techniques in activation analysis, determination of biological damage and effects from fast, slow and thermal neutrons, evaluation of shielding materials and adsorption and scatter patterns.

Industrial applications include an extensive use of many techniques in activation analysis, neutron radiography, radioisotope production radiation effects on materials, metallurgical analysis, geological exploration, and ion implantation for semiconductor development.

Now that neutron yields from generators are approaching $10^{12}$ n·s$^{-1}$, it appears that such devices may find increased use in biology and medicine. In addition to studies on biological effects to cells and tissues, the use of high yield generators for radiotherapy is being actively investigated.

It is beyond the scope of this section to describe in detail or provide specifics on the many applications for which neutron generators are being utilized. The reader must consult the literature for additional applications for fast neutrons.

2. RADIATION HAZARDS AND SAFETY CONSIDERATIONS FOR NEUTRON GENERATORS

The potential radiological health considerations for neutron generators can be put into the following main categories:
(i) Tritium hazards; (ii) Neutron hazards; (iii) Neutron activation; (iv) X-ray production; (v) Shielding requirements; (vi) Safety interlocks; (vii) Warning devices.

2.1. Tritium hazards

The inherent design characteristics of the sealed-tube type neutron generator offers a degree of protection from exposure to tritium. A major concern is associated with the accidental breakage of such tubes, although the amount of tritium released in such a situation has been shown to be small [5]. In addition to any release of gaseous tritium, the occluded tritium remaining in the broken tube presents no more than the normal hazard involved in handling conventional tritium targets. The tubes should be kept away from excessive heat to prevent release of additional tritium and should be disposed of as radioactive waste. Unless the laboratory is equipped to handle tritium contamination problems, sealed tubes should not be removed from their metal heads. The entire head should be returned to the manufacturer.

A much more significant tritium hazard exists with the use of the pumped type of Cockcroft-Walton neutron generator. During bombardment of the target by the deuterium, tritium is released. Most of the tritium is in gaseous form (HT or T₂) when it leaves the target; however, a small fraction of the tritium remains in the system in the form of an oxide (HTO or T₂O).

Tritium is the only radioactive isotope of hydrogen. It emits an 18 keV beta particle, and has a half-life of about twelve years. The range of this radiation is about 0.6 mg·cm⁻², which is less than the thickness of the outer layer of skin on the body [6]. Thus, it is of minimal external radiation hazard. However, within the body, there is no protection to living tissues. Although the half-life of tritium is approximately twelve years, tritium is eliminated by the body with an effective half-life of approximately twelve days [6].

When a person is exposed to possible flaking of tritiated titanium chips or to dust from targets or to an atmosphere containing HTO, the HTO entering the body through the total skin area is approximately equal to that entering through the lungs [7]. Once tritium is absorbed by the body, the isotope becomes uniformly distributed throughout the body fluids within approximately 90 minutes [8]. Tritium gas, in the elemental form, does not present as significant an internal hazard as tritium oxide, since elemental tritium is absorbed into the body at a much slower rate.

Authorities have generally agreed that the permissible soluble and insoluble tritium breathing concentration for a 40-hour week
for the industrial worker should be $5.0 \times 10^{-6} \mu\text{Ci/cm}^3 (185 \text{ mBq/cm}^3).$ The maximum permissible air concentration for tritium recommended by the ICRP for continuous occupational exposure (168-h week) is $2.0 \times 10^{-6} \mu\text{Ci/cm}^3 (74 \text{ mBq/cm}^3)$ [9]. One millicurie (1 mCi = 37 MBq) has been generally established as the maximum permissible body burden for tritium, and is applicable when the body tissues are considered as the critical organ.

Most references also list a maximum permissible body burden of 2.0 mCi (74 MBq) which is to be used when the total body is considered as the critical organ [3, 7]. This value is obtained in essentially the same manner as the 1.0 mCi maximum permissible body burden. However, in the case of the 2.0 mCi maximum permissible body burden, the tritium (HTO or T$_2$O) is considered to be evenly distributed throughout 70 kg of body mass, rather than the 43 kg of body water.

Urinalysis currently constitutes one of the most reliable methods for determining the presence and magnitude of human exposure to tritium. Because of the peculiar radiological characteristics of tritium, including the short effective half-life for gaseous tritium, a preplanned bioassay capability should be readily available for use during any tritium handling and at any time that a possible overexposure is suspected. With the short biological half-life, a routine monthly or semi-annual bioassay will not be adequate. Following are some specific tritium hazards which exist around the neutron generator and considerations which must be evaluated when using such monitoring equipment.

(a) Large quantities of tritium build-up in the electronic ion vacuum pumps. These pumps should not be serviced unless proper facilities and trained personnel are available. Potentially lethal amounts of tritium may be present on the inner surfaces of the pumps.

(b) Many curies of tritium may be released during any restart of ion pumps and should not be performed without serious consideration being given to the potential problems and hazards which will occur.

(c) Tritium accumulates in various mechanical and diffusion vacuum pumps. During vacuum system operation significant quantities of tritium may pass through the diffusion pump. Some tritium will be trapped in the oil. No attempt to service these pumps should be made unless proper facilities and trained personnel are available.

(d) Certain components of the accelerator system may be contaminated by tritium. The tritium can become a hazard when the vacuum system is opened to the atmosphere, for example for target
changes, maintenance, or through leakage or breakage. Target replacement procedures and other manufacturer recommendations should be closely observed. The vacuum system should be opened by personnel knowledgeable about the hazards and well versed in the proper techniques to be used.

(e) Most tritium will be released to the environment through the pump exhaust. Mechanical pumps, used in conjunction with both diffusion pumps and ion-getter pumps, should be vented outside the building. The exhaust should be monitored to ensure that tritium discharge limits for the specific area are not exceeded.

(f) Used oil and targets should be contained in material through which tritium will not readily diffuse (glass is not recommended). Ventilation and temperature control should be provided in the area where tritium waste is held pending disposal as radioactive waste.

(g) The considerations regarding unused tritium targets are very much the same as for other radioactive waste. A slightly greater potential hazard exists in this situation, however, due to larger quantities of tritium. Control of ventilation and temperature in the storage area must be considered. Unused targets should be kept in the container in which they were supplied. Each container should be placed in a ventilated area. Unused targets should not be combined in one large container, as the build-up over several weeks may exceed the maximum permissible concentration.

(h) Nuclear instrumentation capable of accurate tritium detection is commercially available; however, sensitivity, discrimination between tritium and other gases, and calibration of these devices, present problems which must be clearly understood by the user.

Neutron generator instruction manuals should be referred to for specific operating instructions. Additional information and references on the subject of tritium hazards should be consulted. Useful information on a new pumping system for a 150-kV neutron generator to reduce the present tritium hazard will be found in Ref. [10].

2.2. Neutron hazards

Neutrons are classed according to their kinetic energy. For convenience neutron energy ranges have been generally defined as follows:

- **Thermal** 0.025 eV or less
- **Epithermal** 0.025 eV - 1 eV
- **Slow** 1 eV - 1 keV
- **Intermediate** 1 keV - 1 MeV
- **Fast** 1 MeV - 100 MeV
- **Ultra-fast** above 100 MeV
As was previously stated, the primary purpose of a neutron generator is to produce neutrons by either the T(d,n) or D(d,n) reaction. The T(d,n) reaction produces neutrons with an average energy of about 14 MeV at yields of up to $5 \times 10^{11} \text{n}\cdot\text{s}^{-1}$, whereas the D(d,n) reaction produces neutrons with an average energy of about 2.5 MeV at yields of $10^{10}$ to $10^{11} \text{n}\cdot\text{s}^{-1}$. Because of the higher fluxes possible and higher energy attainable, the T(d,n) is of more importance.

A neutron generator producing 14 MeV neutrons at $10^{10} \text{n}\cdot\text{s}^{-1}$ is approximately equivalent to a 700 Ci (26 TBq) radium-beryllium neutron source. Calculations indicate that such an unshielded machine would produce a maximum permissible dose (assuming a 40-h week) at a distance of about 100 m from the target [2].

The biological damage caused by neutrons increases as the energy increases. The maximum permissible flux density (40-h week) for 14 MeV neutrons is $12 \text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ and for thermal (0.025 eV or less) neutrons is $680 \text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$. This is summarized in Table I, which also lists various quality factors (QF; a factor which provides the modification related to radiation quality of the absorbed dose value [12]) for selected neutron energies.

Other aspects of the neutron hazards are described in the sections on neutron activation and shielding.

2.3. Considerations of neutron activation

Neutron induced radioactivity from the primary beam (including during beam alignment) and from secondary radiation can become a significant problem. Many texts have been written concerning neutron activation of materials and it is far beyond the scope of this manual to describe in any depth the reactions involved, radioisotopes produced or levels of radioactivity developed. While additional information is presented in the section on shielding, a description of the considerations which must be evaluated is given.

Any material which the beam strikes or which is exposed to intense secondary radiation could become radioactive. Additionally, the primary beam may strike objects such as vacuum chamber walls and electrode supports. Radiation from these sources may not be a personnel hazard until the machine is turned off and persons enter irradiation rooms and the accelerator room for maintenance, target changes, routine adjustments, or manual placement of samples for irradiation. A survey of these areas should be made to evaluate the radiation hazard before or while entering.

Activation of cooling water around the targets may be a problem. If a recirculating system is used, a portion of the system may
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<th>Quality factor</th>
<th>Average flux density to deliver 100 mrem (1 mJ/kg dose equivalent) in 40 h (n·cm⁻²·s⁻¹)</th>
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<tr>
<td>2.5 x 10⁻³ (thermal)</td>
<td>2</td>
<td>680</td>
</tr>
<tr>
<td>1 x 10⁻⁷</td>
<td>2</td>
<td>680</td>
</tr>
<tr>
<td>1 x 10⁻⁶</td>
<td>2</td>
<td>560</td>
</tr>
<tr>
<td>1 x 10⁻⁵</td>
<td>2</td>
<td>560</td>
</tr>
<tr>
<td>1 x 10⁻⁴</td>
<td>2</td>
<td>580</td>
</tr>
<tr>
<td>1 x 10⁻³</td>
<td>2</td>
<td>680</td>
</tr>
<tr>
<td>1 x 10⁻²</td>
<td>2.5</td>
<td>700</td>
</tr>
<tr>
<td>1 x 10⁻¹</td>
<td>7.5</td>
<td>115</td>
</tr>
<tr>
<td>5 x 10⁻¹</td>
<td>11</td>
<td>27</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td>2.5</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>6.5</td>
<td>17</td>
</tr>
<tr>
<td>14</td>
<td>7.5</td>
<td>12</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>40</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>60</td>
<td>5.5</td>
<td>11</td>
</tr>
<tr>
<td>1 x 10²</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>2 x 10²</td>
<td>3.5</td>
<td>13</td>
</tr>
<tr>
<td>3 x 10²</td>
<td>3.5</td>
<td>11</td>
</tr>
<tr>
<td>4 x 10²</td>
<td>3.5</td>
<td>10</td>
</tr>
</tbody>
</table>
expose personnel in areas which could be occupied during operation of the neutron generator. Any recirculating system should remain within the shielded area and be removed from areas where personnel exposures could occur. Even though the activated water is no hazard during normal operation, the residual activity present during maintenance work on the water system may be hazardous for a time after shutting down the generator. The activated cooling media should be monitored and dealt with according to the levels of activity involved. Shielding may be required around circulating pumps, heat exchangers and holding tanks.

Induced radioactivity may cover a wide range in intensity and in half-life and come from many radioactive nuclides. Many different materials used in and around the neutron generator which can be bombarded by the neutron beam can lead to a spread in half-lives nearly as great as in the fission-product spectrum from a nuclear reactor, with a similar composite decay curve.

Table II lists some expected exposure rates at 10 cm following one hour of operation at $2.5 \times 10^{11} \text{n}\cdot\text{s}^{-1}$ produced by the target backing material and assembly from the neutron activation of aluminium, stainless steel and copper [2].

The combined gamma exposure dose rate for a one-hour bombardment at an output of $4 \times 10^{10} \text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ is estimated to be 200 to 300 mR\cdot\text{h}^{-1}(50 to 80 \mu\text{C}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}) at 10 cm. These estimated exposure rate values show that considerable activity will be induced in the neutron generator components.

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TABLE II. EXPECTED LEVELS OF INDUCED RADIOACTIVITY AT 10 cm AFTER 1 h OF OPERATION WITH A NEUTRON GENERATOR YIELD OF $2.5 \times 10^{11} \text{n}\cdot\text{s}^{-1}$ [2]

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Exposure rate at 10 cm</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mR\cdot\text{h}^{-1})</td>
<td>(\mu\text{C}\cdot\text{kg}^{-1}\cdot\text{h}^{-1})</td>
</tr>
<tr>
<td>$^{27}\text{Al}(n, p)^{27}\text{Mg}$</td>
<td>200</td>
<td>52</td>
</tr>
<tr>
<td>$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$</td>
<td>30</td>
<td>7.7</td>
</tr>
<tr>
<td>$^{63}\text{Cu}(n, 2n)^{62}\text{Cu}$</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>$^{65}\text{Cu}(n, 2n)^{64}\text{Cu}$</td>
<td>60</td>
<td>15</td>
</tr>
</tbody>
</table>

This publication is no longer valid
Please see http://www-ns.iaea.org/standards/
2.4. X-ray production

Unwanted electrons are produced in a neutron generator when the beam strikes gas molecules or atoms or when a small part of the positive beam strikes the walls or components in the accelerating and drift tube areas. These electrons then produce bremsstrahlung (150 keV max.) when drifting back into the accelerating section and are accelerated to the upper electrode. The intensity of the X-rays produced will depend on the vacuum conditions and the amount of positive beam being accelerated. X-ray production generally is higher for high beam currents and poor vacuum. Measured X-ray intensity near the accelerating area is usually about 25 to 100 mR·h⁻¹ (6.5 to 26 μC·kg⁻¹·h⁻¹), but levels as high as 750 mR·h⁻¹ (194 μC·kg⁻¹·h⁻¹) have been noted during neutron production and as high as 450 mR·h⁻¹ (116 μC·kg⁻¹·h⁻¹) when the machine is operating but not generating neutrons [3]. It is important to realize that X-rays will be produced during beam alignments and at other operating times even though no neutrons are being generated. During such operations, it is advisable to shield the operator console with about 0.5 cm of lead or its equivalent. The shielding required during neutron production should be sufficient to stop all X-rays.

It is worth noting that while the standard neutron generator is primarily designed to accelerate ionized beams of hydrogen and deuterium, it can be converted to an electron accelerator for the production of X-rays. An electron beam current of greater than 0.5 mA can be obtained when operating at 150 kV. It should be emphasized that X-ray production during the electron beam mode can be as much as ten times higher than during acceleration of positive ions. This is especially critical during alignment of the electron beam.

2.5. Shielding requirements

Experience has shown that the cost of providing adequate shielding for a neutron generator can often exceed the cost of the machine itself. Shielding for fast neutrons is a complex topic encompassing the entire field of neutron interactions. Detailed information on protection against neutrons may be of limited value in designing specific protective enclosures. Gamma rays and induced radioactivities produced by neutron generators should not present an external hazard, since the shielding requirements for major fluxes of neutrons and X-rays are sufficient to attenuate such relatively low intensity radiation. However, personnel should carefully monitor the area when entering the enclosure following accelerator operation to be assured of safe conditions.
The higher the neutron energy, the more difficult it is to shield. For example, 30 cm of water will attenuate 1 MeV incident neutrons by a factor of approximately $10^5$ whereas the same thickness of water only attenuates 14 MeV neutrons by a factor of approximately $10^2$ [2].

Shielding fast neutrons is usually accomplished by slowing down energetic neutrons to thermal or near thermal energies and final capture. The most effective way to decrease the energy of the neutron is to require that it makes multiple elastic collisions with light nuclei. A hydrogenous material is the logical choice for shielding, since the neutron will lose more energy per collision with hydrogen than with any other atom. After neutrons have been slowed down by collision with light nuclei, they will usually be captured through a nuclear reaction. If the shielding material is water, the most probable reaction is $^1\text{H}(n,\gamma)^2\text{H}$. The energy of the gamma rays is 2.3 MeV, and they are emitted promptly. Gamma rays of this energy are very penetrating, and difficult to shield against.

Materials containing hydrogen, such as water, paraffin wax, polyethylene or concrete are commonly used for shielding fast neutrons. Heavy elements such as iron or tungsten provide very effective fast neutron shields, but are not often used because of their weight and high cost. Water and polyethylene have a higher density of hydrogen atoms than paraffin wax or concrete. Polyethylene is somewhat better than water in this respect, but has the disadvantage of high cost. For 14 MeV neutrons, concrete and paraffin wax (paraffin wax presents a fire hazard) have approximately the same thermalizing efficiency, but concrete is less expensive. Sealed-tube neutron generators can sometimes be installed so that the head is placed below ground, thus utilizing the earth as shielding material for the neutron radiation.

Concrete is a natural choice for shielding material; it is inexpensive, reliable, structurally useful and easily installed. If concrete blocks are used, the shield can be easily removed or rearranged. The blocks should be stacked in such a way as to minimize the number of through cracks in the wall. The criteria to use in selecting concrete are high density and high moisture content.

The 14 MeV neutrons present a shielding problem that seems to be disproportionately great in comparison to the size of the accelerator and the energy of its deuteron beam [13].

The attenuation ratio, R, that is required to ensure a given maximum permissible flux density can be determined from the relation:
Using the inverse square law. At 1 cm distance from a point source, a flux density (per unit solid angle) of $N \text{n} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$ is, to within 0.1%, equivalent to a flux density of $N \text{n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$. Further, at distances greater than 3 cm from a point source, the 'curved' area on the sphere surface can be considered to be flat (with an error of < 1%), while for non-point source this holds for distances greater than ten times the maximum dimension of the source, i.e. with a 3 cm $\times$ 2 cm source it holds for distances greater than 30 cm.

Example

If the observer target distance is 300 cm ($\gg 10 \times$ max. source dimension), the flux density is $10^{10} \text{n} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$ ($= 10^{10} \text{n} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$ at 1 cm), and the maximum permissible flux density is $10 \text{n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$, then, from Eq. (1), the required attenuation ratio is:

$$R = \frac{\text{actual neutron flux density per unit surface area}}{\text{max. permissible flux density per unit surface area}} = \frac{\text{actual neutron flux density per unit surface area at unit distance from source}}{\text{max. permissible flux density per unit surface area at (actual distance from source)}^2}$$

$$R = \frac{10^{10} \text{n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}}{10 \text{n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}} \times \left(\frac{1 \text{ cm}}{300 \text{ cm}}\right)^2 = 1.11 \times 10^4 = 10^4$$

If the tenth-value layer of an average, non-armoured concrete mix, which is the thickness allowing only 1/10 (i.e. 10%) of the neutrons to pass through, is $t$, then for an attenuation factor of $10^4$, a thickness of $4t$ would be required. For 14 MeV neutrons and an average concrete, $t$ is 34 cm — that is:

Thickness of concrete for attenuation of $10^4 = 4 \times 34 = 136$ cm

Many neutron generators are utilized for activation analysis where small irradiation volumes are needed, hence compact design. If the accelerator is used in a more open configuration, e.g. for general research purposes, the wall thicknesses could be somewhat reduced because of the greater distances involved.

Shielding design will vary considerably between installations and for this reason any new installation will require very careful analysis by an expert in this area. As a very general guideline, data indicate that a minimum of 150 cm of water and/or concrete or paraffin wax is required to properly shield a neutron generator [2,14].
Consideration must be given to the effect of skyshine through the roof. This can provide a significant contribution to the total radiation levels observed outside the shielding walls.

Ventilation ducts and penetrations through shielding walls could create a potential radiation hazard. Surveys should be conducted to determine the levels of radiation that exist outside of the shielding in the area of penetration.

If ventilation ducts are large enough for a man to crawl through, an additional hazard may exist. Inspection covers and doors, outside the shielding, should be interlocked to avoid inadvertent opening of the duct during operation. This precaution may prevent the accidental exposure of a person doing a routine inspection of the system or the escape of toxic gases into the building.

Where labyrinths are used, the neutron dose outside the shielding walls may be dominated by scattering through the labyrinth. Each neutron scatter through a small opening such as a doorway will reduce the flux density by a factor of 100, so that provisions should be made for at least two scatters.

The shielding, which may have been adequate at the time of installation, may at a later date be inadequate for one of several reasons:

(a) cracks or other openings may occur,
(b) the machine may be modified to produce higher beam energies or intensities,
(c) the shielding configuration may be changed,
(d) the shield material, or structure, may deteriorate.

Surveys of the area around the shielding should be made periodically. If a defect in the shielding does exist, the background radiation in the immediate area may increase. Steps should be taken to locate the defect and make the necessary corrections. If the defect is difficult to locate, a map of the distribution of radiation intensity, showing contours of equal intensity, may be useful.

In conclusion, and bearing in mind the problems discussed, it will be necessary to consult the literature, of which a few examples are referenced here [15-24]. It should be pointed out, however, that it is always well worth the effort to obtain the services of a qualified expert on shielding before the design of a facility has reached too advanced a stage.

2.6. Safety interlocks

In general interlocks and warning devices (Section 2.7) are no better than the individual responsible for their operation. There is
no electrical or mechanical safety device which is totally 'fail-safe'.

*Each interlock is intended to furnish protection to personnel or equipment in the event of a specific malfunction or improper operating condition.*

Each interlock functions to open or close a pair of electrical contacts, either directly or via a relay. Many pairs of contacts in series must be closed to provide control power for the beam switch. There is a great deal of variation in the interlocking arrangements to be found in different neutron generators. This is due to the inherent differences among machines, specific space or component limitations, and differences in design philosophy, cost factors, and users' requirements. Ideally, the interlock system should be as close to 'fail-safe' in that defects or component failures will prevent operation of the device.

The radiation interlock system has two general functions: to prevent access to areas in which permissible radiation levels are being exceeded; and to prevent operation if such operation will exceed permissible radiation levels in any occupied area.

Access to the target room is either through a maze or through a doorway, which is blocked during irradiation by a shielding door. In either case, it should be necessary for personnel entering the room to open a door which shuts off the accelerator. A key-operated switch should be incorporated in the beam controls. The key to this switch should be required to unlock the door or gate leading to the target area. Thus the beam must be turned off and the key removed from the switch, before anyone can enter the area of most extreme hazard. Additional switches, which are closed only when doors, gates, shielding plugs, and shielding doors are in a safe condition, may be used in series with the key switch.

Personnel must not depend on a door interlock to turn off the beam. If the door interlock fails, a serious radiation exposure is almost certain to occur. The switch on the control console should always be placed in the 'off' position before entering the radiation area. Similarly, the neutron generator should never be turned on from any location other than the control console.

One or more disabling switches should be installed in target areas and experiment rooms, so persons in those areas can turn off the machine or prevent the beam being turned on, in the event that they are trapped when someone else attempts to turn on the beam. It is also advisable to have an intercom or telephone in the target room for use by any individual trapped in the room.

The control circuits should produce a warning by light or sound, or both, for some period after the irradiation rooms are closed and before the beam can be turned on, to allow anyone trapped in a
room to reach the disabling switch. The irradiation room door should be operable from the inside even after power failure. The door handle should open an interlock, whether or not it opens the door.

Radiation-detection instruments should be installed to monitor the radiation levels in various areas, including the control room and other rooms normally occupied when the beam is on. Monitors may be installed in target areas which are not occupied but where the radiation level is an important indicator of generator performance. Sometimes these radiation intensities are recorded automatically. The instruments should turn off the beam and/or give warning, if the permissible radiation level has been exceeded. These instruments should be adjusted to the proper levels and tested periodically.

Not to be overlooked are interlock systems dealing with extreme electrical hazards to personnel, particularly high-voltage d.c. power supplies. Switches on the access doors to high-voltage compartments should interrupt the input voltage to the compartment when the doors are opened, and should discharge capacitor banks. In general, any electrical hazard which has a protective enclosure should have interlock switches installed to open the power circuit if the enclosure is opened.

It should always be remembered that these interlocks seldom act directly to remove the hazard, but rather act through intermediate relay circuits. Even though the interlock switch in a door frame is 'visibly' in the open or safe position, the other parts of the interlock circuit may fail to operate correctly, and the hazard may still exist. Also, relays or switches may fail, or become misaligned, so that these interlocks are not completely dependable. It should never be assumed that the interlocks have removed the hazard.

A complete interlock chain includes many pairs of contacts, arranged in various main and subsidiary sequences; some of these are 'power-on' sequences, but some may be 'power-off' sequences. The complexity of an interlock chain can lead to misunderstanding on the part of inexperienced operators and technicians. Therefore, complete and accurate circuit diagrams of the entire interlock system are essential. These drawings should be readily available to the operators and to the technicians who are responsible for maintenance and such persons should become familiar with the circuits.

Faulty diagnosis or improper repair can create a condition in which the interlock chain appears to be operating correctly, but important elements of the chain have been bypassed or overridden. Any repairs made to the interlock circuits, especially those
involving modifications or substitutions of components, should be carefully recorded in log books and on the circuit diagrams. It is frequently a convenience and a means of conserving operating time to circumvent a troublesome interlock component (such as a sticking relay or an erratic contact susceptible to vibration) by installing a jumper or bypass across accessible terminals in the control room, rather than shutting down the neutron generator until a replacement for the troublesome component can be obtained and installed. Experienced operators may be able to do this and monitor the bypassed interlock function personally, with adequate safety and with considerable benefit to the work of the laboratory. However, if the operator became careless and failed to record the change, or failed to make it conspicuously obvious to all others concerned, an extremely hazardous condition could result. Any temporary change in the interlock system should be made unmistakably evident to every person who could be endangered by the change.

Specific emergency procedures should be established whenever interlocks are bypassed. This should include the presence of at least two individuals to verify the safety of the procedure. In addition, this change should be noted in a log book, signed by the persons present, and normal operation not resumed until the bypass is removed and the log book signed to indicate that it has been removed. A warning sign should also be posted at the control console to indicate that an interlock or interlocks have been bypassed.

Where fail-safe operation of equipment cannot be otherwise assured, a duplicate system of interlocks should be used. In this case, mechanical-electrical interlock systems for doors etc. should be carried through in duplicate, with wiring, contacts, and relays, located so as to make simultaneous failure of both circuits extremely unlikely. The hazard of someone disabling the system (for example, by placing a concrete block on a cable) is avoided by using widely separated cables in the two systems. An important requirement of a duplicate system, however, is that failure of either of the two circuits should be conspicuously signalled, so that it can be corrected. The system is safe only when both circuits indicate 'safe'; it must be broken when the two 'disagree' or both indicate hazard. Whatever type of system is used, a frequent check of its proper operation is essential.

### 2.7. Warning devices

In addition to interlocks to prevent inadvertent entry into hazardous areas during neutron generator operation, warning
devices should be utilized to inform people of the machine status. Lights, signs and audible devices can be used.

(a) Status lights. The location of status lights (lights which indicate the state of the system) is important. They should be located in the irradiation rooms, corridors leading to the irradiation rooms, and on the control console. The status lights should indicate any conditions considered important for the safety of operating personnel. Regular checks should be made to make sure the light bulbs have not burned out.

(b) Signs. Signs should be used to mark areas where hazardous radiation levels could exist. Appropriate radiation surveys should be made.

(c) Horns or other audible devices should be used where practical to indicate that the beam is on or is about to come on. If the audible device must be on for long periods, it should make an intermittent tone which is low enough not to distract people working in the area. If the device is loud, it will probably be disconnected or modified to make it inaudible. A public address system announcement of impending turn-on can be used in addition to an audible warning signal.

3. RADIATION MONITORING AND INTERPRETATION OF MEASUREMENTS

The detection instruments which may be used for radiation surveys are described in this section. The descriptions are intended to give the reader an idea of the types of instruments available. Since the characteristics of each type of instrument may vary from one manufacturer to another, the manufacturers should be consulted for more detailed operating characteristics and recommendations.

In selecting the best instrument for the measurement of radiation for a particular dosimetry problem, the convenience of operation, portability, reliability, economy, type of radiation detected, energy dependence, and exposure rate independence of the instrument should be considered. Each monitoring assignment has its own individual set of considerations. It is necessary to know the characteristics and limitations of any survey instrument or pocket dosimeter in order to use it intelligently.

It should be recognized that all instruments are limited to measuring certain types of radiation within a fixed range of energies, and that for other types of radiation or at certain energies of radiation, their readings may not only be useless but often misleading.
It is extremely important that survey and monitoring instruments be properly maintained and calibrated, and sensitive to those radiations being monitored.

The radiation safety of any facility can be no better than the performance of the survey and monitoring instruments. Instruments should be calibrated at regular intervals using secondary standards. Reference sources are available from some laboratories which have the equipment necessary to calibrate the sources. Where possible, instruments should be calibrated by the use of a source whose activity, energy, and intensity are similar to those to be measured. Each time an instrument is used, the user should be alert for possible malfunctioning, such as indicated by erratic reading, no reading, or rates of change in the readings that do not correspond to expected variations in radiation intensity. When such troubles occur, the operator must not necessarily assume that the meter is wrong, but instead should get another instrument or otherwise attempt to determine the true condition.

The following discussion on monitoring instruments is necessarily brief since it is beyond the scope of this manual to cover the subject in detail. Basic concepts are covered and other references should be reviewed to obtain further technical considerations.

3.1. Tritium monitoring instruments

It is important that proper ventilation techniques be used to ensure that any release of tritium is adequately exhausted from the facility. It is necessary to provide air monitoring for release of tritium gas.

When monitoring for tritium, it is extremely important that the instrument be calibrated against a known concentration of tritium gas under actual conditions of operation. The air flow must also be carefully determined. The manufacturer of such instrumentation should be required to provide this information at the time of purchase. Periodic recalibration should be performed.

A common device for tritium air monitoring is an ionization chamber through which air is drawn at a fixed rate. The ionization current is amplified and related to the concentration of radioactive gas in the air. The ionization chamber may be preceded by an ion collector and/or filter in order to remove other ions or radioactive material.

Tritium contamination can be detected and analysed through the use of smear samples collected with filter paper and properly measured. The most common technique is to place the filter paper in a properly calibrated proportional counter or liquid scintillation
detector. In general liquid scintillation methods are preferable since with the weak beta radiation (about 18 keV max.) from tritium, gross contamination will be present before detection with a proportional counter becomes possible. Examples of the distribution of tritium within an accelerator obtained by taking smear samples are described in the literature [5, 10]. A survey of the techniques that have been developed for measuring tritium in various media is given in a recently published review paper [25].

3.2. Neutron monitoring instruments

The flux density of neutrons outside the shielding of a specific facility will depend on the use of the beam, the beam energy, the nuclear characteristics of the material being irradiated, and the nature of the shielding material. The purpose of a neutron radiation survey is to determine whether the flux density outside the shielding is within permissible limits.

Neutron radiation around the installation may be accompanied by relatively high levels of gamma radiation. Consequently, in order to measure the neutron flux density adequately it is necessary to have an instrument insensitive to gamma radiation.

In selecting neutron survey instruments for a specific accelerator facility, some general aspects of the detection instrument should be considered.

(a) The detection instrument may be calibrated either in first collision neutron dose or in neutron flux. In either case, careful interpretation of the measurements must be made and the calibration procedure must be known.

(b) The gamma response or discrimination of the detector should be known in order that the gamma effects can be excluded from the neutron-field measurement.

(c) Like the response of any radiation detector, that of a neutron instrument is governed by statistical considerations. Since shielding evaluation may ordinarily encompass several orders of magnitude of intensity, the question of adequate sensitivity and linearity of performance over the whole range to be measured is fundamental.

(d) Although absolute dosimetry of neutron fields is an intricate problem relative measurements are frequently all that are required for shielding evaluation. Neutron flux density measurements are more useful for shielding evaluation than are dose measurements. However, even flux density measurements require a good reference
standard to allow measurement of departures from calibration in the detector. The reference standard should have a spectral composition approximating the neutron field being measured.

Ionization instruments are usually not satisfactory for measuring neutron fluxes or neutron dose, since they are also sensitive to gamma radiation.

The boron trifluoride (BF₃) proportional counter provides a sensitive detector for a neutron survey instrument and can be relatively insensitive to gamma radiation. The instrument uses BF₃ gas enriched to more than 95% in the isotope ¹⁰B, and typically the detector has about a 10 cm active length and 16 cm overall length.

The BF₃ counter is sensitive to thermal neutrons. To meet the requirements for a counter suitable for intermediate-energy and fast neutrons, the BF₃ counter can be enclosed by a polyethylene or paraffin wax moderator which moderates the neutrons before entering the BF₃ gas. By suitable selection of the moderator configuration, it is possible to achieve reaction rates which are substantially independent of neutron energy from 10 keV to nearly 10 MeV [25a].

The development of good scintillation survey instruments to measure neutrons depends primarily on scintillating materials with the proper characteristics, since the circuits are essentially the same as those for measuring other kinds of radiation. Examples of scintillating materials used for neutron survey instruments are organic phosphors or proton radiating materials combined with scintillators for fast neutrons, and boron or lithium bearing phosphors for thermal neutrons. Materials sensitive to thermal neutrons can be combined with moderators to provide a detector which gives a rem response for thermal, intermediate, and fast neutrons. Several such neutron monitoring instruments have been described [26-30].

There are other techniques for fast neutron detection which are beyond the scope of this manual, e.g. those using film or plastics. The interested reader is referred to the publications in Refs [31-38] for a more detailed information on neutron dosimetry in general.

3.3. X-ray and gamma-ray monitoring instruments

Many hundreds of textbooks and technical articles have been written on the subject of X-ray and gamma ray instrumentation and measurements. As examples, the reader may refer to Refs [39-41]
for a general introduction. Commercially available instruments and the information supplied by the manufacturer should provide adequate details for such monitoring. As with other types of detectors, however, it is most important to understand the effect on the measurements of the energy characteristics of the radiation being detected as well as the response of the instrument to that energy [42]. And, the importance of good instrument maintenance and calibration cannot be overemphasized.

3.4. Personnel monitoring

Monitoring the exposure and dose to radiation workers can be accomplished by using pocket dosimeters, pocket ionization chambers, film badges and thermoluminescent dosimeters. Dosimeters and pocket chambers are usually limited to beta and gamma radiation. Film badges can be made sensitive to gamma and X-rays, electrons, and neutrons. The use of filters make possible the separation of different kinds of radiation and different energy ranges. Ionizing radiations produce blackening of the emulsion, which can be determined photometrically after development. Since it is possible to prevent the disappearance of the latent image by suitable choice and treatment of the emulsion, as well as by the air-tight enclosure of the film, an almost complete integration of the radiation dose for several weeks can be guaranteed. The continuous sensitivity and ease of handling of photographic film, as well as it being a permanent record of the radiation received, make film dosimeters particularly suitable for individual dosimetry and for periodic examination of the integrated exposure of persons constantly exposed to radiation.

The gamma dose received by the personnel should be measured continuously by two independent methods, e.g. film badge and pocket dosimeter. A personnel dosimeter sensitive to neutrons should be included in this monitoring. The limits for the maximum permissible doses have to be observed but the dose received should be as low as possible.

In addition to the personnel monitoring of external radiation, urinalysis for the detection of tritium should be carried out when necessary, e.g. after work with tritium contaminated components.

4. REQUIREMENTS FOR AN EFFECTIVE SAFETY PROGRAMME

Responsibilities for the establishment of a safety programme and an organization for safety at particle accelerator facilities
have been described [43] and those which are pertinent to neutron generator facilities are presented.

No neutron generator facility should operate without an adequate and effective safety programme; however, one plan for a safety organization will not fit all types of facilities. The programme can be effective only through the actions of a safety organization which meets the needs of the facility.

The safety programme should be designed to protect personnel from injury and equipment from damage. It should: (i) maintain safe working conditions; (ii) enable the facility to meet its statutory and legal obligations; (iii) establish procedures and organizations to deal with emergencies, such as fires, explosions and radiation accidents; (iv) conduct necessary inspections; and (v) instruct personnel in safe attitudes and practices.

Personnel require training to become aware of all the hazards which exist or may develop, and to become familiar with the appropriate safe practices. This is especially true of radiation hazards. It is also true of the many conventional hazards which may exist in equipment and surroundings.

The establishment and support of an effective safety programme is, ultimately, the responsibility of the director of the facility. He should clearly establish the areas and levels of authority for the actual conduct of the programme, since everyone in the facility must contribute if it is to be successful.

Supervisors at all levels should be responsible for safety and should promote the safety programme. Personnel should be informed through appropriate training of the hazards and recommended safe practices related to their work. Individuals should recognize the hazards encountered, and take precautions in their work.

A safety programme must balance between minimizing risks and maximizing the use of the facility. At the same time a proper safety programme should cause negligible interference with the work of the facility. When this small interference and expense is compared with the cost of possible accidents, no one should object to a properly planned and administered safety programme. The establishment and rigorous support of operating and radiation safety procedures in operation and maintenance is of utmost importance. The safety programme should assure:

(a) That an adequate organization is established to formulate, advise on and implement safety policy, beginning at the time the facility is first proposed.

(b) That buildings and facilities provide an environment for safe conduct of experiments, and limit the extent of damage caused by any equipment malfunction.
(c) That safety is integrated in a project from its beginning and that the project is periodically reviewed by responsible persons to ensure that continuing consideration is being given to problems of safety.

(d) That there is an identification and evaluation of hazards at all stages of an experiment or irradiation process.

(e) That emergency plans are developed and implemented to include programmes for immediate decontamination procedures, cooperation with health authorities and notification of fire officials of potential hazards which could exist.

4.1. Safety organization

Organization for safety in a neutron generator installation should provide for radiation safety, equipment safety, and general safety. A safety committee should review proposed experiments, facility changes or deviations from standard operating procedures. The safety committee should also compile and publish rules and procedures for safe practices in their facility. The functions of the safety committee should include the following:

(a) Formulate safety policy
(b) Establish review procedures and standards
(c) Co-ordinate and review safety activities
(d) Examine requests for variances
(e) Advise the director, staff and user groups on safety matters.

A typical constitution of a safety committee would include the head of the department in which the facility is located, the radiation safety engineer, the fire officer, the health physics specialist, and a senior member of the operations staff.

4.2. Radiation safety

Responsibilities for radiation safety should include:

(a) Inventory and control of radioactive sources, targets and other activated materials
(b) Observation and control of radiation hazards
(c) Radiation waste storage and disposal
(d) General radiation monitoring procedures
(e) Instruction of personnel in observation of rules and monitoring procedures
(f) Maintenance of records related to exposures and accumulated doses received by the personnel
(g) Periodic routine survey of the installation
(h) Surveys of new experimental set-ups
(i) Survey of unusual conditions including conditions during maintenance operations.

4.3. Neutron generator safety

The person in charge of safety (safety engineer) should have an adequate background of experience related to the generator. He should be responsible for the mechanical and electrical safety related to:

(a) Targets
(b) Auxiliary mechanical equipment
(c) Special fire protection
(d) Control system.

He should be responsible for instruction of operators and technicians, should keep the operator adequately informed of the radiation fields, and should disseminate information about safety procedures and special hazards.

4.4. General safety

Responsibilities for general safety procedures should include:

(a) Storage and safe use of chemicals
(b) Storage and safe use of gases
(c) Safety supplies
(d) Elimination of fire and mechanical hazards
(e) Emergency lighting and power
(f) Maintenance and use of special safety equipment, such as ventilation systems, respirators, safety glasses, self-contained breathing apparatus and air sampling equipment.
(g) Review of handling procedures involving toxic materials.

Specific guidelines for the safe operation of small particle accelerators have been published [44, 45] and provide useful considerations for neutron generator facilities as well. Individual national laboratories often have available safety information which can be helpful in establishing an effective programme.
Appendix I

NON-RADIATION HAZARDS AND SAFETY CONSIDERATIONS

While it is the purpose of this manual to emphasize the radiation hazards, it is advisable to briefly point out some other hazards which may exist at a neutron generator facility [43].

The principal fire hazard is associated with that of electrical fires. Fire prevention measures and fire protection equipment for electrical fires should be provided. It must be borne in mind that, for example, combustible or inflammable liquids, solvents and gases are used in operation and maintenance.

Fire prevention and protection measures commonly include location of hazardous equipment in non-combustible structures, adequate drainage and ventilation, elimination of all combustible materials from the area and fire detection devices.

Some recommended fire and explosion prevention measures for experimental areas include the following:

1. A periodic review of all current experiments should be made to evaluate the possible interaction of the hazards of each, with the equipment and materials of other experiments.
2. Before approval is given for equipment and materials, as well as experimental procedures, consideration should be given to layout and design with regard to confining any potential incident to the smallest area practicable. Thus damage will more likely be adsorbed within one area without propagating to others.
3. The quantity of flammable materials in the experimental area should be minimized.
4. The facility's electrical, ventilation, alarm, and other systems should be evaluated for each experiment, and particular attention be given to possible interaction of any of these systems in an emergency.

Objects which are not bolted to the floor should be braced or arranged so that they can resist side forces of at least a fifth of their weight without overturning. Pipes, panels, or other components which could be stepped on under any circumstance should either be braced to withstand such loads, or be guarded against being stepped on.
Mechanical vacuum pumps are frequently oil-sealed vane pumps. The area around an oil-sealed pump tends to become slippery as a result of condensed oil vapour and will present a fire hazard unless carefully maintained. Oil spills and leaks also contribute to the problem. Mounting pumps in metal trays can confine the oil to areas which are normally not walked upon.

Diffusion pumps use oil or mercury vapour. Personnel who handle or are exposed to such fluids should acquaint themselves with the degree of flammability or toxicity of the fluid being used. Particular care should be taken when mercury is handled.

Ion pumps use high voltages to ionize and trap gas molecules. The electrical terminals to such pumps typically operate at several thousand volts and should be treated as a serious electrical hazard.

A most serious danger is that of fatal electric shock. However, non-fatal electric shocks can cause severe injury as a result of falls or impacts against nearby equipment. Electric accidents frequently cause serious damage to equipment, including damage by fire and smoke.

Every situation or event will require good judgement and intelligent application of the necessary safety measures to the particular problem of the moment. Each facility should develop its own safety procedures based on its own needs. These safety procedures should include the following:

1. Never work alone on hazardous electric equipment.
2. Never take chances — always assume circuits are energized until you have checked them.
3. Avoid forming a circuit to ground through your body. Stand on insulating material and do not lean on metal cabinets or structures. Use one hand only.
4. Follow approved tag-out and lock-out procedures. Remove fuses whenever possible to prevent accidental application of power.
5. Make sure there is adequate light and free access to the equipment. Avoid working in confined or uncomfortable spaces.
6. Provide and use grounding hooks on capacitor banks and high-voltage equipment.
7. Follow good housekeeping practices.

Because personnel do not expect high voltages in control circuits, it is important to keep such voltages out of the control cabinets. Power circuits should also be kept out of control cabinets because the techniques and instruments used in control
circuits and their testing can fail dangerously on power circuits. It is also important that all control power come from a common source and that interlock contacts operated by power contactors or breakers be supplied from the control power and not from the power circuit through the switchgear to which they are attached.

The operator's console and all other enclosures with which personnel can come into contact should be securely grounded or earthed to prevent electric shock in the event of short-circuits or component failures inside the equipment. High-voltage and power cables should be run in separate cable ducts (wire ways) from control circuits.

Operating and maintenance personnel should always remember that console and meter indications present only indirect information about the condition of the circuits they monitor. There are often several intermediate components between the actual circuit element or voltage which is associated with the indication, and the indicator itself. These components may include resistors, capacitors, relays etc. in addition to the panel light or meter itself. The fact that a meter indicates zero voltage, or that a light is out, does not present conclusive evidence. No circuit should be assumed to be de-energized, and therefore safe, merely because that condition is represented by the indicators.

A toxic material is any substance which has the capacity to produce personal injury or illness through ingestion, inhalation or absorption through any body surface. All chemicals should be regarded with suspicion until proven to be non-toxic. Many chemicals, solvents, and metals have known toxic properties and standard handbooks on toxic materials should be available for easy reference.

It is important to use good common sense when evaluating safety practices. A constant awareness of possible hazards is most important.
Appendix II

CONSIDERATIONS FOR A NEUTRON GENERATOR LABORATORY

Certain basic guidelines can be furnished that will provide assistance regarding cost estimates and shielding considerations for individuals contemplating the installation of a neutron generator laboratory. It must be understood, however, that every such installation will have its own unique characteristics and thus any final plans and/or programmes will require careful and intensive study and evaluation.

COST ESTIMATES

Often the cost of shielding material for a laboratory can be equal to or greater than the initial cost of a neutron generator itself. For the year 1974, these costs were found to vary from as little as about $5000 to greater than $25 000, depending on the type of generator (e.g. sealed-tube or pumped Cockcroft-Walton type), the accessory equipment desired and the design of the laboratory (shielding for a sealed-tube generator or placed underground could cost as little as $3000 to $4000) in a typical industrialized country.

Monitoring instrumentation and radiation protection equipment can be expected to vary from $2500 up to $10 000, again depending upon the specific application and facility design for the neutron generator.

TYPICAL SHIELDING ARRANGEMENTS [2]

One of the most effective ways to shield fast neutrons is to completely surround the target area with a hydrogenous material such as water or paraffin wax, which absorbs the neutrons before they have a chance to escape into the surrounding environment. This principle is applied in the arrangement shown in Fig.A-II-1. The target is in the centre of a five-foot cubical water tank which is surrounded by a 0.25 in (6.4 mm) layer of boric acid. Hydrogen in the water thermalizes the fast neutrons. Boron-10 in the boric acid liner captures most of the slow neutrons which leak out of the tank. A 40 in (~1 m) wall of concrete blocks is situated between the water tank and the operator console.
FIG. A-II-1. Installation used for fast and thermal activations.
The concrete around the tank provides additional shielding against both fast neutrons which escape the water and gamma rays produced by thermal capture in the water.

For operation of the neutron generator at a level of $4 \times 10^{10} \text{n} \cdot \text{s}^{-1}$, the total dose at the console due to fast neutrons or gamma rays is below $2.5 \text{ mR} \cdot \text{h}^{-1} (6.45 \times 10^{-7} \text{C} \cdot \text{kg}^{-1} \cdot \text{h}^{-1})$; the dose due to slow neutrons is well below this value. In the accelerator room, the fast neutron dose is considerably above the maximum permissible dose.

The shielding material shown in Fig.A-II-1 does not remove all neutrons. Many neutrons are slowed down and subsequently captured in the shield. A significant fraction of neutrons escape the shield, but most of these have been degraded in energy, and their contribution to the total dose is much less than the higher energy neutrons. An effective shield need not stop all neutrons, but it must be efficient in lowering their energy. For the arrangement shown in Fig.A-II-1, the average energy of the neutrons at the outside surface of the shield is only a few electron volts. However, the major contribution to the dose results from the relatively small number of fast ($> 0.5 \text{ MeV}$) neutrons present. For purposes of dose estimation, the maximum permissible fluence of fast neutrons at any point outside the water tank may be assumed to be about $20 \text{n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$.

In most cases, if the shielding is sufficient to reduce the level of fast neutrons ($> 0.5 \text{ MeV}$) below the maximum permissible dose, the dose due to slow neutrons and gamma rays will be below tolerance.

After a prolonged period of time, the shielding material itself may become radioactive due to neutron activation. If the shielding is adequate to keep the prompt radiation at a safe level, the radiation level due to induced radioactivity will be negligible, except perhaps at the very outside surface of the shield.

The water tank shown in Fig.A-II-1 serves as a neutron moderator as well as a shield. The water surrounding the target slows the $14 \text{ MeV}$ neutrons to thermal or near-thermal energies. A sample to be activated by slow neutrons is simply lowered into the water and placed close to the target. The samples are transferred to and from the target area by a pneumatic transfer system. With the target area completely surrounded by water, the thermal flux near the target is in the same order of magnitude as the fast flux, and, hence, activation with fast neutrons cannot easily be carried out. Provision is made for fast activation by using a 'dry well'. The dry well is a thin polyethylene cylinder of about 14 in-dia. (356 mm dia,) inserted into the water and placed around the target. The cylinder contains an insert that fits around the target and allows it to be
FIG. A-II-2. Complete activation analysis laboratory.
positioned in the centre of the cylinder. The purpose of the dry well is to remove the moderating material (H\textsubscript{2}O) from the immediate vicinity of the target. The polyethylene cylinder is lined with a cadmium sheet, which captures many slow neutrons that otherwise would leak into the dry well. The sample to be irradiated is contained in a pneumatic tube which is situated inside the well and positioned an inch or less from the target. With the dry well in place, the ratio of the fast to thermal flux, at a distance of about 25 mm from the target, is 150 to 1.

The type of shielding configuration discussed above has several advantages:

1. Optimum utilization of space
2. Versatility — can be used for both slow and fast irradiations
3. Inexpensive
4. Not permanent — the concrete blocks and tank can be moved.

Figure A-II-2 shows an activation analysis laboratory. The accelerator room is a restricted area. The data room and the outside walls are below maximum permissible levels for operation at an output of $4 \times 10^{10}$ n-s\(^{-1}\). The concrete walls are stacked blocks (density = 2.0 g-cm\(^{-3}\)). A sliding concrete door separates the accelerator room from the data room. The brick facing layer is a few inches thick, and the Haydite concrete blocks are hollow, so these add very little to the shielding.

The water tank is equipped with a 'dry' well of the type described above. A pneumatic system transfers samples from the irradiation site to the counting area in the data room. The data room contains the controls for the neutron generator, the sample transfer system, and various detecting equipment. Radiochemical separation and low-level counting are done in the radiochemistry room.

Figure A-II-3 shows an installation where the neutron generator is being used with a subcritical assembly. With the target in the centre of the subcritical tank (no uranium slugs in the subcritical) the measured dosages at the north wall and at the console are shown in the table of Fig.A-II-3.

These measurements were made with a total yield of 14 MeV neutrons of approximately $4 \times 10^{10}$ n-s\(^{-1}\). The subcritical tank was filled with water when these measurements were made. Note that the shielding for this installation is similar to the arrangements described above (Figs A-II-1 and A-II-2).

Certain applications, such as neutron scattering experiments, require that the region of the target be as free as possible of scattering materials. The shielding arrangements previously discussed are not applicable. In neutron scattering experiments it is
FIG. A-II.3. Installation where the neutron generator is used to pulse a subcritical assembly.
FIG. A-II-4. Arrangement employing distance as a shielding factor.
desirable to employ distance as a shielding factor. The disadvantage of utilizing distance is the cost of building space relative to the cost of shielding materials; space always seems to be at a premium. A typical arrangement where the neutron source is separated 30 ft (9.14 m) from the operator console is shown in Fig.A-II-4. The height of the room is 15 ft (4.57 m) and the shielding walls A and B are 10 ft (3.05 m) high. With this arrangement, care must be taken to minimize scattering of neutrons from the floors and walls into personnel operating areas. The movable walls marked A are positioned so that neutrons cannot scatter through the opening to the console room. The ceiling is made of thin metal sheet, and 'skyshine' (scattering from the ceiling) is minimized. The dotted line separates the restricted areas from the unrestricted areas.

If the distance from the source to the console were 50 ft (15.24 m) instead of 30 ft (9.14 m), the thickness of each of the shielding walls could be reduced by about 6 in (152 mm). The shields marked A are mounted in a frame on casters which can be rolled from one location to another. A movable shield is very convenient for this type of arrangement since it facilitates optimum positioning of the shielding material. This type of shield is also useful if the neutron generator is to be used in several applications or different locations.

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