SHIELDING FOR HIGH-ENERGY ELECTRON ACCELERATOR INSTALLATIONS

Handbook 97

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U.S. Department of Commerce Luther H. Hodges, *Secretary*

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Shielding for High-Energy Electron Accelerator Installations

Recommendations of the
National Committee on Radiation Protection
and Measurements

NCRP Report No. 31

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Foreword

This Handbook, prepared by the National Committee on Radiation Protection and Measurements, extends the Committee's recommendations for protection against the radiations from high-energy, high-power electron accelerators. In part this Handbook is an extension of NCRP Report No. 14 on "Protection Against Betatron-Synchrotron Radiations Up to 100 Million Electron Volts" (NBS Handbook 55), issued in 1954.

Since 1931, recommendations of the National Committee on Radiation Protection and Measurements (for many years known as the Advisory Committee on X-ray and Radium Protection and later as the National Committee on Radiation Protection) have been published as National Bureau of Standards Handbooks. The Bureau is pleased to have the continuing opportunity to increase the usefulness of these important reports by providing the publication outlet.

Since the publication of Handbook 55, high-energy accelerators, particularly of the linear type, have come into much wider use in research and industry. Their applications in such areas as food processing and general sterilization have developed radiation control problems not encountered with earlier devices. Actual experience in the protection of personnel around such accelerators is limited and much more information is needed before the most economical shielding design can be developed. The NCRP plans to actively follow new developments in this general field.

The Handbooks prepared by the National Committee on Radiation Protection and Measurements (listed on the inside front cover) have expanded and kept up to date the principles of radiation protection first gathered together in NBS Handbook 15 in 1931. The present publication sets forth new principles, making reference to other Handbooks where more detailed information may be obtained.

A. V. Astin, *Director.*

Preface

The material contained in this Handbook has been under study for some five years. The long delay in issuing a report was caused mainly by the paucity of established data on protection from the radiations from high-energy electron accelerators. While many such accelerators are under design or construction for industrial, medical, and research needs, relatively few are in actual use, and these are mostly operated at moderate energies and limited outputs.

The problem of personnel protection is further complicated by the necessity of considering shielding or protection from electrons, bremsstrahlung, neutrons, and toxic gases—all of which may be present at the same time. Many of the data presented represent extrapolations from known conditions and hence must be used with caution. It is believed that the formulations developed in this report are adequately presented, but their use presupposes that the user will have a substantial knowledge of the field of high-energy physics. It was hoped that a number of relatively straightforward protection recommendations could be made, and that specific examples of their use given. This has proven to be impractical, mainly because of the wide variations in the design and use of each installation.

For the reasons given above this report should be regarded as preliminary, in the sense that it is recognized as being far from as complete as desirable. Nevertheless it gives the best information on the subject available today, and points up clearly areas where more data are needed. As more machines come into operation it is hoped that more detailed protection recommendations can be developed.

The National Committee on Radiation Protection and Measurements (originally known as the Advisory Committee on X-ray and Radium Protection) was formed in 1929 upon the recommendation of the International Commission on Radiological Protection. The Committee consists of a Main Committee and twenty-one subcommittees. Each of the subcommittees is charged with the responsibility of preparing recommendations in its particular field. The reports of the

subcommittees require approval by the Main Committee before publication.

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The present handbook was prepared by the NCRP Subcommittee on Electron Protection with the following members:

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Radiation Protection
and Measurements

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Shielding for High-Energy Electron Accelerator Installations

I. Introduction

A. Preface

This report is intended to give a summary of the presently available data required to calculate the shielding for high-energy, high-intensity electron-accelerator installations. The report is not intended to present specific, all-inclusive recommendations since it is not felt that at the present time the "state of the art" has progressed to the point where such recommendations are feasible. Rather the report is aimed at outlining the present state of our knowledge about the factors governing the shielding required in the vicinity of these accelerators. The recommendations that are made have to do primarily with a procedure to be followed in establishing the required amount of shielding.

B. Scope

1. Energy

This report will deal with electrons ranging in energy between 0.5 MeV and 100 MeV. The lower limit was set because of the limited utility and very small penetration of electrons at such low energies (less than 1.6 mm of H_2O at 0.5 MeV). The upper limit is arbitrary and represents the highest energy of commercial planning of which the Subcommittee has knowledge. Because of rapidly increasing problems of production of radioactivity and neutrons, commercial use of higher energies is expected to develop slowly.

2. Output Power

The range of output power considered is up to 100 kilowatts. It must be emphasized that at the time of writing, such a high output has not been obtained and that the data

presented here, while the best available at the present time, may not be completely adequate for all purposes.

The hazards due to fire and to electrical and mechanical features of the accelerators themselves have been considered by others [1, 2, 3, 4][1] and will not be reconsidered here. No attempt will be made to treat the radiation hazards peculiar to particular accelerators; rather, basic data will be given that can be applied to all machines.

C. Statement of the Problem

A simplified schematic drawing of an electron accelerator installation is given in figure 1. The problem of shielding such an installation is not so much one of stopping or confining the electrons themselves but rather one of shielding for the secondary radiations produced by the electrons. The electrons travel only a finite distance through matter (less than 60 cm in water for a 100-MeV electron). One of the basic interactions of electrons with matter, however, is the bremsstrahlung process which can convert a large fraction (up to 80%) of the electron beam power into x-ray power. In addition to having to shield for the electrons, it then becomes necessary to provide for the shielding of a high-intensity x-ray source. In its interaction with matter, the bremsstrahlung can produce large numbers of fast neutrons through the nuclear photodisintegration process. For a sufficiently high-energy electron beam (>15 MeV), these fast neutrons contribute appreciably to the shielding problem. Finally, there is the problem of residual radioactivity formed both as a result of the neutron production process and as a result of the neutron capture process. Figure 2 indicates a possible flow diagram for the kinetic energy of a single electron. In table 1 the history of a 25-MeV, 10-kW beam of electrons from the point where it leaves the accelerator until its energy is ready to be absorbed by the ionization of matter is summarized. It is assumed that the beam passes through 1 cm of air before hitting a 1.5-cm-thick plate of copper and that the resulting bremsstrahlung beam passes through 2 meters of air before being absorbed in a concrete wall.

As can be seen from the above discussion, the shielding problems connected with a high-energy, high average current electron accelerator are of the same general type as those associated with a nuclear reactor. In fact, some of the handbooks and textbooks written on the shielding problems associated with nuclear reactors provide excellent

[1] Figures in brackets indicate the literature references at the end of this Handbook.

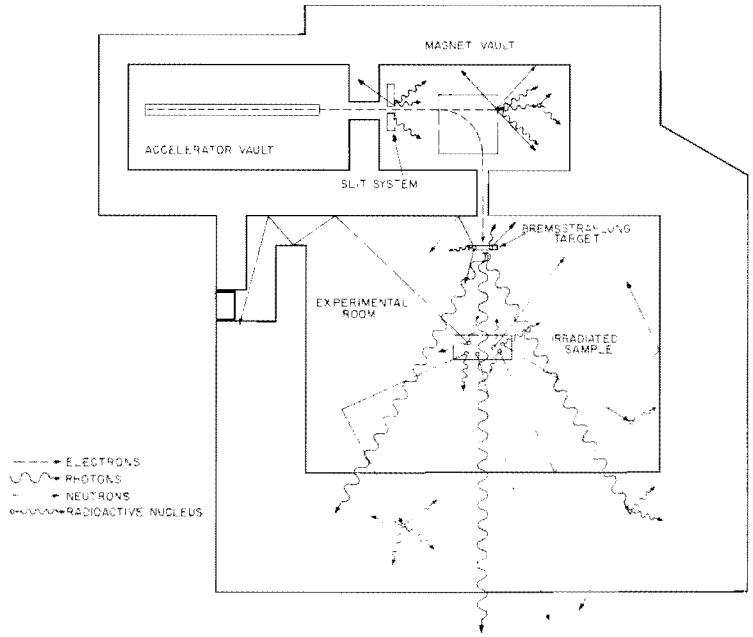

FIGURE 1. *Schematic representation of an electron accelerator installation.*

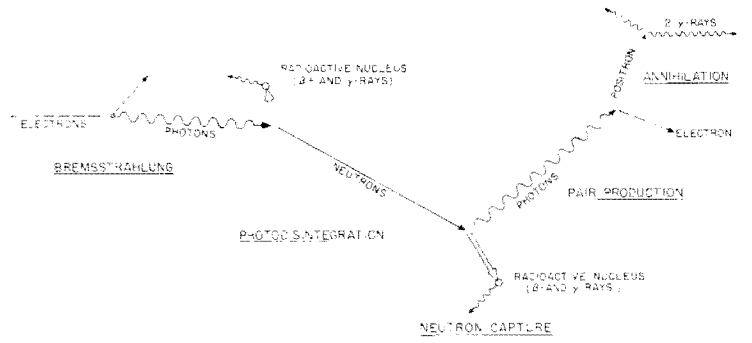

FIGURE 2. *Interactions of radiation with matter.*

background material for anyone considering the shielding problems associated with such an accelerator (see, for instance: Price, Horton, and Spinney, *Radiation Shielding* Pergamon Press, New York, 1957). There are two main

TABLE I. Radiation from a high-energy high-intensity electron accelerator

Yields are based on: 10 kW 25 MeV electron beam passing through 1 cm of air before being incident on 1.5 cm of Cu. Bremsstrahlung beam passes through 2 meters of air before being attenuated in concrete. It is assumed that electron beam is 0.5 cm in diameter. Source strengths in concrete represent that produced in a thickness corresponding to one mean free path for the γ, radiation emitted by the source.

Radiation	Process governing shielding	Problem	Yields
Electrons			25 MeV 10 kW.
	Scattering and ionization.	Radiation damage.	
		Thermal effects	Power dissipation in Cu 33 kW/cm^3.
		Ionization of air	1.7×10^{17} molecules/sec of noxious gas produced.
	Bremsstrahlung	X-ray source	2.7 kW of bremsstrahlung produced: 0.7 kW absorbed in Cu. 2.0 kW absorbed in air and concrete.
Bremsstrahlung.			2.7 kW.
	Scattering and electronic absorption.	Radiation damage.	
		Ionization of air	1.4×10^{18} molecules of noxious gas produced per sec.
	Nuclear absorption.	Neutron source	2×10^{12} neutrons/sec produced.
		Residual activity.	Saturated activities: *Nucleus* — *Half-life* — *Activity (curies)* Cu^{64} — 12.8 hr — 14 Cu^{62} — 10 min — 15 N^{13} (air) — 10 min — 0.026 O^{15} (air) — 2.3 min — .014 Concrete: *Nucleus* — *Half-life* — *Activity (curies)* O^{15} — 2.3 min — 1.6 K^{38} — 7.7 min — 0.14 Na^{22} — 2.6 yr — .16
Fast neutrons.			2×10^{12} neutrons/sec.
	Scattering and absorption.	Radiation damage.	
		Residual activity.	In concrete walls of room if no other shielding material is present. (Saturated Activity.) Na^{24} 2.6 curies.

differences between the shielding problems associated with a reactor and those with a high-energy, high-intensity electron accelerator. Probably the most important point to be considered is the difference in the neutron spectra produced by the two sources. The photoneutron spectrum has high-energy components which are not present in the reactor neutron spectrum. This problem becomes particularly important if the accelerator is operated at energies above 30 MeV. For a high average current electron accelerator operating at 100 MeV, the neutron shielding problem is dominated by photoneutrons having energies greater than

40 MeV. The second point is the highly directional character of the electron and x-ray beams associated with the accelerator. The neutrons produced by the absorption of the electrons and x rays have few directional properties and the shielding for them must surround the output end of the accelerator.

II. Procedure for Determining Shielding Requirements

A. General Consideration

The shielding required for an electron accelerator installation depends not only upon the operating characteristics of the particular accelerator involved but also upon the type of installation (industrial, research, medical, etc.). The first step in setting up the shielding requirements is of course to define the type of installation and the uses to be made of the installation. The general relationship of the accelerator, irradiation, and experimental rooms to those areas or rooms to which personnel will have access during the operation of the accelerator (occupied areas) should be determined. Once these factors have been defined the shielding requirements will depend significantly on the dependence to be placed on interlocking radiation monitoring systems and restrictions to be imposed on operating procedures.

The highest degree of inherent protection is achieved where there is adequate structural shielding for all possible modes of operation, including failure of any component of the beam handling system. This high degree of inherent protection requires the maximum amount of shielding and may not always be feasible due to space and weight limitations; furthermore, such installations generally are less flexible and more expensive. The acceptable degree of dependence on operating restrictions can best be determined after a preliminary estimate of the shielding requirements.

B. Determination of Shielding Requirements

The shielding requirements can be determined by completing the following outline for the particular accelerator installation. (In this outline references of the form (III A–2) refer to later sections of this report where information on a particular subject may be found.)

1. *Establish accelerator characteristics:*
   a. Maximum possible electron energy.
   b. Maximum electron beam current.

c. Maximum beam power.
d. Maximum electron energy at maximum beam power.
e. Electron energy spectrum as it leaves accelerator under all operating conditions.

2. *Determine radiation source points and regions:* A radiation source point or region is any spot or region which for either normal or abnormal operation of the accelerator is in the path of either the electron beam or the bremsstrahlung beam generated as a result of the electron beam hitting a target. Radiation source points include:

a. All bremsstrahlung targets.
b. All slits and collimators.
c. Walls of the vacuum chamber at all magnets.
d. Material in which electron or bremsstrahlung beams are absorbed.
e. Any air path through which electrons or bremsstrahlung beams pass.

3. *Determine source characteristics and yields for each source point and region, using appropriate data in this report.* In calculating yields from various source points assume that it is possible for the entire beam of the accelerator to hit any given source point. Quantities to be determined:

a. Heat generated—(III A–2).
b. Noxious gas production rate—(III A–3).
c. Bremsstrahlung yield and direction of beams—(III B).
d. Neutron yield and probable spectra—(III C).
e. Production of residual radioactivities—(III D).
f. Production of O^{15} and N^{13} —(III D).

NOTE: The last three items, except in unusual circumstances, need only be considered if the maximum electron energy is above 10 MeV.

4. *Determine the geometrical relationship of each radiation source point or region to each occupied area.*

5. *Assign a permissible radiation level for each occupied area and for each type of radiation.* See NCRP NBS Handbooks 59 (revised), 63, 69 and 76.

6. *With no shield present, determine the radiation flux in each occupied area resulting from each radiation source point or region.* (IV A.)

7. *Determine the shielding factor required for each occupied area based on the ratio of 5 to 6, according to the degree of inherent protection being designed into the installation.*

8. *Calculate the shielding required for each occupied area and for each type of radiation.*

a. Electrons—(V B).
b. Bremsstrahlung—(V C).

NOTE: These are the principal radiations to be considered in the shielding around accelerators operating with peak electron energies up to 10 MeV. Such accelerators should be considered essentially as bremsstrahlung sources of peak energy corresponding to the maximum electron energy and x-ray beam power consistent with bremsstrahlung production efficiencies given in section III B–2. See NCRP report No. 14 (NBS Handbook 55).

c. Neutrons—(V D). If electrons are accelerated to energies greater than 25 MeV the spectral distribution of the neutrons generated by the electrons and bremsstrahlung should be considered in calculating the shielding. See Sec. III C–4. *Note that for high-intensity, high-energy accelerators (greater than 30MeV) the high-energy parts of the neutron spectrum determine the shielding required in most areas.*

9. *Additional points to be considered.*

a. Concentrations of noxious gases in radiation rooms and the disposal of these gases—(III A–3).
b. Concentration of radioactive gases in radiation rooms and the disposal of these gases—(III D–1).
c. Radiation damage to materials in radiation rooms—(V–E).
d. Fire hazards in irradiated materials—(V–F).
e. Radioactivities induced in shielding as well as machine components.
f. Possibility of radioactive contamination of subsurface water.

III. Beam Characteristics and Yields

A. Electrons

1. Beam Characteristics

The characteristics of the electron beam leaving an accelerator vary considerably from one type of accelerator to another. It may be concentrated in a well-defined region of space (diameter of the order of a few millimeters) and have a divergence of only a few milliradians. On the other hand, it may be very broad and have a divergence of the order of tenths of radians. Similarly, the energy spectrum can have wide variations. The electrons may be all concentrated within a small energy region of the order of a few percent or less of the operating energy of the accelerator or there may

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be a continuous spectrum extending down from the operating energy with less than 70 percent of the electrons in an interval within 10 percent of the operating energy. For most electron linear accelerators these beam characteristics depend on the way in which the accelerator is operated. In designing the shielding for such an installation it is, therefore, necessary to take into consideration these wide variations in beam characteristics.

In calculating yields of neutrons or induced radioactivity, the electrons should all be assumed to have the operating energy. Calculations should be based on the worst possible conditions of operating energy and current.

Shielding should be calculated on the assumption that the accelerator will operate with the entire beam hitting any aperture or collimator placed in the beam.

Shielding should be calculated on the assumption that at each bending magnet the entire beam can hit the wall of the vacuum chamber.

2. Heat Generated

Assuming that Feather's rule gives the range of an electron of energy T (MeV), the approximate power dissipated per cm^3 in a slab of material thick enough to stop the electrons is given by:

$$\text{Power dissipated/cm}^3=\frac{i\rho\Delta T}{0.54T-0.13}\ (\text{kW/cm}^3). \qquad (1)$$

In this expression i is the beam current density in mA/cm^2, ρ the density of the material in grams/cm^3, and ΔT is the energy loss (MeV) of the electrons by ionization in the material.

3. Noxious Gas Production

It should be assumed that one molecule of noxious gas (ozone or nitrous oxide) is produced per ion pair produced in air. Since it takes 33.7 eV to produce an ion pair, and since an electron loses about 2.2 keV in passing through 1 cm of air at NTP, the number of molecules of noxious gas that will be produced by a beam current of I mA passing through t cm of air will be: ($1\ \text{mA}\equiv 6.25\times10^{15}$ electrons/sec)

$$\frac{\text{Molecules}}{\text{sec.}}=\frac{2.2\times10^3}{33}\times6.25\times10^{15}It=4.0\times10^{17}It. \qquad (2)$$

B. Bremsstrahlung

1. General

Electrons slowing down in a medium radiate a fraction of their energy in the form of x-ray energy. The bremsstrahlung production efficiency, ϵ, for a target is defined as the fraction of an incident electron's energy that is converted into bremsstrahlung energy in the target. For a monoenergetic beam this factor also gives the fraction of the incident electron beam power that is converted into bremsstrahlung beam power. The bremsstrahlung efficiency increases with the atomic number, Z, of the medium and with the electron energy, T. For thin targets the efficiency varies approximately as Z^2 for targets having the same thickness in g/cm^2. For thick targets, those in which the electrons are stopped, the efficiency varies as Z for low atomic number materials and approaches unity for high atomic number materials at high energies.

The x rays are emitted into various angles and energies. At high electron energies, the x rays are emitted predominantly in the forward direction of the electron, and this effect becomes more pronounced as the electron energy is increased. The x-ray energy distribution is a monotonically decreasing function of the photon energy extending up to the initial electron kinetic energy.

2. Total Production Efficiency

The x-ray production efficiency can be evaluated for thin targets from equations given in Heitler [5] and summarized by Koch and Motz [6]. They show that the thin target efficiency is

$$\epsilon=\frac{\Delta T_r}{T}=K\frac{t}{t_r} \qquad (3)$$

where t is the target thickness, t_r the radiation length (neglecting effects of atomic electrons), and K is a radiation probability correction factor. Values of the radiation length, t_r, in units of gm/cm^2 are plotted as a function of atomic number in figure 3. The factor K, which is only slightly dependent on Z and T (the electron kinetic energy), is given in table II.

Targets that are more than one-fourth of a radiation length in thickness will be inadequately treated by eq 3.

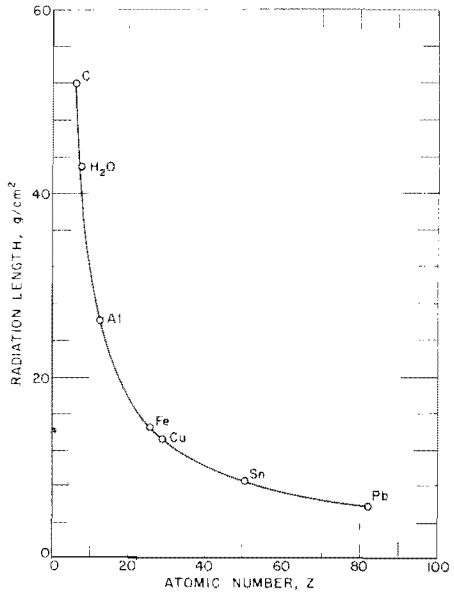

FIGURE 3. *Radiation lengths in grams per square centimeter for various materials.*
Values given neglect effect of atomic electrons [6].

TABLE II. *Radiation correction factor* K.

Material	Kinetic energy, T (MeV)				
	5	10	20	40	100
Water	0.61	0.70	0.77	0.85	0.89
Copper	.66	.77	.82	.88	.92
Lead	.69	.78	.83	.89	.93

Efficiencies for thick targets can be evaluated from an expression given by Koch and Motz [6]:

$$\epsilon = 1 - \frac{\ln[1+1.2\times10^{-3}TZ]}{1.2\times10^{-3}TZ} \tag{4}$$

where Z is the atomic number and T the electronic kinetic energy in MeV. At low energies, or for small atomic numbers, this expression reduces to

$$\epsilon = 5\times10^{-4}TZ. \tag{5}$$

Representative values obtained using eq 4 are given in table III.

TABLE III. *Approximate*[a] *thick target x-ray efficiencies in percent*

Material	Kinetic energy, T (MeV)							
	0.5	1.0	2.0	5.0	10	25	65	130
Water	0.23	0.46	0.92	2.3	4.6	11.5	21	33
Aluminum [b]	.38	.77	1.53	3.7	7.1	15.6	31	45
Iron	.77	1.53	3.00	7.1	13.0	26.1	45	60
Lead	2.5	4.9	9.7	18.9	30.4	49.6	69	80

[a] These efficiency values were derived without including backscattering of electrons from or x-ray absorption in the x-ray target which will be important at the lower energies.
[b] Concrete, a commonly used shielding material, can be assumed to behave like aluminum for the purposes of an efficiency evaluation.

3. Forward Intensity for a Thick Target

Lawson [7] has derived the following expression for $R(O)$, the fraction of an electron's energy radiated into a unit solid angle in the forward direction when the electron passes through a target of thickness t

$$R(O) = \frac{(T+0.51)^2}{440}\frac{K}{\pi}\ln(950t/t_r). \tag{6}$$

In this expression T is the kinetic energy of the electron in MeV, K is the radiation correction factor given in table II, and the target thickness is measured in units of the radiation length t_r given in figure 3. This expression was derived by assuming that in the thickness t the electrons do not lose an appreciable fraction of their original energy but that they are multiply scattered to a considerable degree. It has been pointed out, however [8], that this expression may be used to estimate with sufficient accuracy for most purposes the forward intensity for thick targets. For electron energies whose range is 0.1 t_r or greater, the true forward intensity will lie between the values obtained from eq 6 with $t/t_r=0.1$ and $t/t_r=1.0$. These values differ by 50 percent. For lower energy electrons a value of t/t_r corresponding to the electrons range should be used.

Equation 6 leads to the following expression for $I(O)$, the forward bremsstrahlung intensity resulting from a 1-mA electron-beam current of energy T incident on a thick target

$$I(O) = 0.72\times10^{-4}(T+0.51)^2\ TK\ \ln(950t/t_r)\ \text{(Watts/cm}^2\text{-mA at 1 meter)}. \tag{7}$$

T is given in MeV. The expression does not take into account the bremsstrahlung absorption in the target.

This expression gives intensities that are in reasonable agreement with the measurements made by Buechner, van de Graaff, Burrill, and Sperduto [9] in the energy region of 1.25 to 2.35 Mev, as well as with measurements made by Lawson [10] at 7.3 Mev.

4. Angular Distribution

The angular distribution of the bremsstrahlung from a given target depends upon the inherent angular distribution of the bremsstrahlung process, the multiple scattering of the electrons in the target and the divergence or angular spread of the incident electron beam. For all but extremely thin targets, the multiple scattering is the dominating factor. The inherent spread of the bremsstrahlung process is of the order of $T\theta = 10$ MeV-degrees, where T is the electron energy and θ is the angle with respect to the electron's direction at which the bremsstrahlung intensity is one-half the central value. For a practical bremsstrahlung target and for electrons that are originally collimated, the half-intensity angle of the x rays will be 100 to 200 MeV-degrees (See fig. 4). More exact relationships for the angular distribution are to be found in NBS Handbook 55.

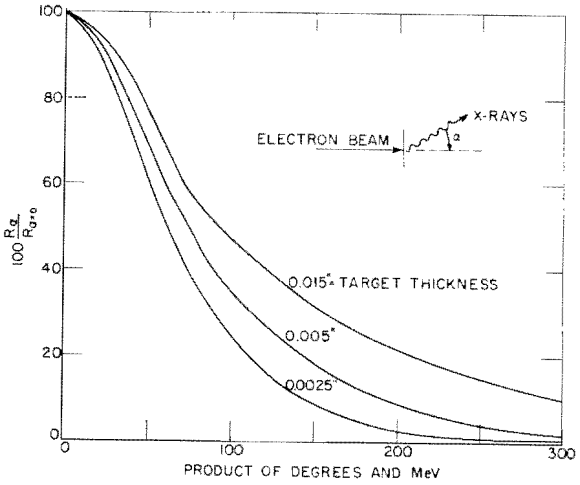

FIGURE 4. *Theoretical bremsstrahlung angular distribution from typical targets for realtivistic energies.*

These curves are from National Bureau of Standards Handbook 55. R is defined as the fraction of the total incident electron kinetic energy that is radiated per steradian at the angle α.

5. Spectra

In estimating the shielding required for a bremsstrahlung beam, a good approximation is to assume the total beam intensity is concentrated at an energy corresponding to one-third of the initial electron's kinetic energy. The photon attenuation coefficients appropriate for this energy can then be used. For more precise calculations of bremsstrahlung shielding, as well as the detailed calculation of the yields of neutrons, as well as of radioactivity, a knowledge of the bremsstrahlung energy spectrum $I(E,T)$ is required. This function gives the energy in a given energy interval (energy per unit energy interval) as a function of the location of that interval, E, in the spectrum. The spectrum extends up to the original kinetic energy, T, of the electron hitting the target.

A detailed discussion of the available information, both experimental and theoretical, is given in the review article by Koch and Motz [6]. For most purposes, the Bethe-Heitler spectrum with screening corrections is adequate to calculate yields of neutrons and radioactivity. Although this spectrum does depend somewhat on the atomic number of the target material, as well as on the angle of emission of the photon with respect to the incident electron direction, both these effects can usually be neglected for normal targets. The bremsstrahlung spectrum can then be represented by the so-called "integrated over angle spectrum." The most complete tabulation of these spectra as a function of the incident electron's energy is that made by Penfold and Leiss [11]. Figure 5 is a plot of the intensity spectra taken from reference [11] for a series of different incident electron energies.

If the target in which the bremsstrahlung is produced is thick enough for the electrons to lose a large fraction of their energy, the bremsstrahlung energy spectrum is modified considerably from that described above resulting from the basic interaction process. This is shown in figs. 6 to 8 where calculated thick target spectra for electrons of incident energy T are compared with the basic thin target spectra. In each case the target was just thick enough to stop the incident electrons. No correction has been made for the absorption of photons in the target.

C. Neutrons

1. General

The major process responsible for the production of neutrons by an electron beam is the nuclear absorption of brems-

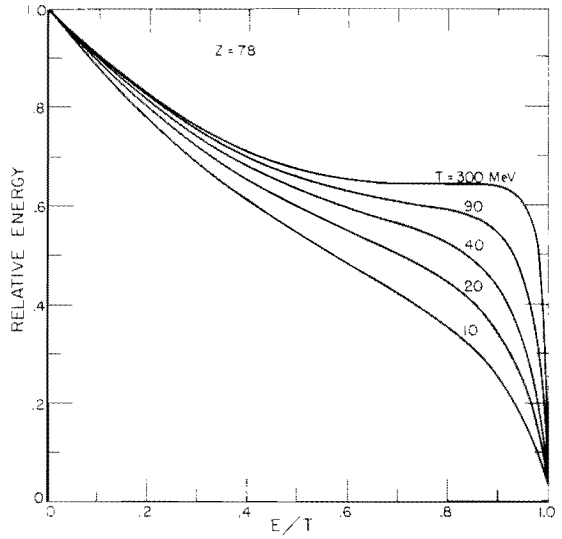

FIGURE 5. *Dependence of the bremsstrahlung spectrum shape on the electron kinetic energy for a platinum target (Z=78).*

The relative energy (defined as proportional to the product of the photon energy and the number of photons) is integrated over the photon direction and is normalized to unity for zero photon energy.

strahlung produced by the electron beam. It is possible for an electron to interact directly with a nucleus and produce a neutron but the probability for this process is about 100 times smaller than that for the x-ray interaction.

For a neutron to be produced it is necessary for the photon absorbed by the nucleus to have an energy greater than the binding energy of the neutron to the nucleus. With a few notable exceptions neutron binding energies lie between about 7 and 15 MeV with most nuclei having binding energies between 7 and 11 MeV. The most notable exceptions and their binding energies are: D, 2.2 MeV; Be^9, 1.7 MeV; C^{13}, 4.9 MeV; C^{12}, 18.7 MeV; and He^4, 20.1 MeV. Unless the electrons have an energy greater than the neutron binding energy of one of the nuclei in either the electron or bremsstrahlung beam, it will be impossible for it to produce any neutrons.

For any given nucleus the probability, or cross section, for producing a neutron depends upon the energy of the x ray absorbed. This probability starts at zero at the (γ,n) threshold and then follows a broad resonance shaped curve. A typical curve is shown in figure 9. The maximum cross

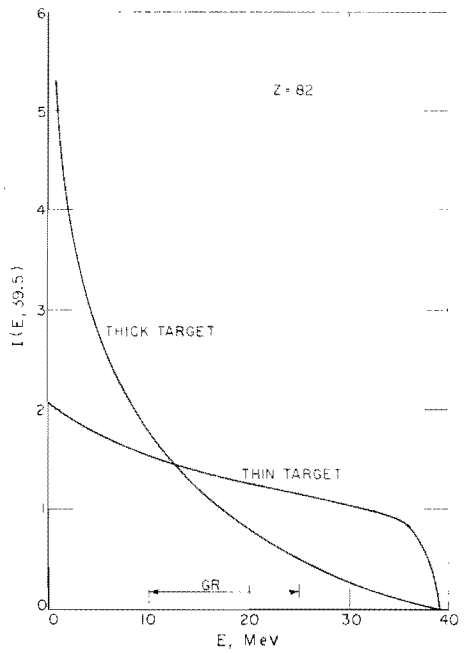

FIGURE 6. *Comparison of bremsstrahlung energy spectrum shape for thick and thin targets.*

Target material is lead and is just thick enough to stop the incident electrons. Electron kinetic energy T=39.5 MeV. Spectra are normalized to have the same area under the curves. No corrections have been made for the absorption of photons in the bremsstrahlung target. Horizontal bar indicates the giant resonance energy region. Data are from Linac Research Group Internal Report 9, Lawrence Radiation Laboratory, Livermore, Calif.

section for producing a neutron is at 13 MeV for heavy nuclei like lead. The energy of the peak increases slowly with decreasing atomic number. For the light nuclei like carbon and oxygen, the maximum is at about 23 MeV. For essentially all nuclei there is a high-energy tail to the neutron production cross section which is responsible for a high-energy neutron spectrum which is of considerable importance in the shielding considerations for accelerators operating above 30 MeV. This high-energy tail extends to energies well above those covered by this report.[12]

For a given electron kinetic energy, T, the neutron yield will depend both on the shape of the neutron production cross section curve and the shape of the bremsstrahlung spectrum generated by the electrons. Typical neutron

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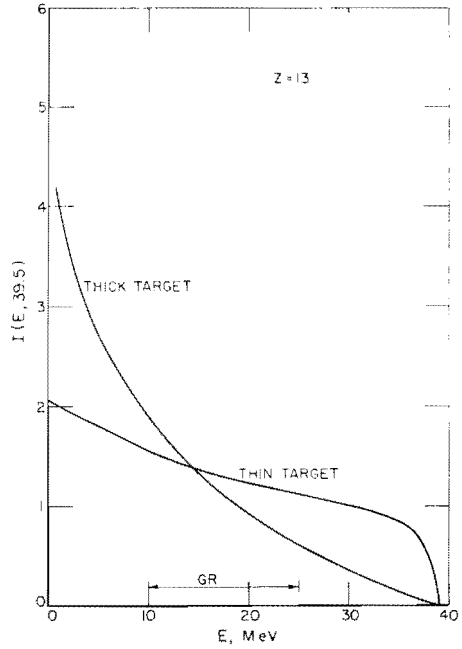

FIGURE 7. *Comparison of bremsstrahlung energy spectrum shape for thick and thin targets.*

Target material is aluminum and is just thick enough to stop the incident electrons. Note the slightly higher cross over energy for the thick and thin spectra compared with that in figure 6. This would indicate that for a thick target the neutron yield per MeV of bremsstrahlung would be higher from aluminum than from lead. For shielding considerations, however, the lower bremsstrahlung production efficiency for aluminum more than compensates for this effect (see Table III and fig. 14). Data are from the Linac Research Group Internal Report 9, Lawrence Radiation Laboratory, Livermore, Calif.

yield curves are shown in figure 10 for a light and heavy nucleus. These curves give the relative neutron yield per kilowatt of bremsstrahlung as a function of the upper energy limit to the bremstrahlung spectrum.

2. Neutron Production by Bremsstrahlung

An estimate (good to within a factor of about 2 for heavy nuclei) of $Y_0(T)$, the yield of neutrons per sec per kilowatt of bremsstrahlung incident on a sample of thickness t, can be obtained from the expression,

$$Y_0(T)=10^{14}\frac{\eta}{T}[1-e^{-\mu t}]\frac{\text{neutrons per sec}}{\text{kilowatt of bremsstrahlung}} \qquad (8)$$

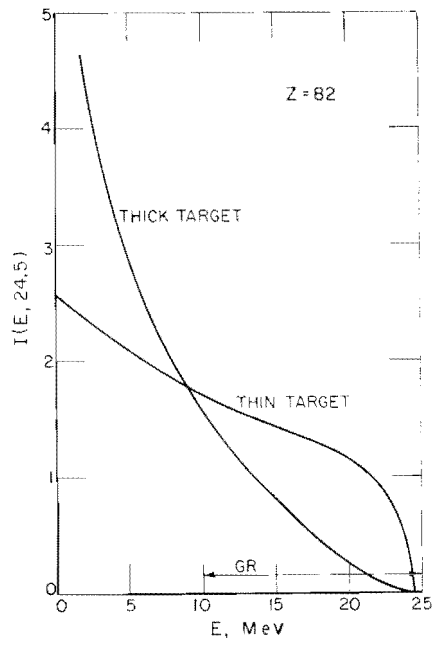

FIGURE 8. *Comparison of bremsstrahlung energy spectrum shape for thick and thin targets.*

Incident electrons kinetic energy T=24.5 MeV. Data are from Linac Research Group Internal Report 9, Lawrence Radiation Laboratory, Livermore, Calif.

where T is the upper energy limit of the bremsstrahlung spectrum (kinetic energy of initial electron), μ is the electronic absorption coefficient at the peak of the giant resonance, and η is the fraction of the photons absorbed in the nucleus that result in the production of a neutron. Representative values of η are given in table IV. This expression will considerably overestimate the neutron yield unless T is greater than 5 MeV above the giant resonance energy. It will also overestimate the yield if the bremsstrahlung is generated in a thick target.

More accurate estimates of neutron yields can be calculated by using the basic cross sections for neutron production and the actual bremsstrahlung spectrum appropriate for a given situation. If I' (E,T) represents the bremsstrahlung intensity spectrum produced by electrons of kinetic energy T, t the thickness of a sample bombarded by the bremsstrah-

TABLE IV. *Neutron yield data*

Nucleus	η	E_T	$\int_0^{25}\sigma_{tn}dE$	"E_r"	"Γ"	$\mu(E_r)$	Ref.
		MeV	*MeV-barns*	*MeV*	*MeV*	*cm²/gram*	
C	0.3	18.7 [a]	0.032	22.5	3.5	0.0152	45
N	.73	10.5	.060	23	5.0	.0164	46
O	.35	15.6	.060	24	3.5	.0173	47
Al	.50	13.0	.144	20	8	.0217	48
Ni [1]	.38	11.9 [b]	.210	19	4	.0335	49
Cu	.80	10.8 [c]	.90	18	8	.0334	50
Ta	1.2	7.4	4.5	14.5	8	.055	14
Pb	1.2	7.4 [d]	5.6	13.8	4.25	.055	14

Note	*Threshold for*	*Thresholds for other isotopes and their abundance*
a	C^{12}	C^{13} 1 percent 4.9 MeV.
b	Ni^{58}	Ni^{60} 26 percent 11.4 MeV; Ni^{61} 1 percent 7.8 MeV; Ni^{62} 4 percent 10.6 MeV; Ni^{64} 1 percent 9.6 MeV.
c	Cu^{63}	Cu^{65} 31 percent 9.9 MeV.
d	Pb^{208}	Pb^{207} 21 percent 6.7 MeV; Pb^{206} 26 percent 8.0 MeV; Pb^{204} 1 percent 8.5 MeV.

[1] Figures given are for Ni^{58}. The low value of η, however, is consistent with the low total neutron yield that has been measured for elemental nickle.

lung, and $\sigma_{tn}(E)$ the cross section for producing a neutron, the yield of neutrons per second is given by:

$$Y=\int_0^T (\text{photons per sec per MeV})\times(\text{cross section per nucleus})\times(\text{nuclei per cm}^2)\times dE$$

$$=\int_0^T \frac{I'(E,T)}{E}\,\sigma_{tn}(E)\,\frac{tN}{A}\left(\frac{1-e^{-\mu t}}{\mu t}\right)dE \qquad (9)$$

where the factor $\{(1-e^{-\mu t})/\mu t\}$ corrects for the fact that photons are absorbed in passing through the sample. The thickness of the sample, t, is given in g/cm², N is Avogadro's number (the number of atoms in a gram atomic weight, 6.02×10^{23}), A is the atomic weight of nuclei bombarded, and μ is the total absorption cross section for the sample expressed in cm²/g.

For all but the most accurate estimates it is possible to neglect the variation of the bremsstrahlung spectrum with energy and write this expression:

$$Y_1=\frac{I'(E_r,T)}{E_r}\,\frac{N}{A\mu(E_r)}\,(1-e^{-\mu t})\int\sigma_{tn}(E)dE \qquad (10)$$

where $(I'(E_r,T)/E_r)$ gives the number of photons per sec per MeV at the energy E_r at which the neutron yield cross section peaks. The quantity $\int\sigma_{tn}(E)dE$ is the integrated

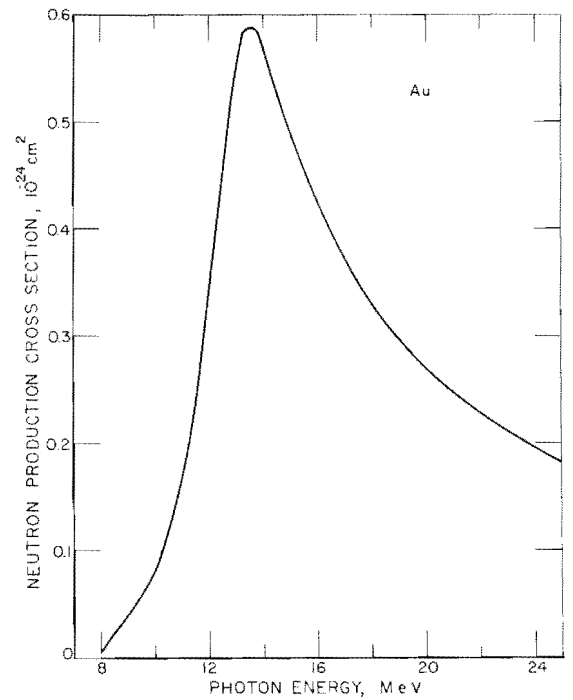

FIGURE 9. *Neutron production cross section for gold.*

The curve represents $\sigma_{tn}=\sigma(\gamma,n)+2\sigma(\gamma,2n)+\sigma(\gamma,pn)$. Data from ref. [14].

neutron production cross section in MeV-barns. These quantities are tabulated in table IV.

In order to obtain the expression for Y_0 given by eq 8, a further approximation is made that the bremsstrahlung intensity spectrum $I'(E,T)$ is a constant, independent of E, i.e., $I'(E,T)=C$. The total power in the bremsstrahlung beam is then CT and the neutron yield per sec per kilowatt of incident bremsstrahlung is:

$$Y_0=\frac{Y_1}{CT}\,\frac{1}{TE_r}=\frac{N}{A\mu(E_r)}\,[1-\exp\,\mu(E_r)t]\int\sigma_{tn}(E)dE. \qquad (11)$$

The integrated neutron production cross section $\int\sigma_{tn}(E)dE$ is a function, η, of the total integrated photon absorption cross section which for a given nucleus is proportional to $NZ/A\approx A/4$ [13]. The product of the energy at which the

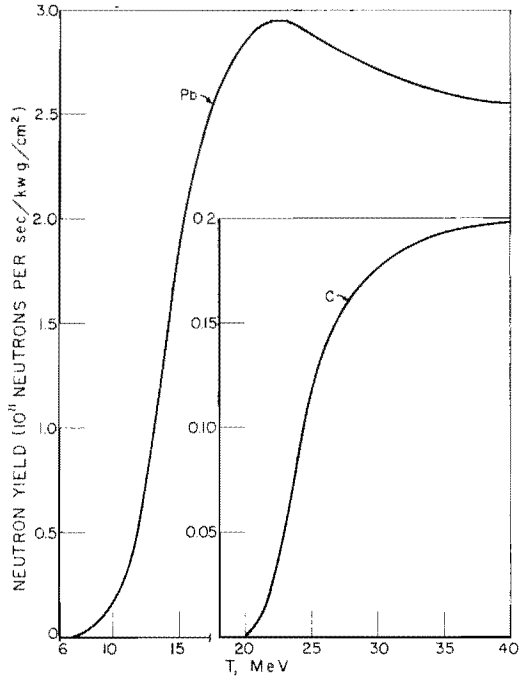

FIGURE 10. *Relative neutron yield per kilowatt of bremsstrahlung from 1 gm/cm² targets of carbon and lead.*

Note change in scale for carbon.

neutron yield cross section peaks and the electronic absorption cross section expressed in cm²/g, $(E_r\mu(E_r))$, varies by less than a factor of two in going from carbon to lead. Making these approximations:

$$Y_0 = k\frac{\eta}{T}[1-\exp\mu(E_r)t]\frac{\text{neutrons/sec}}{\text{kilowatt of bremsstrahlung}}. \quad (12)$$

In eq 8 the constant k was evaluated from the thin bremsstrahlung target yield from lead measured by Fuller, Petree and Weiss [14].

3. Production of Neutrons by Electron Bombardment of Targets

In principle the neutron production resulting from the electron bombardment can be calculated by dividing the

target into a series of thin layers in which the electrons on the average lose only a small fraction of their energy. The procedure of section III–B can then be used to estimate the bremsstrahlung produced in each layer. The methods of section III–C–2 can then be used to calculate the neutron yield. This sort of calculation can be quite involved and an accurate calculation for a target not thick enough to absorb completely the electron and secondary x-ray power is difficult to make. Where possible it is therefore preferable to use experimental data.

Barber and George [15] have measured the neutron yields from targets of C, Al, Cu, Ta, Pb, and U of thicknesses ranging from 1 to 6 radiation lengths and for incident electron energies from 10 to 36 MeV. Figure 11 gives the yield for targets of low atomic number of about 1 radiation length in thickness. Figures 12 and 13 give the dependence on target thickness for Cu and Pb targets. Figure 14 gives the yield as a function of Z for a series of targets all about a radiation length thick.

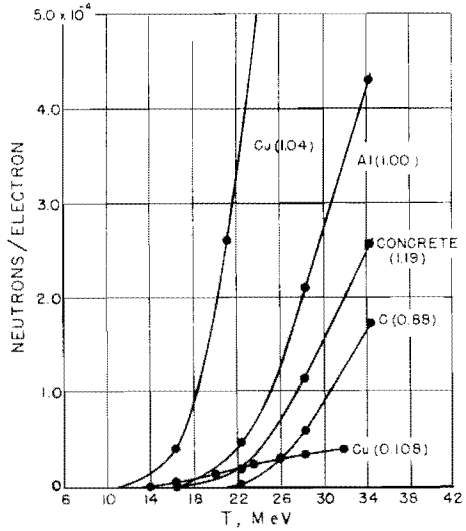

FIGURE 11. *Yield of neutrons per incident electron as a function of initial electron energy for low-Z elements.*

The concrete target is a 3-to-1 sand-cement mixture. Numbers in parentheses give target thickness in units of the radiation length for the material. Data are from ref. [15].

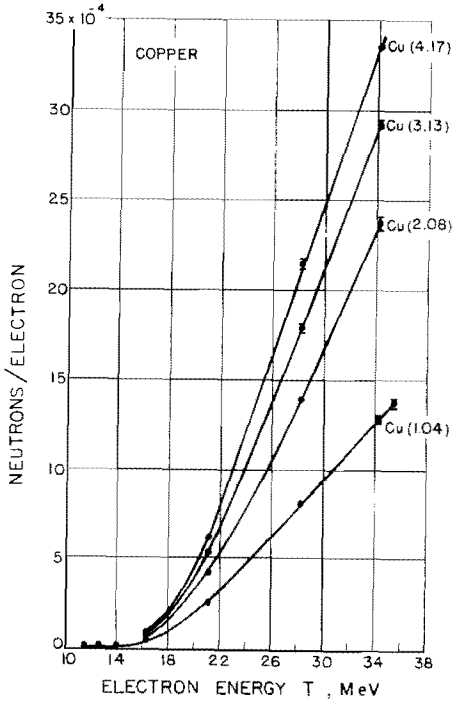

FIGURE 12. *Yield of neutrons per incident electron as a function of initial electron energy for natural* Cu *targets of various thicknesses.*

Target thicknesses are given in units of the radiation length for Cu. Data are from ref. [15].

4. Photoneutron Spectra

The data that are available on the photoneutron spectra are relatively meager. They are sufficient for shielding calculations for accelerators operating in the energy range up to 40 MeV. For high-intensity accelerator operating in the energy range above 40 MeV, however, there are important gaps in the presently available data on the details of photoneutron spectra.

The photoneutron spectra produced by 20 and 30 MeV bremsstrahlung incident on a tantalum sample, as measured by Cortini et al. [16], are given in figure 15. These spectra are normalized to give the fraction of the total number of

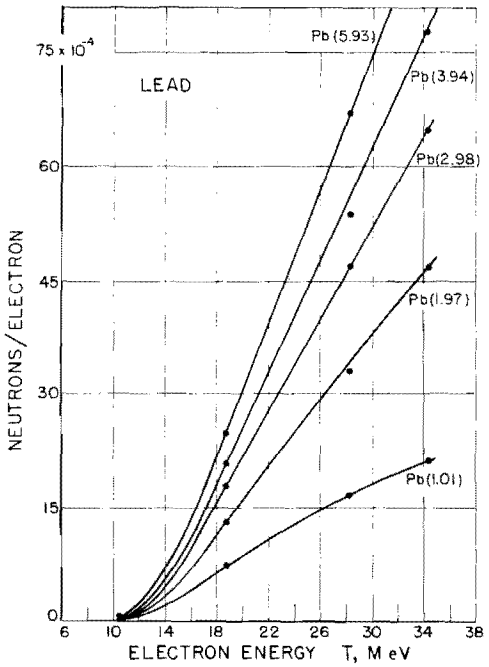

FIGURE 13. *Yield of neutrons per incident electron as a function of initial electron energy for natural lead targets.*

Target thicknesses are given in units of the radiation length for lead. The yield at 34.5 MeV from the target 5.93 radiation lengths thick is 90×10^{-4} neutrons per electron.

neutrons produced per MeV of neutron energy. Also shown for comparison is spectrum of fission neutrons from U^{235} as given by Price et al. [17]. Figure 16 shows the neutron spectra resulting from the bombardment of carbon and oxygen by a 30 MeV bremsstrahlung spectrum [18].

There are three main processes responsible for the production of photoneutrons. Each of these gives its own characteristic spectrum and for a given bremsstrahlung spectrum the resulting photoneutron spectrum is made up of an appropriately weighted superposition of the three types of spectra. The weighting factors depend upon the relative importance of the three processes as a function of photon energy, the shape of the neutron production cross section, and the shape of the bremsstrahlung spectrum.

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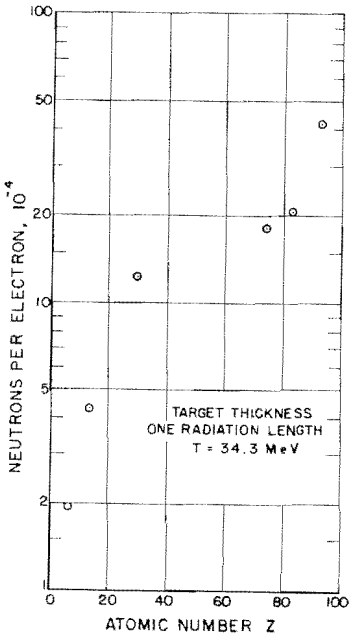

FIGURE 14. *Experimental yields of neutrons per incident 34.3 MeV electron for targets one radiation length thick as a function of atomic number Z.*

The three processes producing neutrons are:

(a) *The direct or "photoionization" process.* In this process essentially all of the photon's energy is given to the neutron. Its energy is given by the difference between the photon's energy and the binding energy of the neutron in the original nucleus. For a continuous photon spectrum the shape of the neutron spectrum is determined by the shape of the product of the photon spectrum and the cross section for the direct process. For the lightest nuclei this is the only process that can take place. Even for nuclei like carbon and oxygen it is probably responsible for a majority of the photoneutrons. For the heavier nuclei this process is responsible for approximately 10 to 20 percent of the neutrons produced by bremsstrahlung spectra with upper energy limits ranging from 15 to 30 MeV [19]. The angular distribution of these fast photoneutrons does tend to peak slightly at 90° to the direc-

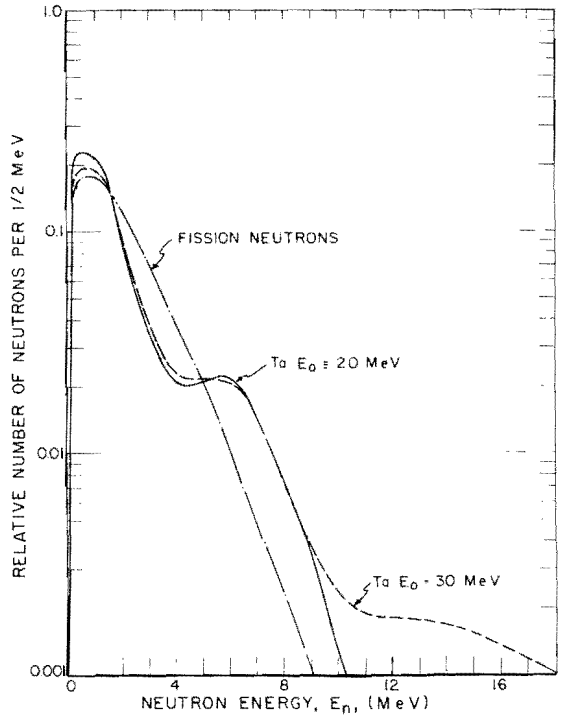

FIGURE 15. *Neutron spectra.*

The photoneutron spectra for Ta with peak bremsstrahlung energies of 20 and 30 MeV are smooth curves drawn through the data points given in ref. [16] The curves are normalized to give the relative number of neutrons per half MeV. The fission neutron spectrum is from ref. [17].

tion of the photon beam. However, the effect is not pronounced enough to be considered for shielding purposes.

(b) *Compound nucleus formation (statistical distribution).* For nuclei with atomic weights greater than about 40 the great majority of the neutrons produced by the absorption of a photon resuit from an evaporation process. The spectral distribution of these neutrons is nearly independent of the photon energy absorbed for photons more than a few MeV above the neutron production threshold. For the heavier nuclei this spectrum peaks near a neutron energy of 1 MeV. The spectrum (number of neutrons per unit energy

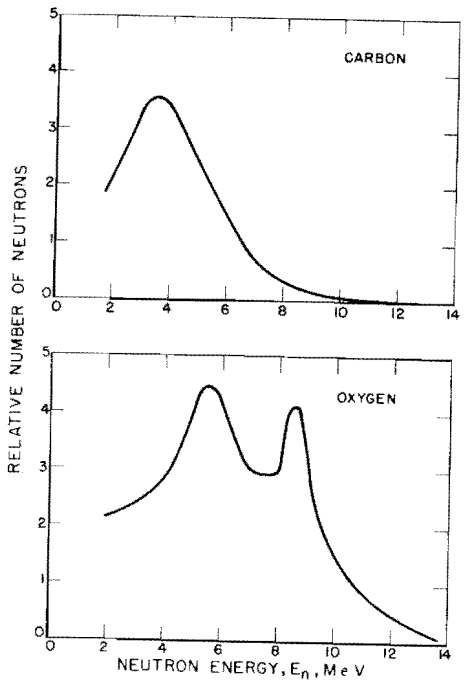

FIGURE 16. *Photoneutron spectra from carbon and oxygen.*

Note the higher mean energy for oxygen resulting from its lower (γ,n) threshold. The maximum brensstrahlung energy was 30 MeV. The figures represent smooth curves drawn through the data points of ref. [18]. Considerably better resolution data for these nuclei have recently been obtained by the Harwell group [53].

interval) can usually be described very well by an expression of the form:

$$\frac{dN}{dE_n}=BE_n e^{-E_n/\theta} \tag{13}$$

where E_n is the neutron energy.

(c) *The quasi-deuteron effect.* For photon energies above 50 MeV the principal absorption process by the nucleus is the quasi-deuteron effect [20]. This results in the emission of neutron-proton pairs each of which carries off approximately half of the photon energy. This process is responsible for the production of very fast neutrons (energies greater than 10 MeV) when a sample is bombarded by high-energy

bremsstrahlung. The neutron spectra resulting from the bombardment of a sample with high-energy bremsstrahlung have not been measured directly. These spectra are, however, expected to follow that of the fast photoprotons. For bremsstrahlung energies of 100 MeV and above [12] these spectra are found to vary as E_p^{-2} (E_p=proton energy) for proton energies from about 15 MeV up to one-half of the bremsstrahlung energy. Above that energy they fall off much more rapidly, perhaps as fast as E_p^{-8}. Very little data area available on the absolute yield of neutrons or protons from this process. At about 260 MeV, Stein et al. [21] have determined the quasi-deuteron cross section for a series of nuclei relative to the cross section for the photodisintegration of the deuteron. These data are plotted in figure 17. Assuming that the quasi-deuteron cross section is given by

$$\sigma_{qd}(E)=k\sigma_d(E) \tag{14}$$

where $\sigma_d(E)$ is the deuteron photodisintegration cross section, an estimate of the relative yield of neutrons from the quasi-deuteron process to that in the giant resonance region can be made. The results of such an estimate, where the cross sections are integrated to 100 MeV, are given for a series of nuclei in table V. Values of k were taken from figure 17 and the quenching of the quasi-deuteron cross section [20] was included by assuming in eq 14 that $\sigma_d(E)$ rose linearly from 0 at 50 MeV to the actual deuteron photodisintegration cross section at 100 MeV.

TABLE V. *Estimated neutron production cross sections*
(Integrated cross sections to 100 MeV)

Nucleus	Giant Resonance*	Quasi-deuteron**	Quasi-deuteron / Giant Resonance
	MeV-mb	*MeV-mb*	
C	0.032	0.004	0.125
O	.060	.005	.083
Al	.144	.008	.056
Cu	.90	.012	.013
Ta	4.50	.019	.004
Bi	5.60	.023	.004

*Based on experimental values. See table IV for reference.
**Estimated cross section integrated to 100 MeV. See text.

For shielding purposes it is sufficient to assume that these neutrons are distributed in a spectrum starting at 20 MeV and given by $\frac{dN}{dE}=B'E_n^{-\alpha}$ where E_n is the neutron energy.

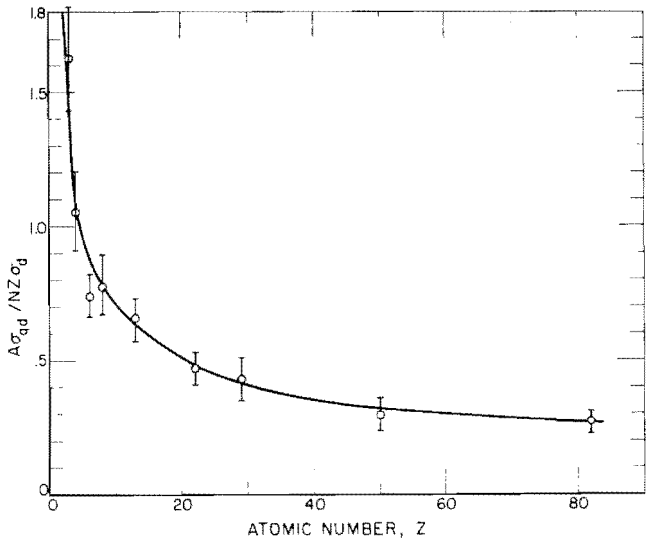

FIGURE 17. *The quasi-deuteron cross section relative to the deuteron photodisintegration cross section.*

Data from Ref. 21.

For neutron energies between 20 MeV and an energy ($T/2$) corresponding to half the upper energy limit of the bremsstrahlung spectrum, $\alpha=2$. For neutrons with energies greater than $T/2$, $\alpha=8$. The constant B' is evaluated by equating the area under this spectrum to the total number of neutrons resulting from the quasi-deuteron process as given by a calculation of the type discussed in the previous paragraph.

D. Residual Radioactivities

1. Production of Radioactivity by Neutron Emission

In a great majority of cases the emission of a neutron from a nucleus results in the production of an isotope that is unstable for positron emission (β^+). It must be remembered that for each positron emitted, two 0.51 MeV photons will be produced in the annihilation process. The radioactivity resulting is frequently a hazard to personnel entering the radiation chamber after an accelerator is turned off. Cases can be envisioned in which normal servicing of the machine would be delayed until the radioactivity could decay to tolerable levels. Not all materials present the same problem and in the following cases radioactivity does not exist or its hazard is greatly reduced.

(1) The product nucleus is stable. This occurs in many even Z and a few odd Z nuclei where stable forms are contiguous in A.

(2) The half-life may be so short or so exceedingly long that there is no problem. For example, aluminum yields two isomeric forms, one of 6.7 secs and the other of 8×10^5 yr.

(3) The radiations may be too weak to produce a hazard. For example, electron capture may result only in weak internal bremsstrahlung and K x rays of the product nucleus.

(4) The parent nuclide may be of low abundance. For example, Ca^{47} has a half life of 4.7 days but the parent nuclide has an abundance of only 0.185 percent.

Yields of radioactivities can be estimated by the same methods as used to estimate neutron yields. Since, however, the various activities of interest are associated only with specific nuclides in the material being bombarded the calculation must be made individually for each nuclide. The properties of the various isotopes can be obtained from one of the various tables of isotopes [22]. In addition since the mean free path for the radiation emitted by the radioactive nuclei is considerably shorter than that for the incident bremsstrahlung radiation not all of the nuclei in a given sample of material are effective as sources of residual radioactivity. For most purposes in calculating yields of radioactivities, it is sufficient to use the number of nuclei per cm^2 of the isotope of interest in a thickness corresponding to one mean free path for the emitted radiation. The quantity usually calculated is the saturated activity for a given isotope. This is the activity of the sample when the nuclei are decaying at the same rate that they are being produced by the accelerator. It is the activity that would be observed in the sample just after the accelerator was turned off if the sample had been bombarded with a constant accelerator output for a time long compared to the half-life of the radioactivity produced.

Radioactivity can also be produced by nuclear fluorescence without neutron emission. This process is not important because the half-lives are generally short and the cross section is small.

In table VI estimates are given for the yield of radioactivities in various materials which are likely to be in the vicinity of an electron accelerator. The yields are given in terms of the saturated activity that would be produced

by one kilowatt of 32 MeV thin target bremsstrahlung. In this table isotopes with half-lives less than one second have been omitted since any such activities will decay to relatively safe values within a short time after the accelerator is turned off. The saturated activities given here are close to the maximum values that can be expected (see neutron yield as a function of bremsstrahlung energy figure 10, section III–C–2).

2. Production of Radioactivities by Neutron Capture

The magnitude of the problem of the radioactivity produced as a result of the absorption of neutrons depends critically on the energy of the neutrons. As is indicated in the following paragraphs, the problem is much more severe if the neutrons are thermalized.

(a) *Thermal neutrons.* The cross sections for capture of thermal neutrons vary widely from nuclide to nuclide, and the resulting products may or may not be radioactive, so each nuclide must be considered separately. The calculation is further complicated by the fact that the thermal-neutron density distribution depends on the capturing materials present in the room.

In the event that most of the neutrons are captured in the concrete walls of the room the calculation is simple. The relevant data are given in reference [8], p. 262. The diffusion length in concrete is about 7 cm. which is comparable with the mean free path of the radiations of the induced activities. Of the materials present in ordinary concrete, sodium is by far the worst offender. If sodium is present to the extent of 1.6 percent by weight, 4.8 percent of the captures will be in sodium and the equilibrium activity of 15-hr Na^{24} will be given by 0.048 times the neutron source strength. (Capture during the slowing-down process is negligible although the fast neutrons will penetrate deeper into the walls.) With a source of 10^{13} neutrons per sec the equilibrium activity will be about 13 Curies. This will be distributed through the walls of the room at an effective depth of about 7 cm.

If there are large amounts of iron or copper present in the thermal flux they will acquire significant activities also. In the case of iron a manganese content of as little as 0.5 percent will be the worst source of trouble. The capture cross section is large (13 barns), and the resulting 2.6-hr Mn^{56} produces γ radiation of up to 3 MeV. Cu^{63} has a cross section of 4 barns and results in 12-hr Cu^{64}, which produces abundant radiation.

TABLE VI. *Radioactivity yields from* (γ, n) *process*

(per kilowatt of 32 MeV bremsstrahlung)

Material and isotopes	Percent abundance by weight	Gamma radiation	Half-life	Threshold	Resonance energy E_0	$\int \sigma(\gamma, n)\, dE$ (over giant resonance)	Effective target thickness	Saturated activity per kilowatt
		MeV		*MeV*	*MeV*	*MeV-barns*	*10^{24} atoms/cm²*	*Curies*
Concrete								
C^{13}	0.10	0.51	20.4 min	18.7	22.5	0.032	0.0056	3.5×10^{-4}
O^{16}	53	.51	2.05 min	15.6	22.5	.060	2.3	2.6
Na^{23}	1.6	.51, 1.3	2.6 yr	12.4	18.5	.081	0.048	0.1
Mg^{24}	0.16	.51	11 sec	16.5	20	.060	.0041	7.3×10^{-3}
Al^{27}	3.4	.51	6.6 sec	13.0	19.5	.045	.087	92×10^{-3}
Si^{28}	31	.51	4.9 sec	17.2	21	.120	.76	2.0
K^{39}	1.2	.51, 2.1	7.5 min	13.1	19.5	.20	.021	0.1
Fe^{54}	0.08	.51	8.9 min	13.3	19	.40	.001	10.3×10^{-3}
Aluminum								
Al^{27}	100	.51	6.6 sec	13.0	19.5	.045	2.6	2.7
Iron								
Fe^{54}	5.8	.51, .37	8.9 min	13.3	19	.40	0.077	0.79
Copper								
Cu^{63}	69	.51	9.8 min	10.8	18	.60	.704	9.5
Cu^{65}	31	.51, 1.35	12.8 hr	9.9	18	1.00	.341	13.3
Lead								
Pb^{204}	1.6	.3, .7	52 hr	8.4	13.5	4.0	.0029	0.46
Air								
N^{14}	0.78	.51	10.1 min	10.5	23	0.015	.04	11.3×10^{-4}
O^{16}	0.21	.51	2.05 min	15.6	22.5	.060	.0095	11.6×10^{-4}

Pure lead or lead containing only bismuth is one common shielding material which acquires very little radioactivity from thermal neutrons.

The radioactivities due to thermal neutrons can be significantly reduced by abundant use of materials which absorb neutrons without becoming active. Among the best elements are boron, hydrogen, and cadmium. The hydrogen can be in water or organic compounds. Page 292 of reference [8] gives properties of several such materials. To be most effective the material thickness should be several diffusion lengths. (The diffusion length is about 3 cm for H_2O or polyethylene.) Approximately 0.02 g/cm^2 of boron on the surface of all the walls will reduce the thermal flux in the room by a large amount (perhaps as much as a factor of 10). However, there will still be some activity produced in the concrete by neutrons which penetrate the wall and then become thermalized. It would be preferable to have about 2 percent by weight of boron in the first 1-ft layer of the concrete wall.

(b) *Fast neutrons.* Fast neutrons will induce radioactivities by $(n,2n)$, (n,p), (n,d), and (n,α) reactions. The cross sections for these are small and except in special cases will not be significant. Aluminum is a material where fast neutrons could possibly be the most important source of trouble. The (n,α) reaction produces the 15-hr Na^{24}. The cross section averaged over the photoneutron spectrum is about 0.6 millibarn. If a fast-neutron flux of 10^{13} n/sec traverses one g/cm^2 of aluminum, the saturation activity will be about 4 millicurie of Na^{24} resulting in a dose rate of about 6 mr/hr at one meter. This is not very serious but it indicates that very thick pieces of aluminum should not be exposed to the fast flux.

IV. Radiation Measurements

A. Units

1. General

In the previous section the yields or source strengths of the various radiations were expressed in terms of the electron beam power or current. A bremsstrahlung efficiency factor was defined that gave the fraction of the electron beam power that was converted into bremsstrahlung power for various types of targets. Similarly, the total neutron yield (expressed as a saturated disintegration rate) produced by either electron or bremsstrahlung bombardment was given in terms of the power in the incident beam. These source

strengths are all readily converted into radiation fluxes which along with the energy spectrum of the radiation are the quantities necessary to carrying out shielding calculations in terms of the basic interaction of the radiation with matter. The results of these calculations are usually in terms of the flux of a given type of radiation at a given point.

For ionizing radiation (electrons, x rays, and γ rays) the permissible levels are not expressed in terms of flux but rather in terms of the absorbed dose, the energy absorbed per unit mass of material. As is indicated in the following discussion, this is a quantity that can be determined with sufficient accuracy for radiation protection purposes with an ionization type survey instrument calibrated to read in roentgens at low photon energies. In the approximation that the energy absorbed in a gram of material is equal to the energy transferred from photons to electrons in that gram (electronic equilibrium conditions), it is possible to give a simple relation between the flux of photons and the dose rate.

If Φ is the flux (number per cm^2-sec) of photons of energy E (MeV), and μ_T (cm^2/gram) is the energy absorption coefficient tabulated by White (see table VII), then the energy transferred to electrons per gram of material is $\Phi E \mu_T$. The dose rate D in rads/sec (1 rad=100 ergs/gram) is

$$D_\phi=\Phi E\mu_T\left(\frac{1.6\times10^{-6}}{100}\right)=\Phi E\mu_T 1.6\times10^{-8}\,\frac{\text{rads}}{\text{sec}}\ \text{(photons)}. \quad (15)$$

since electrons lose on the average 1.85 MeV per gram per cm^2 of material and since 1 mA/cm^2=6.25×10^{15} electrons/cm^2-sec, the dose rate due to an electron current density of i(mA/cm^2) is

$$D_{el}=i\left(\frac{6.25\times10^{15}\times1.85\times1.6\times10^{-6}}{100}\right)=$$

$$i\times1.85\times10^{8}\,\frac{\text{rads}}{\text{sec}}\ \text{(electrons)}. \quad (16)$$

For neutrons the permissible levels are expressed directly in terms of the neutron flux as a function of neutron energy. For completeness the so-called first collision dose resulting from neutron-proton collisions in water resulting from a flux of Φ_n neutrons/cm^2-sec of energy E_n is given by

$$D_n=\Phi_N\frac{E_n}{2}\sigma(E_n)\left(\frac{1\times2\times6.02\times10^{23}}{18}\right)\times1.6\times10^{-8}$$

$$=\Phi_n E_n\sigma(E_n)\times0.53\times10^{-9}\ \text{rads/sec (neutrons in water)}. \quad (17)$$

where $\sigma(E_n)$ is the neutron-proton scattering cross section in barns (see table VII) and the bracketed figures give the number of atoms of hydrogen per gram of water. Since for neutron energies above about 10 MeV, $\sigma(E_n)$ is proportional to $1/E_n$, the relationship between the dose rate and the neutron flux becomes independent of the neutron energy.

TABLE VII. *Interaction cross sections*

Energy	Photon (air)		Neutron-proton $\sigma(E_n)$ (barns)
	μ(cm²/gram)	μ_T(cm²/gram)	
(*MeV*)			
0.01	4.55	4.20	19
.02	0.712	0.479	18
.05	.203	.0376	15.5
.10	.155	.0232	12.5
.20	.123	.0269	9.5
.40	.0953	.0295	6.9
.60	.0804	.0296	5.6
.80	.0706	.0288	4.8
1.00	.0635	.0279	4.2
2.00	.0443	.0237	2.9
4.00	.0307	.0193	1.9
6.00	.0252	.0174	1.4
8.00	.0222	.0162	1.13
10.00	.0204	.0155	0.94
15.00	.0180	.0147	.64
20.00	.0169	.0145	.48
40.00	.0160	.0148	.22
60.00	.0162	.0154	.14
80.00	.0166	.0160	.096
100.00	.0169	.0164	.078

In the following sections the recommended units for describing radiation levels around electron accelerators will be discussed.

2. Primary Electron Beam

For any operating condition of the accelerator the following properties of the electron beam should be known:

(a) *Current.* The total output current in amperes or submultiples thereof.

(b) *Power.* The total average power in watts in the electron beams.

(c) *Energy spectrum.* The number of electrons per unit electron energy interval. (Number per MeV).

3. Ionizing Secondary Radiation (Electrons, x rays, and γ rays)

Relative to the primary beam, the amount of radiation elsewhere is relatively small though often large on an absolute scale. It is of importance primarily from the standpoint of protection of persons. For this reason it should be expressed in terms of the absorbed dose in water. (For protection purposes, the differences in absorbed dose between water, air, plastic compounds such as polystyrene, and various tissues may be neglected.)

(a) *Absorbed dose.* The ionization produced in air by scattered electrons can be measured in esu per cm³. In the measurement of the quantity of x rays, one esu per cm³ (NTP) as collected by most commercial ionization chamber instruments is approximately equal to one roentgen. As is seen from fig. 18, over a wide energy range of electron and x-ray energies, one esu per cm³ of air ionization in a cavity in water is approximately equivalent to an absorbed dose of one rad in water (or other material similar to tissue) [25]. It is, therefore, recommended that secondary radiation be assayed in terms of the absorbed dose it will produce in water, and that this be expressed in rads, or fractions thereof, such as millirads and microrads.

For protection purposes an ionization density in air (NTP) of one esu per cm³ in a chamber whose walls are approximately air or tissue equivalent, may be considered equivalent to one rad in tissue.

4. Neutrons

It is adequate for protection purposes to measure either the flux of neutrons incident on the point in question, or the absorbed dose in tissue like material.

The maximum permissible neutron fluxes are tabulated in Handbook 63, Handbook on Neutron Protection up to 30 MeV, for various energies of neutrons from thermal energies up to 30 MeV. Calculated [23] plots of the depth-dose distribution produced in tissue by one incident neutron per cm² of a specified energy, are reproduced in Handbook 63. These curves permit convenient conversion between absorbed dose in rads and the number of neutrons per cm².

(a) *Flux.* The flux of neutrons at a given point should be measured and expressed as the number of neutrons per cm²-sec.

(b) *Absorbed dose.* The absorbed dose can be measured directly in tissue equivalent material [24] and is expressed in rads. Knowledge of the energy spectrum permits the conversion into rems. The values of the quality factor

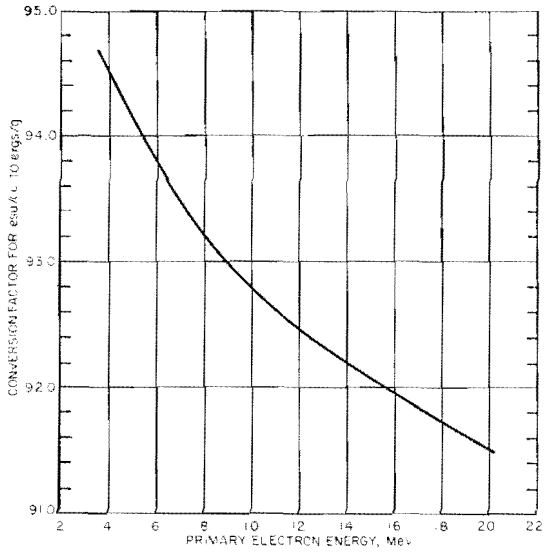

FIGURE 18. *Average energy absorbed per gram of water for each electrostatic unit of air ionization per cubic centimeter in a cavity in water, as a function of the energy of the primary electron.*

Data from Ref. 25.

employed to convert from rads to rems shall be taken from Handbook 63.

(c) *Energy spectrum.* It is important to know at least approximately the energy spectrum of the neutrons in order to evaluate their biological hazard.

B. Survey and Monitoring

1. General

The choice of instruments for measuring the radiation associated with an electron accelerator will depend critically on the type and purpose of the measurement as well as on the radiation level at the point the measurement is made. In all cases of measurements in the vicinity of pulsed accelerators extreme caution should be taken to avoid effects of saturation in the instruments being used. This is particularly true when instruments are calibrated with continuously operating sources and then used in the vicinity of pulsed sources. Not only the calibration but also the

ability of a given instrument to discriminate against one type of radiation in a mixed field can be quite difficult when the radiation is pulsed compared to results obtained with a continuous source. Saturation effects should also be carefully looked for whenever an instrument is calibrated at low flux levels and then used in a high flux field.

Only a brief description of various survey and monitoring methods is given here. Further details will be found in the forthcoming revision of Handbook 51, Instrumentation and Monitoring Methods for Radiation Protection.

2. Primary Electron Beam

(a) *Primary standard.*

(1) *Current.* It is recommended that the Faraday Cup be the absolute instrument for the measure of current in the direct beam where the area covered by the beam is well defined.

The design of the Faraday Cup will depend upon the actual situation and will be affected by such factors as energy of electrons in the beam and area covered by the beam. These factors will, in turn, determine the material of the cup, lateral dimensions, depth, and whether bremsstrahlung absorbing material is necessary.

The depth of the cup must be sufficient to prevent the loss of back scattered electrons. Depth (d) and inside diameter (i.d.) for some Faraday Cups described in the literature are: 5 MeV to 20 MeV [25], d=20 cm, i.d.=5 cm; 40 MeV, d=23 cm, i.d.=10 cm; and 300 MeV [26], d=43 cm, i.d.=13 cm. The incorporation of a permanent ring magnet is desirable to assist in preventing electron loss. A guard electrode can be mounted at the mouth of the cup to study the existence of any electron loss as a function of the polarity and magnitude of the potential of the electrode with respect to the cup.

The bottom of the cup is the primary absorber and should be thicker than the maximum range of the electrons. With increasing electron energy a higher fraction of the electrons will radiate bremsstrahlung as they are stopped in the primary absorber. The absorption of the bremsstrahlung in the cup results in energetic secondary electrons whose escape can detract from the true beam current. This spurious current can be eliminated by minimizing the amount of bremsstrahlung produced by the use of a low atomic number material such as carbon for the primary absorber and by surrounding the primary absorber with an efficient bremsstrahlung absorber to which can be added another layer of

carbon, or similar material, to absorb the secondary electrons. Rosenfeld [27] has analyzed the factors important in Faraday Cup design. In his table VI various thicknesses of either carbon or aluminum for the primary and tertiary absorbers and different thicknesses of a lead secondary (bremsstrahlung) absorbers are presented in different combinations with calculated loss of electrons. For instance, for 70 MeV electrons an efficiency of 99.6 percent is predicted for a primary carbon absorber 17 cm, a secondary lead absorber 10 cm, with a tertiary carbon absorber 10 cm deep.

The walls of the cup need only be sufficiently thick to absorb the less energetic scattered electrons, assuming the primary electrons are well collimated.

(2) *Absorbed dose.* The ionization in cavity ionization chambers can be interpreted to yield the absorbed dose in the chamber walls. Figure 18 exhibits the calculated relationship [25] between the absorbed dose in water which corresponds to 1 esu/cc (NTP) in an air cavity in the medium as a function of incident electron energy. Tissue equivalent ionization chambers [24] with gas of the same composition as the medium have also been developed.

Direct measurement of energy absorbed in tissue equivalent materials can be made by calorimetry [28]. The Fricke ferrous-sulfate chemical dosimeter appears to be quite dependable [29]. It is useful for electron as well for as high-intensity x-ray beams.

(b) *Secondary standards.*

(1) *Transmission ionization chamber.* The output of a medical electron accelerator can be monitored adequately with a thin-walled transmission chamber when the rate of ion production in the irradiated volume of the chamber is less than several hundred esu of charge per cm^3 per minute. Aluminum foil, Mylar coated with aquadag and aluminized Mylar have been used successfully for the plates of such chambers. The plates must be thin and of low atomic number material in order to minimize attenuation and bremsstrahlung production. The chamber is calibrated against a primary standard in terms of current, or absorbed dose.

(2) *Thimble ionization chamber.* For dose rates less than a few hundred rads per minute, thimble chambers can be calibrated to monitor the output. The chamber must be calibrated against a primary standard.

(3) *Calorimeter foil monitor.* The technique of monitoring electron beam intensity by means of the energy dissapated in a transmission foil [30] has been developed and successfully applied to a 50-MeV linear accelerator. This method

has the advantage over ionization collection in that it responds linearly even at high intensities. This method may be developed to become a primary standard.

(4) *Chemical reactions.* A variety of chemical reactions are suitable as secondary dose standards. In the low dose range (less than 100 rads) the fluorescence of irradiated silver phosphate-activated glass [31] is proportional to radiation dose. In the dose between 3,000 rads and 30,000 rads, the Fricke ferrous-sulfate reaction [29] is suitable. As a function of radiation dose, the ferrous ion is oxidized to ferric with a resulting increase in optical density in the ultraviolet. For higher doses, the optical density change in lucite and other transparent organic polymers has been found to be proportional to dose.

3. Secondary Radiation (Electrons, x rays, and γ rays)

(a) *Survey Geiger counters.* Although Geiger counters are useful for preliminary surveys to determine the presence of radiation, ionization chamber instruments are recommended for quantitative measurement. Counters must be used with care around pulsed machines because, under normal conditions, their maximum indication is limited by the pulse repetition rate of the machine.

(b) *Survey ionization chambers.* There are several commercially available sensitive survey instruments which incorporate ionization chambers with walls sufficiently thin to be sensitive to low-energy elctrons. The instrument should be of the type which has the ionization chamber mounted externally where it is accessible. Cups which fit over the chamber and have walls of different thicknesses should be employed to insure that the maximum reading is obtained. The cups should be of some low atomic number material such as polyethylene, polystyrene, lucite, etc. There is no need to distinguish between x rays and electrons since their biological effect is similar. The thinnest wall available will ordinarily be adequate to obtain the maximum electron induced ionization, but the minimum wall thickness required to obtain the maximum ionization produced by high-energy x rays depends upon their energy. As described above, the ionization measurements in esu/cm^3 can be expressed in rads.

4. Neutrons

For high-energy electrons the cross section for neutron production is very much less than for bremsstrahlung. For protection purposes, however, it is still necessary to give

attention to the neutrons because of their high quality factor and the consequent low permissible dose set for them.

Neutrons can be detected with the aid of any of their various interactions, but the production of hydrogen recoils is the most pertinent since this interaction is their most important biologically in hydrogenous man. The recoils can be detected by the collection of the ionization they produce in gas, collection of the light they initiate in scintillation crystals, photography of droplet tracks they produce in cloud chambers, or by observation of the grains that develop along their path in photographic emulsions. Most detectors must be calibrated with sources of known intensity and spectrum.

Since the neutrons produced by an electron accelerator are always accompanied by a considerable flux of photon radiation, the measurement of the neutron flux or dose rate in the vicinity of an accelerator must be made with some care. Most detectors of neutrons will also detect photons and while it is possible to design a detector which discriminates against photons very well when used in a continuous source of radiation, most of this ability to discriminate is lost when the detector is used in the vicinity of an accelerator with a low duty cycle. This is because of the high instantaneous fluxes of photons that exist during the short yield pulses from such an accelerator. Since the principal hazard from neutrons in the vicinity of an electron accelerator results from the high-energy neutrons (energies greater than 5 MeV), and since the maximum permissible flux for these neutrons has been set so low, the personnel responsible for the radiation surveys around high-intensity, high-energy electron accelerators should be thoroughly trained in the techniques and physical principles of measurement of radiation produced by pulsed accelerators.

(a) *Ionization chambers.*

(1) Twin ionization chambers, one with nonhydrogenous walls (carbon) and the other with hydrogenous walls may be employed to detect x rays, and x rays plus neutrons, respectively. This is a difference method which requires major corrections and is not capable of great accruacy.

(2) As mentioned above, tissue equivalent ionization chambers have been developed [24], but in the presence of an x-ray field the subtraction of ionization produced in a graphite chamber is necessary and is a source of inaccuracy.

(b) *Proportional counter.* A proportional counter [32] has been developed with walls of polyethylene which employs ethylene as the gas. Pulses are linearly amplified and are

added so that the resultant reading is proportional to the energy absorbed in the gas, which is proportional to the energy absorbed in the wall. X rays and electrons are discriminated against. This is the optimum instrument for determination of neutron dose in the presence of x rays, or electrons. See, however, the above remarks concerning pulsed accelerators.

(c) *Scintillation crystal.* Plastic materials with a relatively high hydrogen content have been loaded with phosphors such as zinc sulfide. The associated photomultiplier responds to the light initiated by proton recoils. The crystal is relatively insensitive to x rays, and this discrimination can be increased by pulse height discrimination in the associated circuitry. These instruments are commercially available and are the most convenient for survey use. Again, see the above remarks concerning pulsed accelerators.

(d) *The (n,2n) reaction.* An interesting possibility for determining the flux of very high energy neutrons ($E_n > 20$ MeV) is the use of the reaction C^{12} $(n,2n)C^{11}$. Above a neutron energy of about 60 MeV the cross section for this reaction is relatively independent of neutron energy. An efficient way in which to detect the C^{11} activity is to have the carbon in an organic scintillator placed in the neutron flux. Baranov, Goldanskii, and Roganov [33] have pointed out that with 50 cm^3 of a terphenyl in xylene solution it is possible to measure a neutron flux of 20 neutrons/cm^2-sec with an uncertainty of about 6 percent if the scintillator is exposed to neutrons for 30 min and then counted for 40 min.

(e) *Threshold detectors.* These involve the use of various neutron induced reactions to obtain a measure of the total neutron flux above a cutoff determined by the threshold of the reaction used. By using reactions with different thresholds as well as with different dependences on neutron energy various parts of the neutron spectrum can be sampled. A typical reaction is $Si^{28}(n,p)Al^{28}$ which has a threshold at 3.9 MeV. The cross section rises to a broad peak for a neutron energy of about 8 MeV and then falls off slowly up to 18 MeV, the highest energy for which measurements exist [54]. The half-life of Al^{28} is 2.3 min.

V. Interaction of Radiation with Matter (Radiation Shielding)

A. General

The basic cross sections which describe the interactions of electrons, photons and neutrons with matter are with a

few exceptions well-known. While these cross sections govern the penetration of radiation through matter, they usually cannot be used directly to give the absorption of the radiation in a given thickness of material. Rather, what must be done is to make appropriate averages over the basic cross sections to take into account the effects of the geometry of the particular shielding problem. These averages usually result in the definition of either an effective cross section or of a buildup factor which when used with the basic absorption cross section describes the attenuation of the radiation for a given shield and geometry. These effective cross sections and buildup factors are often very difficult to calculate so it is often necessary to use empirical data to determine them.

It is not the purpose of this report to describe in detail the basic interactions of radiation with matter. These are discussed to some extent in the various Handbooks covering the particular radiations and in a more complete manner in the available text books on radiation shielding (e.g., see Price, Horton, and Spinney, *Radiation Shielding*, Pergamon Press, New York, 1957). It is the purpose of this section to give the procedures and data necessary for estimating the shielding required for an electron accelerator operating at energies up to 100 MeV and to point out where basic information appears to be missing or uncertain.

A problem common to all types of radiation is that of "skyshine," i.e., the radiation that scatters over the top of a shielding wall. It is found to be a problem with high-intensity accelerators when the shielding does not cover the roof of the accelerator or experimental area. An empirical rule seems to be that for an accelerator operating with no roof the radiation from skyshine will be of the order of 1/50 of the direct radiation. For air scattering and on simple geometrical considerations the ratio of the intensity of the radiation from air scattering above the source I_S to that coming directly from the source I_D at a distance r from the source is given by [43]:

$$\frac{I_S}{I_D} \approx \frac{r}{\lambda} \frac{A_S}{A_D} \tag{18}$$

where λ is the mean free path for scattering of the particular radiation in air, A_S is the attenuation in the scattered beam, and A_D that in the direct beam. The attenuation A_S should include the fractional solid angle subtended by the roof which normally will be of the order of 0.1 or less. A rather complete discussion of this problem has been given by Lindenbaum [51].

B. Electrons

1. General

The penetration of fast electrons is strongly influenced by three factors.

(a) Energy loss through ionization and excitation.
(b) Energy loss in the production of bremsstrahlung.
(c) Scattering.

Other forms of energy loss occur such as direct nuclear excitation, but the cross sections for these are so low that their effect on the depth of penetration is negligible.

2. Ionization and Excitation

A fast charged particle produces ionization and excitation of the atoms along its path. The energy loss per cm path of the particle is directly proportional to the number of electrons per cm^3 of the material. It is a well-known fact that the latter number, when divided by the density, is nearly the same for all materials except hydrogen; therefore, with this exception, the energy loss per cm divided by the density (energy loss per gm per cm^2) is nearly constant. Theoretically other characteristics of the material enter only in logarithmic terms.

The average ionization loss of electrons in various materials is plotted as a function of energy in figure 19 [34]. It may

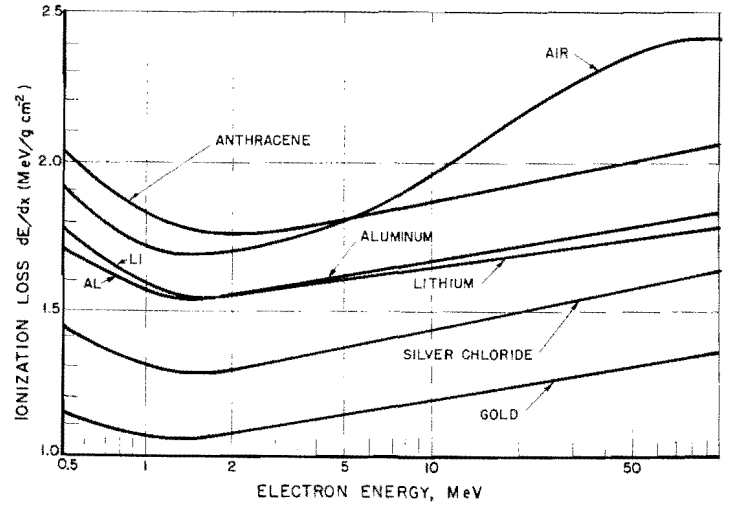

FIGURE 19. *Average ionization loss of electrons in various materials as a function of electron energy.*

Data from Ref. 34.

be seen that the various materials differ by a factor of less than two. The rate of energy loss decreases with increasing energy of the particle to about 1.5 MeV and then increases slowly in the relativistic region. The rate of increase is less for condensed materials than for air because of the "density effect."

3. Bremsstrahlung

A fast electron passing through matter will lose energy in discrete amounts by the bremsstrahlung process. The energy lost can be any amount up to the electron's total kinetic energy. The probability for this process increases with electron energy. For high energies in heavy materials it is the dominant process by which electrons lose energy. Figure 20 gives the fractional energy loss per unit radiation length by ionization and radiation for different materials as a function of the electron's total energy. It is apparent that bremsstrahlung production can be minimized by stopping electrons in as low atomic number materials as possible.

4. Scattering

Electrons do not follow a straight path in a medium, but are deflected or scattered in their encounters with nuclei and other electrons. The probability for an electron to scatter in a given thickness of material increases rapidly with decreasing electron energy. For electrons with energies under 5 MeV

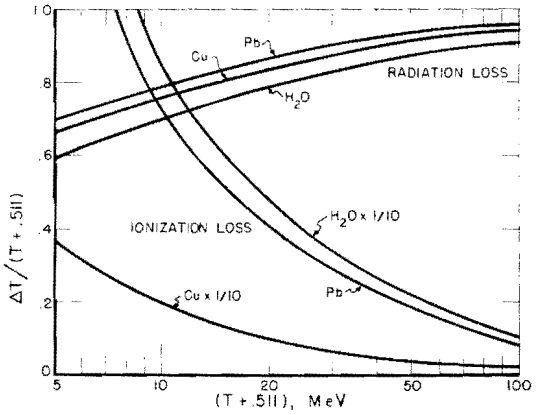

FIGURE 20. *Fractional energy loss per radiation length by ionization and by radiation as a function of the energy of the electron.*

there is an appreciable probability that an electron entering a thick slab of material will undergo a large number of scatterings and leave the slab without an appreciable loss of energy. This backscattering is of considerable importance in designing ducts and mazes that enter an irradiation area. Figure 21 gives the fraction of the electrons backscattered as a function of the electron energy and the atomic number of the scattering material [35]. Figure 22 gives the energy distribution of the electrons backscattered through an angle of 150° by various materials [35]. Note that the backscattered electrons have an appreciable fraction of the energy of the incident electrons.

5. Range of Electrons

In shielding problems, the effective range of electrons is important rather than the true range which is measured along the tortuous path of scattered electrons. The true range is given by the integral over the energy loss curve, and figure 19 indicates it may be of the order of 50 percent greater for high Z than for low Z materials. On the other hand, the scattering is larger for high Z materials which makes the effective range a smaller fraction of the true range. This effect is shown by calculations of Spencer [36] for 0.5 MeV monodirectional electrons in Be, Al, and Au.

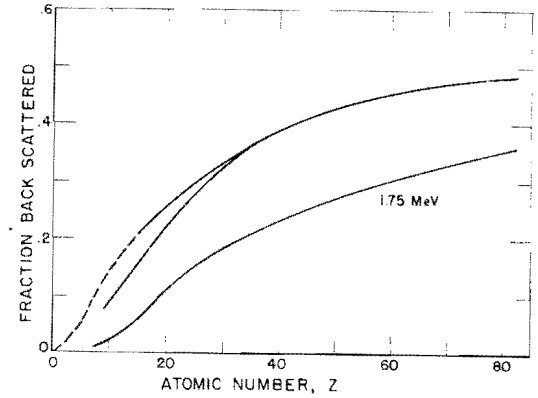

FIGURE 21. *Fraction of incident back-scattered as a function of the atomic number Z.*

Electrons are incident normal to the back-scattering material. Upper curve from measurements made with electrons between 10 and 700 keV. For energies above about 1 MeV the fraction back-scattered should depend only on (Z/T). Data are from Ref. [35].

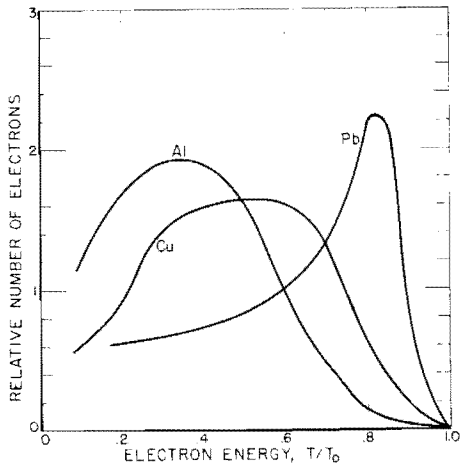

FIGURE 22. *Energy distributions of electrons back-scattered at an angle of 150°.*

Incident electron energy, T_0, was 1.75 MeV. Data from ref. [35].

The effective ranges are 95, 85, and 45 percent, respectively, of the true range. The overall result is that the effective range expressed in grams per cm² is nearly independent of the material. A convenient expression (accurate to ±10 percent) for the effective range of electrons having energies above about 1 MeV is [37]

$$R=0.530\,T-0.106, \tag{19}$$

where R is gm/cm² and T is in MeV.

6. Shielding for Electrons

Since electrons have a definite maximum range in all materials, their shielding is not particularly difficult. The range given by the above equation is probably sufficiently accurate for shielding purposes. This expression will tend to give an overestimate of the amount of material necessary to stop high energy electrons which can lose a significant fraction of their energy by radiation. In order to cut down on the amount of bremsstrahlung produced, it is advisable to stop the electrons in as low atomic number materials as possible.

C. Photons (Monoenergetic and Bremsstrahlung)

1. General

The sources of photons produced by an electron accelerator are of two spectral types: (a) the bremsstrahlung produced when the electrons hit a target or a part of the accelerator system, and (b) the essentially monoenergetic sources resulting from the residual radioactivity in various parts of the accelerator and shielding. The bremsstrahlung is highly directional in its emission pattern while the residual radioactivity is emitted uniformly in all directions. For shielding purposes both of these sources can usually be considered point sources. (Where the residual activity is extended over a considerable region, it may be necessary to consider it as a number of individual point sources distributed over the region.) The flux density of radiation at a given point is then given by:

$$\phi(R)=\phi_1/R^2 \tag{20}$$

where ϕ is the flux at one meter from the source and R is the distance from the source in meters. For bremsstrahlung ϕ_1 depends on the direction of observation with respect to that of the generating electron's direction. It can be obtained from the data given in Section III–B. For residual radioactivity $\phi_1=S\times 0.8\times 10^{-5}$ where S is the source strength in photons emitted per second.

2. The Absorption of Photons (Good Geometry)

For an extremely narrow beam of photons and for a detector that is well shielded so that it will detect only photons arriving along the beam direction the attentuation in an absorber of thickness t measured in g/cm² along the beam direction is exponential, i.e.,

$$\phi(x)=\phi(0)e^{-\mu t} \tag{21}$$

where $\phi(0)$ is the flux that would be measured without the absorber and μ is the mass absorption coefficient. In terms of the density ρ and the linear thickness x of the absorber, $t=\rho x$. For a heterogeneous absorber the simple exponential is replaced by:

$$e^{-\Sigma\mu_i t_i}. \tag{22}$$

Values of the mass absorption coefficient and the density for various typical shielding materials are given in Tables VIII and IX.

TABLE VIII. *Mass absorption coefficients* (cm^2/gm)*

Photon energy	Material			
	H_2O	Al	Fe	Pb
(*MeV*)				
0.5	0.0967	0.0844	0.0840	0.152
.6	.0894	.0779	.0769	.119
.8	.0786	.0683	.0668	.0866
1.0	.0708	.0614	.0598	.0703
1.5	.0576	.0500	.0484	.0523
2.0	.0493	.0431	.0422	.0456
3.0	.0396	.0353	.0359	.0413
4.0	.0339	.0310	.0330	.0416
5.0	.0302	.0284	.0314	.0430
6.0	.0277	.0266	.0305	.0445
8.0	.0242	.0243	.0298	.0471
10.0	.0221	.0232	.0300	.0503
15.0	.0194	.0219	.0308	.0567
20.0	.0180	.0217	.0321	.0625
30.0	.0170	.0221	.0346	.0709
40.0	.0167	.0228	.0366	.0773
50.0	.0167	.0230	.0384	.0817
60.0	.0168	.0237	.0399	.0855
80.0	.0170	.0246	.0419	.0907
180.0	.0173	.0254	.0436	.0945

*Values from G. R. White as quoted by C. M. Davisson in Appendix 1, Beta and Gamma-Ray Spectroscopy, edited by K. Siegbahn, Interscience Publishers (1955), Amsterdam.

TABLE IX. *Densities of commercial building materials*

Material	Density range	Density of average sample
	g/cm^3	g/cm^3
Brick	1.6 to 2.5	1.9
Granite	2.60 to 2.70	2.63
Limestone	1.87 to 2.69	2.30
Marble	2.47 to 2.86	2.70
Plaster		1.54
Sandstone	1.90 to 2.69	2.20
Siliceous concrete	2.25 to 2.40	2.35
Tile	1.6 to 2.5	1.9
Aluminum	2.5 to 3.0	2.7
Steel	7.6 to 7.9	7.8
Lead		11.4

3. Attenuation of Broad Beams

For most shielding calculations the use of the narrow-beam good-geometry absorption coefficients and the simple exponential attenuation of section 2 will result in an overestimate of the effectiveness of a given shield. This is because of the scattering of the primary beam in the thick absorber and the buildup of secondary radiation which can penetrate the shield. This effect can be taken into account by the use of a buildup factor $B(E, \mu t)$ [38]. If D_0 is the dose that would be observed at a distance of one meter from a source with no shielding present, the dose at a distance L meters from the source would be:

$$D(L)=\frac{D_0}{L^2}B(E,\mu t)e^{-\mu t}. \tag{23}$$

Calculated dose buildup factors for a point isotopic source of monoenergetic photons in an infinite medium are given in table X for several materials. The product μt (where t is the distance in the absorber from the point source expressed in g/cm^2) represents the penetration in units of "mean free paths." The unit of mean free path is $1/\mu$, where μ is the appropriate value of the mass absorption coefficient for the material and energy under consideration.

The dose buildup factors of table X should be used with care at the higher photon energies and for the heavier materials since the calculation took into account the scattering of photons only. No attempt was made to include the generation of secondary photons by radiative processes. Note also that the geometry used for this calculation is not that usually encountered in a shielding problem (i.e., t/ρ does not usually equal L in eq 23) and that the buildup factors of table X may therefore be somewhat over-estimates of the actual effect.

4. Attenuation of Bremsstrahlung

In principle the attenuation by a given shield of the dose produced by a bremsstrahlung spectrum can be calculated by treating each energy band in the spectrum individually, using the appropriate absorption coefficients, buildup factors, and flux-to-dose conversion factors. This calculation would be extremely laborious and at best would require a considerable extrapolation and interpolation of existing data. Where possible it is far better to use empirical data and to use the well-known narrow beam absorption coefficients for extrapolation purposes only.

The attenuation of bremsstrahlung (thin target spectrum) in ordinary concrete has been measured [39]. Figure 23 gives the attenuation of the dose as a function of concrete thickness for various bremsstrahlung energies. Note that above 20 MeV, the attenuation per unit thickness of concrete is independent of the upper energy limit to the bremsstrahlung spectrum. This is a result of the minimum in the basic absorption coefficient which occurs in this energy

TABLE X. *Dose buildup factors for point isotropic sources* [38]

E_o	μt					
	2	4	7	10	15	20
Water						
MeV						
0.5	5.14	14.3	38.8	77.6	178	----
1	3.50	7.21	14.6	24.0	44.7	----
2	2.77	4.88	8.46	12.4	19.5	----
3	2.42	3.91	6.23	8.63	12.8	----
4	2.17	3.34	5.12	6.94	9.97	----
6	1.91	2.80	4.08	5.33	7.34	----
8	1.77	2.49	3.51	4.50	6.05	----
10	1.63	2.22	3.04	3.82	5.07	----
Aluminum						
0.5	4.24	9.47	21.5	38.9	80.8	141
1	3.31	6.57	13.1	21.2	37.9	58.5
2	2.61	4.62	8.05	11.9	18.7	26.3
3	2.32	3.78	6.15	8.65	13.0	17.7
4	2.08	3.22	5.01	6.88	10.1	13.4
6	1.85	2.70	4.06	5.49	7.96	10.4
8	1.68	2.37	3.45	4.58	6.56	8.52
10	1.55	2.12	3.01	3.96	5.63	7.32
Iron						
0.5	3.09	5.98	11.73	19.23	35.42	55.6
1	2.88	5.39	10.21	16.18	28.31	42.7
2	2.38	4.08	6.99	10.47	16.83	24.0
3	2.12	3.44	5.74	8.35	13.25	18.8
4	1.94	3.03	4.91	7.11	11.23	16.0
6	1.72	2.58	4.14	6.02	9.89	14.7
8	1.56	2.23	3.49	5.07	8.50	13.0
10	1.42	1.95	2.98	4.35	7.64	12.4
Lead						
0.5	1.42	1.69	2.00	2.27	2.65	----
1	1.69	2.26	3.02	3.74	4.81	----
2	1.76	2.51	3.66	4.84	6.86	----
3	1.68	2.43	3.75	5.30	8.44	----
4	1.56	2.25	3.61	5.44	9.80	----
5.11	1.46	2.08	3.44	5.55	11.74	----
6	1.40	1.97	3.34	5.69	13.80	----
8	1.30	1.74	2.89	5.07	14.05	----
10	1.23	1.58	2.52	4.34	12.54	----

region for the medium weight elements of which concrete is composed. Figure 24 shows that the relative dose distribution across a bremsstrahlung beam is little affected when as much as 78 in. of concrete is placed in the beam.

D. Neutrons

1. General

It was pointed out in section III–C that the photoneutron spectrum can be considered to be made up of two parts. The great majority of the neutrons are in a statistical

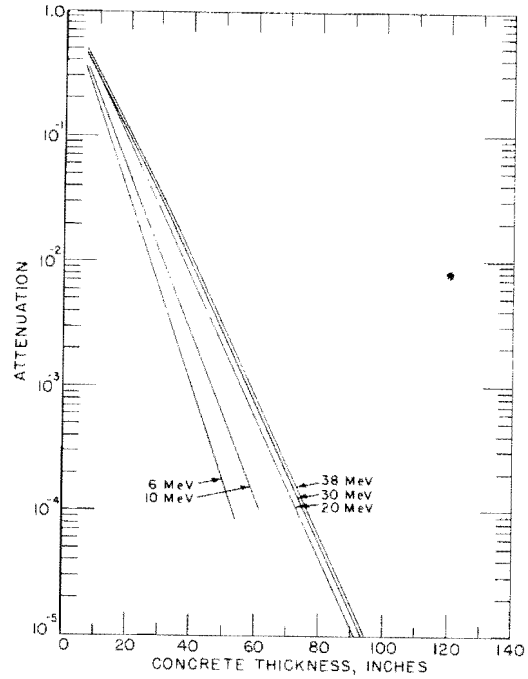

FIGURE 23. *Attenuation by concrete of the dose produced by bremsstrahlung.*

Data from ref. [39].

distribution which for shielding purposes can be considered to attenuate like the fission neutron spectrum. These neutrons are essentially emitted isotropically. There is also, however, a high energy component to the spectrum resulting both from direct interactions as well as from the quasi-deuteron effect which must be considered separately. While accounting for approximately only 10 percent of the total neutrons emitted, the higher energy components of this spectrum can dominate the shielding requirements for accelerators operating with energies above 40 MeV. For the energies involved in this report (electrons up to 100 MeV), and for shielding calculations these neutrons should also be considered to be emitted isotropically. This may somewhat underestimate the shielding requirements at right angles to the beam and overestimate them along the beam direction.

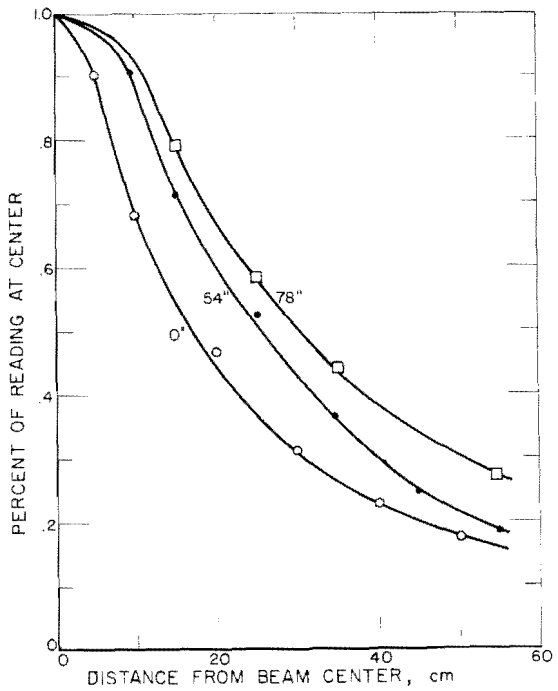

FIGURE 24. *Relative distribution behind concrete of dose produced by bremsstrahlung.*

Source is a betatron operating at 38 MeV. Target to detector distance was 611 cm. Data from ref. [39].

The sources of neutrons in the vicinity of an electron accelerator are all intimately connected with the bremsstrahlung sources since the major source of neutrons is the nuclear photoeffect. For most shielding purposes the dimensions of these sources are small compared to the distances involved in the shielding and the sources can usually be considered as point sources. Since the great majority of the photoneutrons are emitted essentially with an isotropic angular distribution the neutron flux at a distance of R meters from a source point is given by

$$\phi_N = S_n \frac{10^{-4}}{4\pi R^2} = \frac{0.8\times 10^{-5}}{R^2} \times S_n \text{ (neutrons/cm}^2\text{—sec)} \quad (24)$$

where S_n is the neutron source strength in neutrons per sec. In calculating the attenuation of these neutrons by a shielding

wall of thickness t, the actual normal thickness t should be used rather than the line of sight distance through the wall from the point at which the flux is to be calculated to the source point. This procedure will tend to compensate for the scattering of neutrons through rooms and passageways.

In calculating shielding requirements all points at which the electrons can hit material, as well as the center of all regions where the resulting bremsstrahlung is absorbed, should be considered as source points for neutrons.

2. Neutron Interactions with Nuclei

Neutron interactions with nuclei are so complex that anything but the briefest review is beyond the scope of this handbook. It is worthwhile, though, to consider some of the interactions most important for shielding.

(a) *Neutron cross sections.* The magnitude of nuclear interactions are measured in terms of a cross section. The probability of an interaction when a neutron passes through a thin slab of material containing N nuclei per unit area is $N\sigma(E_n)$ where $\sigma(E_n)$ is the cross section. The attenuation coefficient (in cm^{-1}), sometimes called the macroscopic cross section, is given by the relation

$$\tau = 0.602 \frac{\rho\sigma(E_n)}{A} \, cm^{-1} \quad (25)$$

where $\sigma(E_n)$ is measured in barns (10^{-24} cm^2), ρ is the density (gm/cm^3), and A is the atomic weight of the absorbing material. For a mixture of materials of different cross sections, density, and atomic weight,

$$\tau = 0.602 \sum_i \frac{\sigma_i(E_n)\rho_i}{A_i} \, cm^{-1}. \quad (26)$$

Values of τ for several materials are given in table XI as a function of neutron energy. The composition of these materials are given in table XII. The attenuation of a monoenergetic beam of neutrons by a slab of thickness x when measured in good geometry is given by $e^{-\tau x}$.

(b) *Types of nuclear interactions.*

(1) Elastic scattering can occur at all neutron energies. Except in the lightest elements, there is no appreciable energy loss (moderating effect). The neutron direction is usually changed substantially at each interaction. The

TABLE XI. *Total neutron attenuation coefficients*

Material	Ordinary concrete	Barytes concrete	H_2O	Earth	Al	Fe	Ta	Pb
Density (g/cm^3)	2.3	3.1	1.0	1.0*	2.7	7.8	16.6	11.4
$E_n(MeV)$	$\tau(cm^{-1})$							
1	0.38	0.37	0.49	.25	0.21	0.21	0.42	0.21
2	.161	.18	.25	.116	.18	.24	.41	.19
3	.166	.18	.22	.110	.16	.27	.39	.25
4	.157	.18	.19	.101	.14	.31	.34	.25
5	.159	.18	.17	.096	.14	.31	.31	.24
6	.135	.152	.14	.079	.13	.31	.30	.22
7	.144	.166	.15	.087	.11	.31	.29	.19
8	.10	.133	.12	.066	.11	.29	.27	.17
9	.104	.130	.11	.062	.11	.28	.26	.16
10	.105	.128	.087	.057	.11	.26	.27	.16
20**	.134	.134	.087	.061	.11	.20	.29	.19
30	.113	.127	.07	.055	------	.20	.25	.17
40	.0976	.113	.06	.047	------	.20	.23	.15
50	.0875	.103	.05	.042	------	.20	.22	.14
60	.0777	.092	.043	.036	------	.19	.22	.15
70	.0663	.086	.037	.033	------	.18	.23	.15
80	.0654	.080	.033	.030	------	.17	.23	.16
90	.0600	.073	.03	.027	.066	.16	.23	.16
100	.055	.067	.027	.025	.060	.15	.23	.15

*Densities can be as high as 1.5, in which case these numbers should be multiplied by the density.

**Data for 20 MeV and above are based on an extrapolation of data given in "Neutron Cross section" BNL 325 and Supplements. Available Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402.

TABLE XII. *Composition of shielding materials*

[Percent by weight]

Element	A	Concrete	Barytes concrete	Earth with 30% H_2O
H	1	0.63	0.44	3.3
C	12	0.4	1.1	------
O	16	51.1	35.4	60.8
Na	23	0.33	------	2.0
Mg	25	------	------	1.5
Al	27	2.0	------	5.8
Si	28	35.8	8.9	19.7
K	39	------	------	1.8
Ca	40	8.6	7.4	2.6
Fe	56	1.2	1.5	3.6
Ba	137	------	35.8	------
S	32	------	9.0	------

process therefore has a large influence on the amount of material which a neutron must penetrate in a given radiation shield before emerging. Hydrogen has a unique position as a neutron moderator because of the equality of its mass

with that of the neutron. In hydrogen the direction of elastic scattering is always forward in the laboratory coordinates; but, more importantly, the neutron can lose any amount up to the total of its energy in a single collision. The cross section is relatively large except at very high energies. No other process occurs in hydrogen at the energies considered here except radiative capture of thermal neutrons. In the range of intermediate energies in most shielding materials, elastic scattering in hydrogen is the only effective moderating process of importance.

(2) Inelastic scattering is the process whereby the neutron transfers part of its energy to the target nucleus to raise it to an excited level. This process is prominent at high energies and in materials of high atomic number where there are many levels. It is the predominant moderating effect in most shielding materials at 10 Mev and higher energies where the total cross section of hydrogen (which is elastic scattering only) has become small.

(3) Radiative capture results in the disappearance of a neutron and the production of a nucleus of mass $(A+1)$. The excitation energy of approximately 7 Mev is radiated as one or more γ rays. The process is an important sink for thermal neutrons in radiation shields. The cross section exhibits resonance effects in many nuclei even at low energies; e.g., the 0.18 eV capture resonance of cadmium. When the thermal region is far from a resonance in the target nucleus, the cross section varies inversely with the neutron velocity. At intermediate and high energies, the cross sections are too small to have any appreciable effect.

(4) Charged particle reactions also act as a neutron sink. The reaction may be produced in many nuclei by thermal neutrons and the cross section is very large in some cases; e.g., 4,000 barns for the reaction B^{10} $(n,\alpha)Li^7$, and 950 barns for Li^6 $(n,\alpha)He^3$. In other nuclei, there is a threshold energy which must be supplied by the neutron before the reaction can proceed.

(5) The $(n,2n)$ reaction is considered separately since it has the unique effect of increasing the number of neutrons. This is also a threshold reaction, the threshold being the same as that for the (γ,n) reaction plus the recoil energy taken up by the target nucleus. The process competes with inelastic scattering, the cross section rising rapidly above the threshold to become the dominant effect. It has a moderating effect for, while the number of neutrons is increased, the total energy is substantially decreased.

3. Neutron Attenuation in Thick Shields

The attenuation of neutron beams in thick sections of material containing substantial amounts of hydrogen is primarily determined by the fast neutron component. The fast neutrons are degraded mostly through inelastic collisions and, if the material contains hydrogen, they will not diffuse far from the point of collision before being absorbed. Since the absorption is not immediate the removal of neutrons from the fast component results in a substantial buildup of intermediate and thermal neutrons.

There are several methods available for the calculation of neutron attenuation, but most are beyond the scope of this handbook and reference should be made to the literature for solution of unusual problems [40, 41].

Usually an empirical approach can be used to calculate the shielding for a given situation. This involves the use of either a measured or calculated removal coefficient, τ_R, in place of the attenuation coefficient defined above. The use of this attenuation coefficient corrects for effects of poor geometry and buildup which govern the penetration of neutrons through thick shields. This removal coefficient is not expected to apply unless the beam has penetrated a few removal mean free paths, λ_R, defined by

$$\lambda_R = 1/\tau_R. \tag{27}$$

From reactor work it has been found that in most materials and for neutrons around 8 MeV the removal coefficient is of the order of 0.6 to 0.7 times the attenuation coefficient, τ, defined above [42].

Figure 25 gives the removal mean free path for neutrons in concrete as a function of neutron energy [43]. There is some question as to what value should be used for the removal mean free path for neutrons at 100 MeV. The measured poor geometry value of concrete for density 2.3 g/cm^3 given in figure 25 is 35 cm. However, there have been values quoted as high as 51 cm for thick shields [44]. Shielding design based on the mean free paths given in figure 25 should therefore be carried out with caution.

E. Radiation Damage to Electrical Safety Devices

1. General

Electrical safety devices operating within the radiation vault are subject to failure as a result of radiation damage

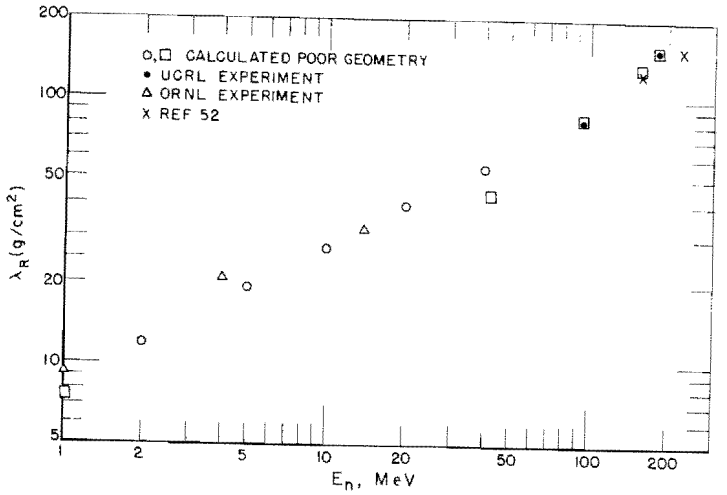

FIGURE 25. *Removal mean free path for neutrons in concrete as a function of neutron energy.*
Data from ref. [43].

unless special precautions are taken. Typical safety devices, some of which will normally be a part of every high energy electron accelerator installation include (1) access-door interlock switches, (2) personnel safety-off switches, (3) flashing warning lights within the vault, (4) fire detectors, (5) electrical interlock switches on high-voltage equipment which may be a part of the installation, (6) ozone monitors, and (7) residual radioactivity monitors.

Hazard will arise if accumulated radiation damage to such devices renders them inoperative through internal failures not detectable by a casual inspection. Failure for such devices to operate may arise from two general causes: (1) radiation induced mechanical or electrical failure of insulation materials within the device, and (2) paralysis of sensitive electronic circuits in a radiation field.

2. Radiation Damage to Insulating Materials

With the possible exception of damage by high-energy neutrons, a given radiation dose produces radiation damage in insulating materials which is approximately independent of the nature of the damaging radiation, i.e., x rays, fast electrons, or energetic ions. Of course, energetic particles will dissipate their energy in a smaller volume than hard

x rays because of their shorter range. Great variability exists in the sensitivity of insulating materials to radiation damage. Plastic materials are relatively sensitive and ceramics are usually quite insensitive. Even within the categories substantial variations exist. However, for purposes of safety hazard evaluations certain damage thresholds may be assumed. When the integrated radiation dose received by a particular insulator or insulation material within an electrical safety device exceeds this level it may be assumed that a hazardous situation exists. The suggested thresholds are:

a. Plastic insulating materials (including rubber)---------- 10 megarad
b. Ceramics (including glass)---------- 1000 megarad
c. Composite insulators (Fiberglass, for example)---------- 50 megarad

3. Radiation Paralysis of Electronic Safety Devices

Large radiation fluxes can cause temporary or permanent paralysis of electronic devices through ionization effects or through changes induced in the circuit components. Very little information is available on these effects, and it is clear that wide variation will exist in the onset of difficulties, depending on the sensitivity of the circuits involved. Based on a limited amount of actual experience, a rule of thumb would be that temporary paralysis of sensitive circuits might be expected to appear at radiation rates of about 1 roentgen per second, since this radiation rate can produce collective ion currents of about 1 microampere on exposed charged conductors within the equipment, assuming about a liter of free air around the conductor. Pulsed electron beams may be more effective in producing paralysis of this kind, since higher instantaneous ion currents would be involved. Some components, such as transistors or gas filled tubes (i.e., thyratrons, ignitrons, and mercury vapor rectifiers) may be much more sensitive than simple vacuum tubes. There are indications that transistors may undergo substantial permanent changes in electrical properties at radiation dosages as low as 1 megarad. Permanent paralysis may also arise from insulation or other failure of the general kind indicated in Section 2.

4. Recommendations

It is recommended that wherever possible electrical safety devices and their associated wiring be protected from direct

or scattered electrons by the use of suitable low-Z housings of a thickness greater than the range of the electrons in the primary beam. Where this is not possible it is recommended that special attention be given to the types of insulation materials being used and that ceramic or composite ceramic materials be used.

Where possible, "fail safe" circuits should be used so that radiation damage effects are positively indicated. If reliance is placed on sensitive electronic circuits within the vault for safety purposes, they should be protected by auxiliary shielding where possible, or tested for operability in radiation levels in excess of those normally encountered.

Periodic preventative maintenance and replacement should be undertaken on safety devices, using spot radiation surveys and the damage threshold levels indicated in 2 as guides.

F. Fire Hazard in Irradiated Material

1. General

Material subjected to bombardment by intense electron beams presents a fire hazard problem of a somewhat unusual nature. This fire hazard may result from any one or a combination of three basic causes:

(a) High rate of internal thermal input through energetic electrons stopping within the material.

(b) Radiation catalysis of exothermic chemical reactions.

(c) Initiation of explosive reactions in volatile vapors through electrical breakdown and sparking.

Some of the effects can be latent, and thus present a more severe hazard.

2. Thermal Heating Effects

Because of their limited range, electrons are capable of delivering large quantities of energy within relatively limited volumes of irradiated material. Almost 100 percent of the energy of an absorbed electron will appear as local heating in the material. If the material is a poor conductor of heat, high internal temperatures may be produced. For example, if a solid material with about the density and specific heat of water is irradiated by a 1 kilowatt beam of electrons at 10 million volts, substantial heating will be produced to a depth of about 5 cm. If the beam cross section is 1 cm^2, then the initial rate of temperature rise will be about 50 °C per second. If the volume of the sample is large, so that heat transfer to the boundaries is slow, then the interior

temperatures may easily reach several hundred degrees centigrade in a few seconds. Because of convection cooling, the surface temperature of the sample may at the same time be very much lower than the interior. It is a matter of observation that the interior of a block of wood may be severely charred by electron irradiation, while the surface remains almost unaffected. Under unfavorable circumstances an internal slow burning could be initiated which could later burst into an open flame. Heat sensitive chemical reactions could be internally initiated by electron irradiation. Solid materials are probably somewhat more susceptible to this type of heating than are liquids, since convection within the liquid would tend to reduce thermal gradients.

In some critical cases, the high instantaneous rates of heating produced by pulsed machines could also be an important contributing effect.

Finally, thermal expansion effects of tightly sealed irradiated samples may result in an explosion and subsequent fire.

3. Radiation Catalysis

A considerable number of chemical reactions can be catalyzed by electron beam irradiation. If these reactions are sufficiently exothermic they may be self-propagating in large samples and thus may give rise to extra explosion and fire hazards. In general, the irradiation dose necessary to produce radiation catalysis may be considerably below that which produces severe thermal effects, so that additional caution must be exercised.

4. Initiation of Explosive Reactions in Volatile Vapors Through Electrical Effects of the Radiation

Whenever substantial currents of high-energy electron beams are used it is observed that charging and ionization effects occur in the vicinity which usually lead to a cascade of tiny electrical sparks from surrounding objects. The most striking example of these effects is to be seen in the "trees" which can be produced by electrical breakdown in the interior of a block of transparent plastic exposed to an electron beam. If volatile organic materials are under irradiation the vapors from the materials may form an explosive mixture. The presence of radiation induced sparking them provides a triggering mechanism for such reactions. In some cases it is possible that even where the primary irradiated material does not produce an explosive vapor, one of its radiation decomposition products may be

an explosive gas, leading to a potentially dangerous situation. The problem is probably, however, no more severe than in many other industrial processing situations, and can be handled in an essentially similar way, except that it probably must be assumed that electrical sparks will be present at all times.

5. Recommendations

It is recommended that in installations involving the use of high-energy electron beams it be assumed that a potential fire hazard exists at all times the machine is in operation and that appropriate fireproofing and extinguishing equipment be provided. Where volatile compounds are irradiated it is further recommended that adequate ventilation be provided to prevent the accumulation of explosive concentrations of vapors.

VI. Definitions of Terms and Symbols

1. Terms

Absorbed dose. The quantity of radiation delivered to a specified mass of material. Units are the rad (100 erg/g).

Barn. Unit of cross section measurement equal to 10^{-24} cm^2.

Bremsstrahlung. X-radiation, the spectrum of which is continuous and which arises from the acceleration of charged particles.

Buildup factor. A quantity that described the effects of the buildup of secondary radiation in the passage of radiation through thick barriers.

Cross section. The effective target area of an atom for a particular process. The product of cross section and number of atoms per square centimeter in an infinitesimally thin section represents the probability that the process will occur in that section.

Density effect. The effect of condensed materials which reduce, through their atomic polarization, the amount of ionization produced by very high energy charged particles.

Divergence of a beam. The angular spread of a beam of radiation.

Duty cycle. The fraction of the operating cycle of an accelerator during which radiation is produced.

Effective range. The range or depth of penetration of a particle measured from the front surface of the absorber to the limit of penetration.

Energy. As applied to the output of a machine, the term refers to the energy carried per particle (or per photon). The unit is usually one million electron volts (1.6×10^{-6} erg).

Faraday cup. A device which attempts to collect all the electrons of a beam, enabling the quantity of electronic charge to be measured as a current to ground.

Flux. Number of particles per unit time passing through a surface.

Flux density. Number of particles per unit time passing through one square cm.

Half-life. The time taken for a radioactive source to decay to half its initial activity.

Half-value layer. The thickness of absorber required to reduce a beam of radiation to one-half its incident dose rate.

Mean free path. The distance in which on the average $1/e$ of the particles in a beam interacts with the medium through which the beam is passing.

Output power. The output power of a machine is the total energy flux per second of useful radiation emerging from the machine. Units are watts (1 watt$=0.624\times10^{13}$ MeV/sec).

Primary protective barrier. Barrier sufficient to attenuate the useful beam to the required level.

Primary radiation. Radiation coming directly from the accelerator target (includes x rays, electrons, and neutrons).

Rad. The unit of absorbed dose. 1 rad is 100 ergs per gram.

Radiation length. The mean path length required to reduce by radiation losses the energy of a relativistic charged particle by a factor of $1/e$.

Saturated activity. The strength of a radioactive source produced in a sample when it has been exposed to a constant flux of radiation for a time long compared to its half-life for decay.

Scattered radiation. Radiation that has been deviated in direction during passage through matter. It may also have been modified by a decrease in energy. It is one form of secondary radiation.

Secondary protective barriers. Barriers designed to reduce the dose rate produced by stray radiation in occupied spaces.

Secondary radiation. Radiation (electrons, x rays, γ rays, neutrons, or protons) produced by the interaction of primary radiation with matter.

Sky shine. Radiation scattered over the top of shielding barriers.

Thick target. A target of such thickness that the electrons may lose their original direction and part of their original energy before a bremsstrahlung process occurs.

Thin target. A target in which all bremsstrahlung processes must occur before the electron suffers appreciable deviation or loss of energy.

True range. The range or distance traveled by a particle in an absorber measured aong the actual path followed by the particle.

X rays. Electromagnetic radiation (photons) of energy above a few hundred electron volts that originates outside the atomic nucleus. Photons of the same energy arising from the nucleus or by the annihilation of positrons, etc., are called gamma rays.

2. Symbols

Symbol	*Name*	*Unit*
A	the atomic weight	
$D(L)$	dose rate at a distance L from a source.	rads/sec.
E	photon energy	MeV.
E_n	neutron energy	MeV.
E_p	proton energy	MeV.
E_r	energy of the giant resonance	MeV.
I	total electron beam current	mA.
i	beam current density	mA/cm^2.
$I(E, T)$	bremsstrahlung energy spectrum.	MeV/MeV.
$I'(E, T)$	bremsstrahlung intensity spectrum.	MeVMeV/-sec.
K	radiation correction factor table I).	
k	quasi-deuteron normalization factor (eq. 13).	
N	Avogadro's number	6.02×10^{23} atoms per gram atomic weight.
R	range of electrons	g/cm^2.
S	source strength	number/sec.
T	electron kinetic energy	MeV.
t	thickness of target, absorber, absorber, etc.	g/cm^2 $t=\rho x$.
t_r	radiation length	g/cm^2.
$Y(T)$	neutron yield produced by bremsstrahlung.	neutron/sec^{-1} kW
$Y_o(T)$	approximate expression for neutron yield.	neutron/sec-kW
x	thickness of target, absorber, etc.	cm.

Symbol	*Name*	*Unit*
ΔT_r	energy loss due to radiation	MeV.
ϵ	bremsstrahlung production efficiency.	
η	fraction of photons absorbed by a nucleus, resulting in the production of a neutron	
λ	Mean free path	g/cm^2.
λ_R	removal mean free path for neutron.	g/cm^2.
μ	electronic mass absorption coefficient.	cm^2/g.
μ_T	Energy mass absorption coefficient defined by White.	cm^2/g.
ρ	density	g/cm^3.
σ	cross section	10^{-24}cm^2.
σ_{tn}	Cross section for producing a neutron by photon absorption.	10^{-24}cm^2.
$\sigma(E_n)$	neutron interaction cross section.	10^{-24}cm^2.
σ_{pd}	quasi-deuteron cross section	10^{-24}cm^2.
σ_d	deuteron photodisintegration cross section.	10^{-24}cm^2.
τ	absorption coefficient $\tau=\sigma\rho$	cm^{-1}.
Φ	flux density of radiation	number/sec-cm^2.

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