PROTECTION AGAINST BETATRON-SYNCHROTRON RADIATIONS UP TO 100 MILLION ELECTRON VOLTS

Handbook 55

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U. S. Department of Commerce Sinclair Weeks, Secretary
National Bureau of Standards A. V. Astin, Director

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Preface

The recommendations made by the National Committee on Radiation Protection, which are published as National Bureau of Standards Handbooks, serve as guides for protection against general hazards of radiation sources. A new class of radiation source has resulted from the rapid development since 1940 of such high-energy electron accelerators as linear accelerators, electron cyclotrons, electron synchrotrons, and betatrons. Of this group, betatrons and electron synchrotrons are being built commercially. Because these accelerators are sources of high-energy radiations and because of their widepread applications, they represent a potential hazard to operating personnel, to patients in hospitals, and to the public. Therefore, the operators of these accelerators require suitable protection recommendations for the safe application of the high-energy radiations.

The present Handbook attempts to supply these recommendations. Only betatron and synchrotron sources are considered. The hazards resulting from the various radiations produced by the sources are included, as well as those due to certain associated effects, such as noise, electricity, and ozone production.

The experimental data that relates to protection requirements for betatrons and synchrotrons are far from complete. Accordingly, measurement techniques and systems of units are not well established. Because there is a general deficiency of standard procedure in the high-energy field, complete appendixes to this Handbook are given to provide detailed discussions of proposed units and measurement procedures. These details are ordinarily not required in a protection handbook.

The following issues have received special attention:

(1) The choice of the units for radiation intensity (watts/cm^2) and for dose (ergs/g).

(2) The choice of a radiation-intensity secondary-standard.

(3) The choice of a 5-cm-thick Lucite cover for the sensitive element of a survey instrument.

(4) The recommendation for high-energy installations of the standard personnel-monitoring procedures presently in use below 2 Mev.

The Handbook was prepared by Subcommittee 5 of the National Committee on Radiation Protection, which is designated to investigate protection against radiations (electrons, gamma rays, and X-rays) above two million volts. The NCRP operates under the sponsorship of the National Bureau of Standards with the cooperation of the leading radiological organizations. It was formed upon the recommendation of the International Commission on Radiological Protection. Each of the subcommittees is charged with the responsibility of preparing protection recommendations in its particular field. The reports of the subcommittees are approved by the main committee before publication.

The following parent organizations and individuals comprise the main committee:

American College of Radiology: R. H. Chamberlain and G. C. Henny.
American Medical Association: P. C. Hodges.
American Radium Society: E. H. Quimby and T. P. Eberhard.
American Roentgen Ray Society: R. R. Newell and J. L. Weatherwax.
National Bureau of Standards: L. S. Taylor, Chairman, and M. S. Norloff, Secretary.
National Electrical Manufacturers Association: E. Dale Trout.
Radiological Society of North America: G. Failla and R. S. Stone.
U. S. Air Force: S. E. Lifton, Maj.
U. S. Army: J. P. Cooney, Brig. Gen.
U. S. Atomic Energy Commission: K. Z. Morgan and J. C. Bugher.
U. S. Navy: C. F. Behrens, Rear Adm.
U. S. Public Health Service: H. L. Andrews and E. G. Williams.
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The following are the subcommittees and their chairmen:

Subcommittee 1. Permissible Dose from External Sources, G. Failla.
Subcommittee 2. Permissible Internal Dose, K. Z. Morgan.
Subcommittee 3. X-rays up to Two Million Volts, H. O. Wyckoff.
Subcommittee 4. Heavy Particles (Neutrons, Protons, and Heavier), Dean Cowie.
Subcommittee 5. Electrons, Gamma Rays, and X-rays above Two Million Volts, H. W. Koch.
Subcommittee 6. Handling of Radioactive Isotopes and Fission Products, H. M. Parker.
Subcommittee 7. Monitoring Methods and Instruments, H. L. Andrews.
Subcommittee 8. Waste Disposal and Decontamination, J. H. Jensen.
Subcommittee 9. Protection Against Radiations from Radium, Cobalt-60, and Cesium-137 Encapsulated Sources, C. B. Braestrup.

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Protection Against Betatron-Synchrotron Radiations Up to 100 Million Electron Volts

I. Definitions [1]

The following definitions include the terms used in this Handbook. It is not intended to be a complete list of radiation terms.

1.1. *Acceleration chamber.* The annular vacuum tube, commonly called a "donut," in which the electrons are accelerated in a circular electron accelerator.

1.2. *Accelerator operating energy.* See *continuous spectrum of X-rays.*

1.3. *Betatron* (induction accelerator). A device for the acceleration of particles, ordinarily electrons, in a circular orbit in an increasing magnetic field by means of magnetic induction.

1.4. *Bremsstrahlung.* See *X-rays.*

1.5. *Burst of X-radiation.* The pulse of X-rays emanating from a circular electron accelerator as a result of one electron acceleration cycle. The duration of the burst is generally of the order of a few microseconds.

1.6. *Circular electron accelerator.* A circular electron accelerator in this Handbook refers to a betatron or synchrotron that accelerates electrons to energies between 2 and 100 Mev. The electrons can be used to strike a target and produce X-rays within the accelerator structure, or the electrons can be removed from the accelerator.

1.7. *Condenser r-meter.* An instrument consisting of an ionization chamber, together with auxiliary equipment for charging the chamber and measuring its voltage. It is used as an integrating instrument for measuring quantity of electrons, X-rays, or gamma radiation with energies below 2 Mev and is calibrated in roentgens.

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[1] Many of the definitions are based on those that have appeared in National Bureau of Standards Handbook 41, "Medical X-ray Protection Up to Two Million Volts," and in "A Glossary of Terms in Nuclear Science and Technology," by the National Research Council.

1.8. *Cone of X-radiation.* A cone, with apex at the X-ray target, that contains the major portion of the primary X-radiation from an electron accelerator.[2]

1.9. *Continuous spectrum of X-rays.* The continuous energy distribution of X-radiation produced by an accelerator. This distribution extends up to the kinetic energy of the electrons striking the X-ray target. The maximum kinetic energy of the electrons obtainable from an accelerator defines the accelerator energy rating (e. g., 40-Mev betatron). The spectra of the continuous X-rays from betatrons and synchrotrons are given in appendix G.

1.10. *Control cubicle.* The cubicle containing the auxiliary circuits required for the operation of the accelerator, such as the injection, ejection, contraction, and radio-frequency supply circuits.

1.11. *Donut.* See *acceleration chamber.*

1.12. *Dose.* A measure of the energy imparted to a unit mass of a medium by the ionizing particles present in the place of interest. The term dose as used in this Handbook is expressed in ergs per gram. This is the unit recommended by the International Commission on Radiological Units for use at energies above 3 Mev. See *rad.*

1.13. *Dose rate.* The dose delivered per unit time. Dose rates in this Handbook are expressed in ergs per gram per second.

1.14. *Duty cycle.* The fraction of the total operating time of the accelerator during which X-rays are being produced. The duty cycle for an accelerator that produces a burst of X-rays during each magnetic-field cycle is the product of the X-ray burst time in seconds and the number of magnetic-field cycles per second.

1.15. *Equilibrium orbit.* The circle of theoretically constant radius on or near which the electrons spend most of their acceleration cycle in a circular electron accelerator.

1.16. *Equilibrium or transition thickness.* The depth in a sufficiently thick absorber at which a monodirectional X-ray beam, initially electron-free, produces the maximum ionization per unit volume.

1.17. *Equivalent quanta per square centimeter.* A unit of radiation exposure. The number of equivalent quanta per square centimeter in an X-ray beam equals the total X-ray energy crossing a square centimeter measured normally to the direction of flow, divided by the peak-value X-ray-photon energy. The interrelationships of this unit with other radiation units are summarized in table 6, appendix A.

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[2] See appendix G for a more precise description of the angular distribution of the X-radiation.

1.18. *Erg.* A unit of energy in the cgs system. See *kilo-electron-volts.*

1.19. *esu per cm*^{3}. One electrostatic unit of electric charge carried by ions of either sign, which are produced by the interaction of radiation in 1 cm^3 of air at standard temperature and pressure.

1.20. *Film badge* (photographic dosimeter). A pack of photographic film with proper filters used for the detection or evaluation of dose produced by ionizing radiation.

1.21. *Flux density.* An amount of radiation flowing per unit time and per unit area, measured normally to the direction of flow. For example, electron (or X-ray photon) flux density is the number of electrons (or X-ray photons) per second per square centimeter; also, energy flux density (also called intensity) is the energy flow per unit time per unit area. See *radiation intensity.*

1.22. *Gamma rays.* See *X-rays.*

1.23. *Half-value layer* (HVL). The thickness of absorbing material necessary to reduce the dose rate produced at a point by an X-ray beam to one-half of its original value. A statement of half-value layer at high X-ray energies should always be accompanied by a statement on the amount of previous filtration. The concept of a half-value layer, especially at the high energies, must be applied with caution since the rate of change of dose rate with thickness or depth is not always a unique characteristic of the primary radiation.

1.24. *Intensity.* See *radiation intensity.*

1.25. *Kilo-electron-volts* (kev). A unit of energy. One kev is the change in kinetic energy of an electron when it moves across a potential difference of 1,000 volts. One kev is equivalent to 1.6×10^{-9} erg.

1.26. *Kilovolt* (kv). A unit of electrical potential equal to 1,000 volts.

1.27. *Leakage radiation.* All radiation coming from the accelerator outside the limits of the useful beam.

1.28. *Magnet.* The laminated steel structure of an accelerator in which the magnetic flux circulates.

1.29. *Maximum permissible dose.* The maximum dose to which the body of a person or any part thereof shall be permitted to be exposed continually or intermittently in a given period of time. The maximum doses permitted in 1 week are given in table 1.[3]

[3] The source of the basic data used in table 1 is National Bureau of Standards Handbook 47, "Recommendations of the International Commission on Radiological Protection and of the International Commission on Radiological Units, 1950." Handbook 47 lists permissible doses in roentgens per week, a unit that is strictly applicable only to X-rays below 3 Mev. For the present Handbook it has been assumed that 0.3 r measured in air for 1 week corresponds to a dose value of 30 ergs/g for 1 week for X-rays measured in tissue. The value of 30 ergs/g divided by the relative biological efficiencies for other radiations, as listed in table 4, page 6, gives the maximum permissible doses for 1 week for radiations other than X-rays.

TABLE 1. *Maximum permissible doses in 1 week*

Type of radiation	Ergs/gram in 1 week
X-rays and gamma rays	30
Beta rays and fast electrons	30
Protons	3
Slow neutrons	3
Fast neutrons of energy not greater than 20 Mev	3
Alpha rays	1.5

1.30. *Maximum permissible neutron flux density.* The maximum number of neutrons permitted for a given unit of time per square centimeter of body surface perpendicular to the neutron beam. The maximum permissible flux densities corresponding to the various neutron energies are listed in table 2.

1.31. *Million electron volts* (Mev). A unit of energy equal to 1,000 kev.

1.32. *Milliwatt.* One one-thousandth of a watt (10^{-3} watt).

1.33. *Neutron energy classifications.* Neutron energy ranges that are discussed in this Handbook are defined in table 3.

TABLE 2. *Maximum permissible neutron flux densities*

Neutron energy	Number of neutrons/cm²/sec [a]	Neutron energy	Number of neutrons/cm²/sec [a]
Mev		*Mev*—Continued	
Thermal	2,000	2.0	40
0.00001	1,000	3.0	30
0.010	1,000	4.0	30
0.1	200	5.0	30
0.5	80	10.0	30
1.0	60		

[a] A mean of several sets of calculations, which were based on a 40-hr week. The mean values of table 2 were agreed upon by the International Commission on Radiological Protection at the Seventh International Congress of Radiology, Copenhagen, July 1953. The following articles provide some of the background material: T. C. Evans, Nucleonics **4**, No. 3, p. 2 (1949); J. S. Mitchell, Brit. J. Radiol. **20**, 79 (1947); J. H. Tait, AERE T/R 273, 416, 564; J. H. Tait, Med. Res. Council T/R 718, 1951; W. S. Snyder, Nucleonics **6**, No. 2, p. 46 (1950); W. Ham, Nat. Res. Council, Committee on Radiation Cataracts, 1950; W. S. Snyder and J. Neufeld (to be published).

TABLE 3. *Neutron-energy classifications*

Classification	Energy
Slow	Thermal to 0.1 kev.
Intermediate	0.1 kev to 0.02 Mev.
Fast	0.02 Mev to 10 Mev.
High energy	10 Mev to 500 Mev.

1.34. *Occupied space.* The space neighboring an electron accelerator that is occupied or may be occupied by persons during times when the accelerator is producing radiation.

1.35. *Personnel monitoring.* The systematic periodic estimate of radiation dose received by personnel during working hours.

1.36. *Power cubicle.* The cubicle containing the power equipment for the accelerator, such as the capacitors, the power transformers, the d-c rectifiers.

1.37. *Primary protective barriers.* Barriers designed to reduce the dose rate produced by the useful beam in occupied spaces.

1.38. *Primary radiation.* Radiation coming directly from the accelerator target, which includes X-rays (bremsstrahlung), electrons, and neutrons. It includes the useful-beam radiation and part of the leakage radiation.

1.39. *Protection.* Provisions designed to reduce exposure of personnel to radiation. For external radiation this involves the use of protective barriers, the assignment of adequate distance from radiation sources, the reduction of operating time or beam intensity, or any combinations of these.

1.40. *Protection survey.* Evaluation of the radiation hazards associated with the production and use of the radiations from an electron accelerator.

1.41. *Protective barriers.* Barriers of radiation-asborbing material, such as lead, concrete, or steel, that are used to reduce radiation hazards.

1.42. *Qualified expert.* A person having the knowledge and training needed to measure radiations from an electron accelerator and to advise the safety officer regarding radiation hazards. The physician, safety officer, or plant superintendent employing him shall be responsible for seeing that he has the necessary qualifications. Certification by competent authority or by a board set up for the purpose is desirable.

1.43. *Rad.* The unit of absorbed dose, which is 100 ergs/g. The rad is a measure of the energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. It was recommended and adopted by the International Commission on Radiological Units at the Seventh International Congress of Radiology, Copenhagen, July 1953.

1.44. *Radiation.* In general, radiation is energy that is propagated through space; in particular, for the purposes of this Handbook, it consists of the energy that is propagated in the form of X-rays, gamma rays, electrons, and neutrons.

1.45. *Radiation exposure.* The time integral of the radiation intensity incident at a given position. Radiation exposures as used in this Handbook are expressed in watt-seconds per square centimeter. (1 watt-sec/cm^2 is equal to 10^7 ergs/cm^2.)

1.46. *Radiation field.* The space irradiated by the accelerator.

1.47. *Radiation hazard.* A hazard resulting from the presence of radiation in amounts capable of producing dose rates greater than the maximum permissible dose rates.

1.48. *Radiation intensity* (radiation energy flux density). The radiation energy flowing through unit area perpendicular to the beam per unit time. When separate beams of the same or different radiations are considered, the intensity and direction of each individual beam should be specified.

Radiation intensities in this Handbook are expressed in watts per square centimeter. This quantity is of particular interest in the specification of accelerator performance, and must not be confused with dose rate, which measures the rate of energy *absorption* per unit mass of an irradiated medium. (See *dose*.)

1.49. *Radiation room.* The room to which the bulk of the radiation produced by the accelerator is confined. For the purposes of this Handbook, this room is also assumed to be the room in which the radiation is utilized.

1.50. *RBE.* The abbreviation of the term "relative biological effectiveness," which is evaluated numerically as the inverse ratio of the doses of two different radiations necessary to produce the same biological effect. The ratio is not the same for all biological effects. Values of RBE with reference to the gamma rays of radium as a standard are listed in table 4 as they are used in this Handbook. They are of an interim nature and are intended only for use in calculating the maximum permissible dose levels.

TABLE 4. *Relative biological efficiencies*

Radiation	RBE
Gamma rays from radium (filtered by 0.5 mm of Pt)	1.0 (Standard).
X-rays of energy 0.1 to 100 Mev[a]	1.0
Electrons of energy 0.1 to 100 Mev	1.0
Protons	10.0
Fast neutrons	10.0
Alpha rays	20.0

[a] Some experimental evidence for an RBE of less than 1 has been found for the X-rays generated by betatrons operating in the region of 20 Mev. However, until these results are well established, the more conservative RBE of 1.0 is adopted in this Handbook for these X-rays.

1.51. *Roentgen* (r).[4] In the energy range up to 3 Mev, the International Commission on Radiological Units [5] has continued the recognition of the roentgen as a unit of X- and gamma-ray quantity with the following definition:

"The roentgen shall be the quantity of X- or gamma-radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign." [6]

1.52. *Safety officer.* The individual directly responsible for the safety of all persons at an accelerator installation. This individual should have the authority to stop operations whenever he believes that persons are being endangered.

1.53. *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.

1.54. *Secondary protective barriers.* Barriers designed to reduce the dose rate produced by stray radiation in occupied spaces. (See section 1.34.)

1.55. *Secondary radiation.* Radiation (electrons, X-rays, gamma rays, or neutrons) produced by the interaction of primary radiation with matter.

1.56. *Shall.* Indicates necessity in order to meet currently accepted standards of protection.

1.57. *Should* or *is recommended.* Indicates advisory requirements that are to be applied when possible.

1.58. *Stray radiation.* Radiation other than that in the useful beam. It includes leakage radiation and secondary radiation from irradiated objects.

1.59. *Synchrotron.* A device for the acceleration of particles, ordinarily electrons, in a circular orbit in an increasing magnetic field by means of an alternating electric field applied in synchronism with the orbital motion.

1.60. *Tissue dose.* The dose imparted to tissue by ionizing radiation.

1.61. *Useful beam.* That part of the primary radiation that passes through the aperture, cone, or other collimator. In

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[4] See appendix A, The roentgen and radiation units above 2 Mev.

[5] See footnote 2.

[6] The X-ray output of many circular electron accelerators is improperly stated in terms of roentgens per minute measured at 1 m from the X-ray target, when the energy is above the limit at which the roentgen is applicable. The desirable specification of the beam intensity is in terms of the radiation intensity (e. g., in terms of watts per square centimeter). This quantity can be measured in an absolute manner by a total absorption calorimeter. A secondary-standard method that is convenient for use in this field is the measurement of X-ray output with a condenser r-meter located at the center of a suitable shell. The quantity measured by the r-meter should be expressed in terms of the measured number of electrostatic units per cubic centimeter per minute and the shell material and dimension. The conversion of the number of electrostatic units per cubic centimeter per minute to the unit of watts per square centimeter can be accomplished by means of the graph in appendix B for two secondary standards that are in common use.

those accelerators on which these devices are not used, the useful beam consists of the primary radiation.

1.62. *Watt.* A unit of power in the cgs system equal to 10,000,000 (or 10^7) ergs/sec. The unit is used in this Handbook in the specification of radiation intensity and dose rates.

1.63. *Work factor.* The fraction of the personnel working time per week during which an accelerator may be operated without exposing personnel in a given occupied space to weekly radiation levels above those defined as permissible. (See *maximum permissible dose,* section 1.29.)

1.64. *X-rays.* Electromagnetic radiations having wavelengths shorter than 10^{-6} cm. The X-radiation resulting from the interaction of external electrons with the nuclear and electronic fields of target atoms is produced by a process called bremsstrahlung. It is customary to refer to electromagnetic radiations originating in atomic nuclei as gamma rays.

1.65. *X-ray apparatus.* Any source of X-rays, its power supply and controls, coming within the scope of this Handbook.

1.66. *X-ray monitor.* A device for indicating the X-radiation level from an accelerator for purposes of control or comparison. Frequently the X-ray monitor consists of an ionization chamber and a current-measuring device to indicate continuously the average ionization current in the chamber gas produced by the action of the X-rays.

1.67. *X-ray target.* The structure subjected to bombardment by accelerated electrons in an accelerator for the production of X-rays.

II. Protection Against Operation Hazards

2. Electrical Protection

2.1. *Installation.* Installation of electrical components of accelerators shall comply with the applicable requirements of the latest approved edition of the National Electrical Code. The National Electrical Code is the standard of the National Board of Fire Underwriters and is approved by the American Standards Association. In the following, the term "approved type" refers to approval by the National Board of Fire Underwriters.

2.2. *Location.* Accelerators shall not be installed or operated in dangerous locations, for example, anesthetic rooms in which flammable or explosive gases or dusts may be present, unless the apparatus is of an approved explosion-proof type or is approved for the location by the authorities having jurisdiction.

2.3. *Connection to power mains.* (a) A supply of more than 600 volts between lines or to ground shall not be brought to the operator's control desk.

(b) Accelerators shall be provided with suitable wiring terminals for the connection of conductors of at least the size corresponding to the maximum continuous input rating of the apparatus and for grounding. Unless the terminals are located within the control cabinet or within other enclosures, they shall be protected with suitably grounded cover-plates or guards.

(c) All cords, cables, and external wiring employed for supply connections and for connections between components shall be adequate for the purpose and be maintained in good condition. Provision shall be made to protect them from mechanical damage, and those that are likely to be exposed to oil or water shall be of an approved type.

(d) For all stationary equipment and for mobile apparatus, the disconnecting means may be an approved enclosed switch or circuit-breaker. The switch or circuit-breaker shall be provided with a means of locking in the "OFF" position to prevent unauthorized use of the equipment and shall be enclosed in a grounded metal box. The switch or circuit-breaker shall have a pole in each ungrounded conductor. A double-pole switch shall be used for direct- and single-phase current and a triple pole for three-phase current where none of the conductors is grounded. A fuse or circuit-breaker protection shall be provided in each ungrounded conductor.

(e) The disconnecting means shall not be a part of the apparatus but should be readily accessible to the operator, preferably within sight of the control desk.

2.4. *Overload protection.* There shall be provided an overload protective device in addition to the fuses. This device shall open all ungrounded supply conductors to the magnet power circuit, and shall be such that it cannot be held closed under overload conditions. The device shall provide suitable positive indication of whether the contactor is open or closed.

2.5. *Control switches.* (a) The control desk shall contain a remotely controlled mainline-switch that will deenergize the apparatus. This switch shall break all ungrounded conductors of the incoming line.

(b) Hand or foot switches used to energize the accelerator, while a person is in the radiation room, shall be so constructed that they must be held "ON" for operation and return automatically to the "OFF" position when pressure is removed.

(c) No locking device to hold the hand or foot switch in the "ON" position shall be permitted. If the switch operates through a relay, the relay shall open when the switch is released.

(d) Means shall be provided for protection against failure of electrical controlling switches used in moving the magnet structure and elevating the tables. Positive mechanical stops shall provide for stopping all devices that might crush the patient or specimen.

2.6. *Electrical components.* (a) All components of accelerators together with the interconnecting wiring shall be of approved types complying with such electrical codes as are applicable.

(b) Switches, magnetic locks, and other electrical components comprising electrical interlocks intended to prevent access to high-voltage enclosure, and the like shall be of approved type.

2.7. *Protection from high-voltage circuits.* (a) High-energy accelerators, capacitors, and conductors, unless of fully enclosed shockproof type, shall be made inaccessible by means of insulating enclosures or of grounded metal barriers or enclosures.

(b) Any door, gate, port, or panel permitting ready access to the interior of high-voltage enclosures shall be provided with reliable interlocks, which shall deenergize the primary excitation circuit of the accelerator when they are opened.

(c) There shall be provided within the high-voltage enclosure an emergency switch, by means of which a person trapped there can prevent the energizing of the high-tension transformer.

(d) Enclosures and barriers for exposed high-voltage capacitors or the conductors to such capacitors should have in addition to access interlocks, devices so arranged that both sides of the high-voltage circuit are automatically short circuited and grounded when the door or cover to the enclosure is opened.

(e) All high-voltage capacitors shall be of a type approved by the National Electrical Manufacturers Association.

(f) A grounded metal grid or screen may serve as the protective enclosure for high-voltage circuits, if sufficiently rigid.

(g) Protective walls of insulating material, including the air space between the latter and any high-voltage part, shall provide the necessary insulation to withstand twice the maximum operating voltage to ground. They shall in no case be placed nearer to any high-voltage part than the equivalent needlepoint spark-gap distance, corresponding to the maximum operating voltage of the conductor to ground.

(h) Any high-voltage parts of oil or water coolers shall comply with all regulations pertaining to high-voltage apparatus.

(i) All flexible high-voltage shockproof cables shall be provided with a metal sheath that is grounded.

2.8. *Grounding.* (a) All exposed noncurrent-carrying metal parts of accelerators, including protective guards, barriers, enclosures, and shields, shall be permanently grounded in accordance with the applicable provisions of the latest edition of the National Electrical Code. Other metal objects in the vicinity of exposed high-voltage parts, which may become charged by induction, should also be grounded.

(b) The high-voltage excitation circuit for the magnet shall be grounded.

3. Warning and Safety Devices

3.1. *General.* Equipment shall be fitted with suitable safety devices of the latest approved type for covering all moving parts of electrical connections that may cause injury to the operator.

3.2. *Electrical interlocks.* (a) All access-doors to the capacitor bank shall be electrically interlocked to prevent excitation with these doors open.

(b) A safety sequence shall be incorporated in control circuits to provide for electrical interlocks on all doors or passageways leading to the radiation room.

3.3. *Warning horns and lights.* (a) The control panel shall be equipped with warning lights indicating "Ready to Operate" when all auxiliary circuits, doors, cooling systems, safety devices, etc., are in proper operating condition.

(b) A warning horn and time-delay circuit should be automatically actuated by the magnet power switch before the magnet can be energized.

(c) A red light on control panel shall indicate when magnet is energized.

(d) A safety sequence shall be incorporated in the control circuit to permit connection of various warning devices such as flashing lights, horns, etc., at strategic places throughout the building.

3.4. *Warning signs.* At entrances to and within rooms that contain radiation sources or radiation generating equipment, there shall be prominent signs of the danger of radiation. The signs shall refer to automatic visual or audible signals that operate when the equipment is energized or when radioactive sources are exposed, e. g., "Warning—Flashing Lights Indicate High-Energy X-rays Being Generated Within Enclosure."

4. Operational Precautions

4.1. All auxiliary circuits shall be automatically timed and interlocked to prevent incorrect sequence of operation.

4.2. During routine donut-replacement, great care should be exercised in reassembly of the magnet structure in order to prevent donut breakage and possible injury to personnel from implosion of the donut. Personnel shall wear glasses or goggles during this operation.

5. First Aid and Fire Protection

5.1. A supply of suitable first-aid and fire-extinguishing devices, and equipment approved for use with electrical apparatus shall be provided in conspicuous places and be appropriately labeled.

5.2. At the location of above first-aid equipment, instructions should be posted for the proper procedure for washing of hands and other parts of the body that may have come in contact with the liquid that may be contained in capacitors and transformers. Exposure to this liquid may produce local skin irritations.

6. Inspection and Preventive Maintenance

6.1. Before any accelerator or high-voltage part is touched or any electrical enclosure is opened, care shall be taken to insure that the apparatus is disconnected from the power line and all capacitors discharged and grounded. Before any servicing operation is begun, the disconnecting means should be secured in the "OFF" position; or, where a plug and receptacle are used, the plug should be removed by the person servicing the equipment and should be placed within his sight during the service period, if practicable.

6.2. When the work being done requires more than one person, distinct signals shall be given and receipt acknowledged before high voltage is applied.

6.3. Periodic inspections should be made of high-voltage systems for possible loose connections and parts, faulty insulators, or corona breakdown of high-voltage barriers and interlocks. A general inspection of electrical components should be made at least every six months.

7. Additional Precautions

7.1. *Ozone production resulting from electron ionization in air.* No special precautions need be taken to protect against breathing ozone, since the normal precautions required to eliminate the radiation hazard from radioactivity in air (see section 19.4) would also eliminate the ozone hazard.

7.2. *Noise hazard.* Many of the present-day betatrons and synchrotrons produce low-frequency noise levels above 90 db. Personnel exposure of several hours to noise levels above 110 db should be regarded as a health hazard and should be avoided.

III. Protection Against Radiation Hazards

8. Units of Measurement

TABLE 5. *Units for electrons and X-rays* [a]

Term	Recommended unit above 2 Mev	Unit in use below 2 Mev [b] (should not be applied above 2 Mev)
Dose	erg per gram (1 erg/g= 1/100 rad)	Roentgen.
Dose rate	erg per gram per second (1 erg/g/sec=10^{-7} watt/g).	Roentgen per second.
Radiation exposure	watt-second per square centimeter (1 watt-sec/cm^2=10^7 ergs/cm^2).	Roentgen.
Radiation intensity	watt per square centimeter (1 watt/cm^2=10^7 ergs/cm^2/sec).	

[a] See appendix A, The roentgen and radiation units above 2 Mev.
[b] The International Commission on Radiological Units has recommended the use of the roentgen up to 3 Mev. To be consistent with the coverage intended for this Handbook, the energy value used in this table is 2 Mev rather than 3 Mev.

9. Methods of Measurement

9.1. *X-rays.* (a) Beam intensity. The calorimetric method[7] is recommended as the standard laboratory method of measuring the X-ray beam intensity in the region from 2 to 100 Mev. This method determines as directly as possible the radiation intensity (watts per square centimeter) in the beam at the point in question. In this method a beam of known cross section is absorbed, and the energy content of the beam, which is integrated over a given time, is determined from the temperature rise of the absorber, making proper correction for the energy escaping in any form from

[7] See appendix C, Calorimetric method of determining X-ray intensities.

the absorber. It is not practical for general use because of the skill and technique required in the application of the method.

Secondary standards are recommended for use where great accuracy is not required. Ionization chambers may be used as secondary standards of measurement. The secondary standard for which data are provided in this Handbook is the 25-r condenser r-meter chamber inserted in an 11.5-cm cube of Lucite.[8]

(b) Dose. There is no adopted standard method of determining the dose imparted to a medium by X-rays.

However, dose can be measured conveniently by an ionization chamber inserted into a cavity in the medium at the point where the dose is to be measured. From the Bragg-Gray theory it can be shown that the dose in ergs per gram in tissue or similar materials (e.g., water or Lucite) of density 1 g/cm^3 is given approximately by E_{abs} (ergs/gram) $= 93\ J$ (esu/cm^3), where J is the ionization measured in an air cavity located at the point of interest,[9] and E_{abs} is the energy absorbed.

9.2. *Electrons*. (a) Electron-beam flux or current. The use of a deep Faraday cage mounted in a high vacuum is recommended as the standard method for measuring electron-beam currents. The electron current flowing from the cage to an electrical ground can be measured in a standard manner. This current measures the current in a high-energy electron beam directly if the proper precautions in the construction of the cage have been taken.

A method of greater convenience but less certainty than the Faraday cage is the use of parallel-plate ionization chambers that are oriented with their plates parallel to the electron-beam direction. The current in the electron beam may be obtained from the ionization current measured and the number of ion pairs that are produced by the electrons per centimeter of effective path.

(b) Dose. Thimble-type ionization chambers are suggested for this measurement until a primary standard method can be defined.[10]

9.3. *Neutron flux density*. (a) Recommendations regarding standard and secondary-standard methods for neutron measurements will be given in a future report.[11] The neutron

[8] See appendix B, Secondary standards for measuring X-ray intensities.

[9] See appendix D, Determination of the dose produced in a medium by X-rays.

[10] See description in appendix D of a method of measuring dose. This method for X-rays can be applied to electrons. However, it should be stated that an energy-dependent chamber will not yield an accurate depth-dose curve for electrons unless it is calibrated for electrons of the energy distribution existing at each point along the curve.

[11] Neutron recommendations are being prepared by the National Committee on Radiation Protection, Subcommittee 4, designated to investigate heavy particles (neutrons, protons, and heavier).

recommendations insofar as they apply to radiation protection measurements with a circular electron accelerator, are incorporated in the suggested methods listed in section V.

(b) The methods to be applied to neutron measurements shall interpret neutron flux densities in terms of at least the three lowest energy classifications.[12]

9.4. *General.* In the evaluation of X-ray, electron, and neutron intensities according to the specific methods listed in section V, these procedures should be followed:

(a) Each instrument should be periodically calibrated.

(b) More than one measurement should be employed, when possible and practical.

(c) A qualified expert should be consulted in order to evaluate the limitations of each method and to advise on calibration procedures.

10. Methods of Protection

10.1. *X-rays.* (a) Space and distance considerations. The X-ray beam direction should be restricted wherever possible in order to take advantage of the fact that high-energy X-rays are produced within a fairly narrow cone and that secondary products of high-energy radiations are projected mostly in the forward direction.

The distance of personnel from the X-ray target of an accelerator should be made as great as possible in order to take advantage of the reduction of the primary-beam intensity with distance and thus to reduce the required thickness of the protective barriers. The primary-beam intensity in any direction is approximately inversely proportional to the square of distance to the target.

(b) Practical protective materials.[13] Concrete is recommended as the best choice for permanent installations. Where space is at a premium and greater attenuation than that afforded by ordinary concrete is necessary, the concrete may be loaded with uniformly distributed material of high atomic number (e. g., scrap steel, iron ore, and barium rock).[14]

(c) Thickness of shield required. Shield thicknesses can be computed according to the method outlined in appendix I.

10.2. *Electrons.* (a) Materials used for shielding of accelerators producing free beams of electrons should be of low atomic number to minimize the production of X-rays.

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[12] See table 3, Neutron energy classification, p. 4.

[13] See appendix F, Theoretical half-value layers of various materials for 7.5-Mev X-ray photons.

[14] Too few experimental data are available on combinations of shielding materials to suggest more efficient and economical shields. However, to a first approximation the relative thicknesses required of different materials can be obtained from the inverse ratio of the mean absorption coefficients. See appendix E, X-ray absorption coefficients for monoenergetic X-rays.

Concrete is recommended, from the standpoint of economy, efficiency, and structural adaptability.

(b) No specific recommendations are made for shielding against electron beams. However, the shielding of an accelerator used as an X-ray machine will be adequate for that accelerator when it is used as a generator of an electron beam if primary X-ray protective barriers are provided in all directions.

10.3. *Neutrons.* Hydrogenous materials are usually the most practical neutron shields. Concrete is recommended because it contains a good percentage of hydrogen and is frequently used for X-ray shielding. Shielding against X-rays is of primary importance and neutron shielding is *usually* of secondary importance at an accelerator installation *that falls within the scope of this Handbook.*

IV. Installations [15]

11. Structural Details

11.1. Primary protective barriers shall be provided for any area exposed to the primary beam. Adequate shielding at the highest operating energy of the accelerator will generally be more than adequate at lower energies.

11.2. The required thickness of the primary protective barrier should be determined from table 12 of appendix I, together with the accompanying explanation.

11.3. The degree of attenuation offered by the barrier should be at least equal to that of the barrier indicated in table 12.

11.4. The data in table 12 are based on a concrete density of 147 lb/ft^3. If the density is different from this value, the barrier thicknesses shall be increased or decreased in inverse proportion.

11.5. The shielding requirements on the door to the radiation room can be reduced by putting the door at the control-room end of a maze leading to the radiation room.

11.6. The area containing the accelerator controls should be separate from the radiation room.

11.7. Holes in the barrier for pipes, conduits, and louvers shall be provided with baffles, so that the radiation transmitted through them does not exceed that transmitted through the surrounding barrier.

11.8. Windows and doors shall offer the same degree of attenuation as that required of the barrier in which they are located.

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[15] Sample computations on installations and barriers for X-rays up to 2 Mev are described in National Bureau of Standards Handbook 50, X-ray protection design.

11.9. Lead, if it is necessary in such structures as doors, shall be mounted in such a manner that it will not creep because of its own weight. It shall be protected against mechanical damage.

11.10. Welded or burned lead seams are permissible, provided that the lead equivalent of the seams is at least as large as that required of the lead sheet.

11.11. At the joints between different protective barriers the overlap shall be at least as great as the thickness of the thicker barrier.

12. Layout Plans

12.1. Location of radiation rooms. The cost of radiation protection for a high-energy X-ray installation depends to a large extent upon the occupancy of surrounding areas. Therefore, the installation should be located as far as practicable from other occupied regions. If the useful beam is directed frequently toward the floor, the installations should preferably be located on the bottom floor with the earth directly below the floor of the radiation room. By using a one-story building, the protection requirements are further reduced by minimizing the need for shielding of the ceiling of the radiation room, providing the scattering over the wall is insignificant. Further economy may be attained by restricting the orientation of the beam.

If possible, all personnel should be stationed at a considerable distance from the X-ray target and in directions at large angles with the useful beam. If this is done, less structural protection will be required, because the primary radiation in these directions is lower in intensity and the scattered radiation, in most instances, is less penetrating than in a more forward direction. Advantage should be taken also of the shielding afforded by the iron magnet structure of a circular electron accelerator.

12.2. The radiation emitted in a backward direction from the accelerator shall be regarded for protection purposes as primary radiation originating in the X-ray target with the same quality as that in the concentrated beam emitted in the forward direction. The backward beam shall be assumed to be a fixed percentage [16] of the forward beam. This percentage must be defined for each type or model of accelerator operating at a given intensity and peak energy.

12.3. For an accelerator with restricted beam directions, considerable saving in structural shielding requirements can

[16] A typical value of the ratio of back-beam intensity to forward-beam intensity of 1 percent has been obtained for a 22-Mev betatron operating with 2 milliwatts/cm^2 in the forward beam at 1 m from the target.

be obtained by enclosing the accelerator with a shielding barrier close to the magnet and provided with a small aperture; thereby practically limiting the primary radiation to the useful beam.

12.4. All wall, floor, and ceiling areas that can be exposed to the useful beam shall be provided with primary barriers.[17]

12.5. The factors to be applied in using table 12 shall be those resulting in the greatest barrier thickness for any operating condition. By "operating condition" is understood any orientation of the useful beam, any target distance, and degree of occupancy that may apply during the normal operation of the equipment.

12.6. All wall, floor, and ceiling areas not provided with primary protective barriers shall be shielded with secondary protective barriers. The secondary barrier shall be of thickness sufficient to reduce the direct and scattered radiation in occupied spaces below maximum permissible levels.[18]

13. Special Requirements for Medical Installations

13.1. Means shall be provided for the continuous observation of the patient during treatment.

13.2. Observation windows, periscopes, or similar arrangements provided for this purpose shall give at least the same degree of shielding as that required of the barriers in which they are located.

13.3. The observation window shall be so located that it cannot be exposed to the useful beam.

13.4. A wall or barrier that is sufficient to reduce the leakage radiation to 0.1 percent of the useful beam shall be between the accelerator and the patient. Both measurements shall be made at the target-to-patient distance.

13.5. Permanent diaphragms used for collimating the useful beam shall provide the same degree of protection as the shielding wall just described. Adjustable beam-defining diaphragms shall prevent transmission of more than 5 percent of the primary X-ray intensity outside of the useful beam.

13.6. All linear and angular adjustments of the accelerator magnet shall be provided with mechanical locking devices to prevent shifting during treatment.

13.7. An ionization chamber fixed in or near the useful beam should be provided to indicate either radiation intensity, or total radiation exposure. A reliable check of the

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[17] The thickness of such barriers may be zero if the distance to the occupied areas is sufficient to reduce the exposure below the permissible level.

[18] At the time of printing, no data are available on secondary protective barriers.

monitor equipment by an independent standard ionization chamber should be made before each treatment day.

13.8. The exposure control shall be provided with a means to terminate the exposure after a preset time or exposure.

14. Special Requirements for Industrial Installations

14.1. A shielding barrier attached to the accelerator, or close to it, should be used where practical.

14.2. The orientation of the X-ray beam should be restricted as much as possible.

14.3. The useful beam should be so directed that it must be scattered at least twice before it can go through openings in secondary protective barriers.

14.4. Solid concrete blocks may be used for barriers provided the blocks are so stacked that no continuous crack extends through more than 50 percent of the barrier. In the useful beam no continuous crack should extend through more than 25 percent of the barrier.

14.5. Consideration should be given to the protection of crane operators and other workers who may occasionally be located directly above the radiation room. As an example, interlocks should be provided in order to limit the crane operation to locations shown safe by a radiation survey.

15. Special Requirements for Research Installations

15.1. Research installations may be operated without the degree of shielding required for a medical or industrial installation, *provided:*

(a) The average weekly exposure to radiation in occupied surrounding areas does not produce a dose in 1 week that exceeds one-half the permissible value listed in table 1, page 4. The low dose can result either from personnel spending short times in the specified areas or from a small work factor of the accelerator.

(b) All persons in the neighborhood of the equipment carry pocket dosimeters, ionization chambers, or film badges.

(c) A record is kept of the operation of the equipment, including the direction of the beam.

(d) A diagram is posted at the control desk that clearly indicates the accelerator, protective barriers, and occupied areas. The radiation levels should be given at representative points for the highest anticipated output of the accelerator.

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V. Surveys [19]

16. Responsibility and Time of Survey

16.1. Routine operation of the accelerator shall be deferred until the complete survey has been made and the installation has been declared in compliance with the recommendations presented in this Handbook.

16.2. A qualified expert shall conduct the survey, and shall make a complete report of its results, as described below, to the official responsible for the installation.

17. Radiations to be Measured

17.1. The survey should include determinations of the distributions and magnitudes of the following quantities unless otherwise decided by the qualified expert:

(a) Useful beam within the radiation room.

(b) For medical installations only, leakage and scattered beams (including X-rays, neutrons, and ionizing radiations) within the radiation room.

(c) Dose rates in all occupied areas.

(d) Radioactivity in the radiation room.

18. Characteristics of Acceptable Instruments [20]

18.1. In general, Geiger-Müller counter instruments should not be employed in surveying occupied areas, because they are not capable of measuring the high instantaneous radiation fluxes obtained from circular electron accelerators.

18.2. Ionization chambers, which measure the average current or total charge collected during exposure, are acceptable instruments provided their linearity, correction for ion recombination losses, and calibration have been established. The instruments shall be tested at the high instantaneous radiation fluxes obtained from circular electron accelerators.

18.3. Photographic film is a suitable substitute for ionization chambers, provided it is properly processed and calibrated.

18.4. The detection of high-energy X-rays by the production of radioactivity (photonuclear reaction) is not recommended for a protection survey because of its low sensitivity.

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[19] Surveys in this section include electrical, mechanical, and noise surveys as well as the radiation survey at an accelerator installation.

[20] See National Bureau of Standards Handbook 51, Radiological monitoring methods and instruments.

18.5. All survey instruments or films that are being used to determine the dose produced by X-rays and electrons on the outside of protective barriers should be covered with a thick shell of Lucite (5 cm of Lucite is recommended). Surveys should be made with and without the shell.

18.6. Neutron detection methods are numerous.[21] The following are the methods that are considered the most acceptable when properly applied:[22]

(a) *Slow-neutron detection.* (1) Pulse counting [23] with proportional BF_3 counters by means of the $B^{10}(n,\alpha)Li^7$ reaction.

Note: (a) Counter walls should be essentially transparent to neutrons.

(b) B^{10}-enriched BF_3 can be employed to increase sensitivity.

(c) The response to neutrons above 0.5 ev should be established by placing a 0.030-in. cadmium shield around the counter. Such a shield will eliminate nearly all neutrons below this energy.

(2) Balanced-ionization-chamber method to eliminate the effect of stray radiation and to avoid the basic objection to the use of a counter (see section 18.1). One chamber is filled with BF_3 and the other with argon. This method can be applied to measure slow-neutron flux densities from 10 to 10^4 neutrons/cm^2/sec.[24]

(b) *Intermediate-neutron detection.* (1) A paraffin moderator placed around the slow-neutron proportional counter, ionization chamber, or appropriate foil will reduce the incident energy of the intermediate neutron so that the resultant slow neutrons can be measured.

(2) Cadmium shields outside the paraffin moderator can be used to eliminate the neutrons that were originally slow.

(c) *Fast-neutron detection.* (1) Proportional counter and twin ionization chambers using methane filling in place of BF_3 filling are useful because they have no directional characteristics.

(2) "Tissue equivalent" proportional counters [25] discriminate against low values of X-ray intensities, but have the usual directional characteristics.

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[21] See B. J. Moyer, Survey methods for neutron fields, UCRL 1694, Feb. 1952; B. J. Moyer, Survey methods for fast and high-energy neutrons, Nucleonics **10**, No. 5, p. 14 (1952); and H. H. Rossi, Status of neutron dosimetry, Nucleonics **10**, No. 9, p. 26 (1952).

[22] The degree of acceptability of the methods available depends to a large extent on the neutron energy range in question, the complexity of the neutron energy distribution, and the technique used in making the measurement. For accelerator measurements, where the pulsed nature of the X-rays and the complication of stray X-rays influencing the neutron measurement are unavoidable, the two simplest methods are the use of calibrated foils of indium or rhodium and the nuclear-plate technique of detecting recoil protons. However, both these methods, although simple in principle, are difficult to calibrate accurately.

[23] The moderation (slowing-down) time of neutrons is several microseconds. This long time prevents the pileup of neutron counts and helps overcome the objection to a neutron pulse counter, which is the same as that of a Geiger-Müller counter in this respect (see section 18.1).

[24] See footnote 21.

[25] See G. S. Hurst, R. H. Ritchie, and H. N. Wilson, A count-rate method of measuring fast neutron tissue dose, Rev. Sci. Instr. **22**, 981 (1951).

19. Survey Procedure

19.1. Electrical, Mechanical, and Noise Hazards

The survey should ascertain whether adequate protection is provided against electrical, mechanical, and noise hazards, as recommended in section II.

19.2. Primary Beam

(a) *X-rays.* (1) The useful beam shall be located and measured in a standardized manner.[26] [27]

(2) The beam position [28] and intensity [29] should be measured in any case and if practical should be measured at the accelerator operating energies of maximum output.

(3) The possibility of stray beams arising from portions of the accelerator tube other than the intended target should be investigated.

(4) Radiographic or ionization methods should be employed to survey the entire orbit plane of the accelerator, [30] the latter being operated at its highest practical output. If practical, this should be repeated at several operating-energy settings.

(b) *Electrons.* (1) The electron-beam intensity should be evaluated as discussed in section 9.2.

(2) Machines generating an emergent primary electron-beam produce considerable X-radiation. Therefore, the X-ray-beam location [31] and intensity [32] should be determined in addition to the location and intensity of the electron beam.

19.3. Regions Outside Protective Barriers

(a) *X-rays.* (1) The stray radiation for regions outside protective barriers shall be measured for all accessible areas with the accelerator operated at its highest practicable output. If the accelerator magnet is mobile, the

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[26] The X-ray beam can be located by radiographic procedure, employing lead intensifying screens. Alternatively, one may employ an array of pocket-type condenser r-meter chambers exposed simultaneously; or an ionization chamber mounted on a traveling carriage that can be remotely positioned; or equivalent means.

[27] No standard instrument is generally available that will give directly the energy flux density in the primary X-ray beam (see section 9, Methods of measurement). A simple practical approximation to this quantity can be obtained by the use of a condenser r-meter chamber calibrated to read esu/cm^3 and surrounded by a suitable shell. This should be placed in the primary beam at a sufficient distance from the target to insure practically uniform irradiation of at least twice the maximum dimension of the chamber. The reading of the r-meter, which will be called the esu/cm^3, divided by exposure time in seconds gives a figure that is proportional to the primary beam intensity. The approximate relationship between the condenser r-meter chamber reading and the radiation exposure (intensity$\times$time) as a function of X-ray energy is given in appendix B for two secondary standards that are in common use. These are a condenser r-meter chamber (1) mounted at the center of a 11.5-cm cube of Lucite and (2) mounted at the center of a ⅛-in.-thick cap of lead. Reference should be made to section III, Protection against radiation hazards.

[28] See footnote 26.

[29] See footnote 27.

[30] The orbit plane of the accelerator is assumed to be the same as the median plane of the donut.

[31] See footnote 26.

[32] See footnote 27.

stray radiation should be measured for all representative positions.

(2) The procedure outlined in section 19.2 (a) is applicable. Ionization-chamber readings with and without [33] the thick Lucite shell [34] (5-cm thickness is recommended) should be made. The readings should be determined as close to the outside of the protective barrier as possible. (Reference should be made to section 18.5 and footnote 42.)

(3) The primary-beam intensity shall be measured and reported along with the stray radiation.

(4) Rate-indicating ionization instruments are suitable for establishing the stray radiation distribution rapidly. However, several representative points on this distribution shall be checked by means of integrating ionization chambers or photographic film.

(5) The survey results shall be reported in the form of a scale drawing of the surveyed area, showing the accelerator, protective barriers, and occupied areas on which the radiation levels are given at representative points for the highest practicable output of the accelerator.

(6) Where radiation levels exceed the recommended permissible levels, the source of the radiation should be determined and the possibility of additional shielding should be investigated. If special circumstances preclude this remedy, the area in question shall be plainly indicated on the report and warning signs should be erected that state plainly the maximum weekly period permissible for occupancy.

(7) The report shall include a statement of the instruments employed, date of the survey, recommendations for improvement of the protection if any were found to be necessary, and a signed statement by the qualified expert as to whether the installation is or is not, in his opinion, compliant with the code.

(8) The survey should include measurements made with an object that has appreciable size and absorptive power placed in the primary beam. This object should preferably be typical of those likely to be placed in the primary beam in routine use of the accelerator. If the scattering produced by the object raises the radiation levels in occupied areas,

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[33] The ionization reading with a 5-cm-thick Lucite shell is expected to be slightly less than the reading without the Lucite shell when the chamber is close to the outside of a concrete protective barrier.

[34] The usefulness of the thick low-atomic-number wall material (5 cm of Lucite is recommended) is apparent from the fact that this instrument can be used to measure the primary beam intensity as described in footnote 27. Also, on the outside of a protective barrier, the same instrument will record a value of the measured ionization in esu/cm^3 that can be converted to a dose at the position. In the case of a concrete protective barrier, the dose will be, for the purposes of protection, a good approximation of the dose received by personnel at the position in question. The conversion factor from the ionization reading to the dosei s 93 ergs/g for 1 esu/cm^3 of ionization. (See fig. 8, p. 37.)

the higher reading should be taken as the radiation level at the point surveyed.

(b) *Electrons.* Machines generating external electron beams should be surveyed by the same general procedure as for X-rays. The reference beam intensity shall be the current of primary electrons, determined by the methods suggested in section III.

(c) *Neutrons.* (1) The neutron flux densities for at least the three lowest energy ranges (see neutron energy classification, section 1.32) shall be measured[35] for all accessible areas with the accelerator operated at its highest practicable output.

(2) The survey procedure outlined in section 19.3(a) for X-rays shall also apply to neutrons.

(d) *General.* If the output intensity of the accelerator is increased by a factor of more than two, or if the general disposition of the accelerator is changed appreciably at any time subsequent to the original survey, a new survey shall be instituted in order to insure that no dangerous change in the radiation pattern has occurred.

19.4. Additional Radiation Hazards

In addition to the radiation existing within the radiation room during normal operation[36] other hazards may exist. Measurements should be made in the radiation room in order to evaluate the extent of hazards of the following type:

(a) Dangerous amounts of radioactivity that may exist immediately after ceasing accelerator operation.[37]

(b) Stray radiation that may be present when the accelerator is operating under abnormal conditions.[38]

VI. Working Conditions

20. Responsibility

20.1. The safety of the working conditions of the personnel of a circular electron-accelerator shall be the responsibility of the safety officer.

[35] See section 18.6 for the characteristics of instruments for measuring neutron flux densities.

[36] See section III, Protection against radiation hazards.

[37] (a) A person entering (and remaining in) the radiation room containing an accelerator with an external electron beam immediately after a 20-min exposure of the air to a 50-Mev electron beam could receive a total dose of the order of 1 rad. This dose was calculated by assuming that a saturation activity in the air is attained in about 20 min because the N^{13} and O^{15} radioactivities have a 10-min and a 2-min half-life, respectively. The electron beam current that was assumed would produce an X-ray beam with an intensity of 4 milliwatts/cm^2 at 1 m from a tungsten target.

(b) Magnet components and particularly the donut in an X-ray betatron or synchrotron could be dangerously radioactive. The extent of this hazard should be evaluated during the survey.

[38] Examples: (a) Even though the electron ejector is disconnected during accelerator operation, the electrons can still produce a dangerous level of radiation. (b) Operation of the accelerator and the apparent elimination of X-ray production by a misadjustment of the injection timing may constitute a radiation hazard.

20.2. The safety officer shall be responsible for the instruction of new personnel in safe working practices and in the nature of injuries resulting from overexposure. He shall also promulgate safety rules for the installation, including restrictions in operating procedure indicated to be necessary by the radiation survey (see section 21).

20.3. Every new employee shall be required to familiarize himself with those sections of this Handbook selected by the safety officer as pertinent to his job, and sign a statement to this effect. This statement should be kept by the safety officer.

20.4. Extreme care should be taken to prevent unnecessary exposure and the misuse or intentional omission of protective devices.

21. Personnel Monitoring

21.1. Unless the qualified expert decides otherwise, the safety officer shall require that all personnel associated with the operation of an accelerator shall be continuously monitored individually for identification of any overexposure and indication of any remedial action necessary.

21.2. The personnel monitoring [39] data shall be retained in a permanent record by the safety officer and should be available for examination by all personnel.

21.3. Either a single film badge [40] or two pocket meters, [41] or both, [42] should be used in monitoring personnel.

21.4. A portable ionization-chamber-type survey meter should be available at all times during the operation of an

[39] The radiation from circular electron-accelerators can be very well defined and the exposure of all contiguous areas under any condition or orientation of the accelerator can be accurately predicted. Accordingly, the construction precautions, together with the preliminary surveys discussed in earlier sections, should make it possible to define those areas in which no personnel should be present during operations of the accelerator. Major reliance for personnel protection should rest on such provisions and not on personnel monitoring.

[40] Film badges provide an effective and convenient method of monitoring the approximate integral dose received by an individual in a given time interval. An effective system is one in which each staff member wears a suitably calibrated photographic dosimeter during each working day of 1 week and exchanges the film for a new one at the beginning of each week. The integral dose received on the film during the week can then be evaluated from density measurements on the exposed film emulsion. Great care is necessary in the handling, developing, and densitometry of films used for this purpose. Process control films should be processed simultaneously with the personnel films. Commercial film-badge service is now available. A limitation inherent in the conventional photographic method is that the dose received during any week is not known until a few days after the termination of that particular week. For routine use of an accelerator in which all procedures have been standardized, this limitation is not a serious disadvantage. Reference should be made to: M. Ehrlich and S. H. Fitch, Photographic X- and gamma-ray dosimetry, Nucleonics **9**, No. 3, p. 5 (1951) and a National Bureau of Standards Handbook, Photographic dosimetry (in preparation) by M. Ehrlich.

[41] Various types of pocket meters are now commercially available. A useful type is the self-reading meter, which consists of a condenser ionization-chamber, together with an optical system, scale, and self-contained electroscope. This meter is pen-shaped and is charged on a small battery-operated charger. The accumulated dose is read by viewing the scale against any source of light. Full-scale sensitivity is of the order of 0.20 r. Such meters should be made available to personnel when engaged in new operations or on any occasion when it is desirable to know the accumulated dose during or immediately after the course of the work.

[42] Recommendations of monitoring procedures specifically suited for high-energy accelerator personnel cannot be made at present. However, in general, the procedures in use at low-energy installations should be applicable.

accelerator, so that rapid checks for radiation hazards can be made.

22. Health

22.1. The safety officer shall be responsible for the protection of personnel against radiation and electrical injuries and for the enforcement of the following regulations for all employees.

22.2. Preemployment examination.

(a) The safety officer shall keep as a record the preemployment examination report of each one of the accelerator personnel.

(b) The preemployment examination shall entail an occupational history; a description of any unusual radiation exposure resulting from previous occupations, diagnostic radiographic examinations, or any radiation therapy received (including infancy and childhood); a detailed family history (for hereditary disease); and a complete physical examination, including a routine urinalysis, a chest X-ray, eye examination, and a blood count. In the case of a married individual without children, it is desirable to have a record of whether or not the absence of children is due to contraceptive measures.

(c) The eye examination shall pay particular attention to the presence of cataracts because the eyes are believed to be particularly susceptible to such damage by the fast neutrons that are produced by accelerators.

(d) The safety officer shall review all reports and take action when significant changes are found. When any worker exhibits any effects attributable to radiation overexposure, he shall be removed from his job and be placed under the care of a physician. An immediate survey shall be made to determine the source or cause of his overexposure.

22.3. The complete physical examination shall be repeated annually.

22.4. All reports of physical examinations shall become a permanent record.

VII. Appendixes

Appendix A. The Roentgen and Radiation Units Above 2 Mev

The roentgen [43] (see sections 1.52 and 8), which refers to a "quantity of X-radiation," is defined in terms of the energy

[43] L. S. Taylor and U. Fano, Dosage units for high-energy radiation, Radiology **55**, 743 (1950).

transferred from X-rays to ionizing particles in a standard mass of air at the point considered. If the ionizing particles deposit their energy in the immediate vicinity of the point, the quantity of X-radiation in roentgens is directly proportional to the energy absorbed per gram of the medium at that point. The roentgen is also related to the incident quantity of X-rays (i. e., intensity$\times$time) if the effective absorption coefficient is known. Therefore, at energies below about 2 Mev, the roentgen can be used, either to specify the quantity of radiation or to specify the eventual energy absorption in an irradiated medium. It is a convenient and useful unit because of this dual capability.

At X-ray energies above 2 Mev, the roentgen is not recommended for use, either as a unit of X-radiation quantity or as a unit of dose.

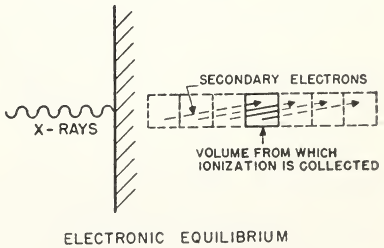
However, if high-energy X- or gamma-radiation were to be measured in roentgens, a measurement would have to be made of the total dose (or ionization) produced by the secondary electrons that have originated in 1 cm^3 of air at normal temperature and pressure.

Since the range of the secondaries, even in solid materials, is so large at energies above 2 Mev, measurements in roentgens become meaningless and impractical. As an illustration, the knowledge of the *quantity of high-energy X-rays* in *roentgens* at a point would give no clue to the energy absorbed in the medium at that point.

Conversely, the measurement of *dose* in *roentgens* becomes increasingly difficult at energies above 2 Mev. In order to illustrate this difficulty, figure 1 is provided to show the principle of electronic equilibrium. By the proper application of this principle, under certain conditions, the total ionization resulting from the secondary electrons produced in 1 cm^3 of air can be derived from the ionization from electrons entering and crossing that same air volume. Thus if equilibrium exists it is possible to measure the ionization equivalent of a roentgen.

FIGURE 1. *Conditions for electronic equilibrium.*

Electronic equilibrium requires that for each electron leaving the measuring cavity, an equal energy electron enters. As illustrated above, the ionization from the segments of tracks in the volume from which ionization is collected is equivalent to the ionization along the entire track of the electron that originated in that volume.



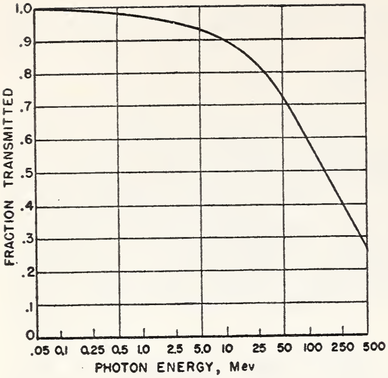


FIGURE 2. *Fractional number of photons transmitted through an air wall of thickness equal to the maximum range of the secondary electrons.*

For electronic equilibrium [44] to exist it is necessary that secondary electrons are produced uniformly throughout the entire volume from which the electrons may reach the cavity. In particular, it is necessary to have the radiation intensity constant in the wall of the measuring cavity for a distance at least equal to the maximum range of the secondary electrons.

Figure 2 shows the fraction of X-ray photons transmitted through a thickness of air equal to the range of an electron whose energy equals the photon energy.[45] For electronic equilibrium to exist, this fraction should be 1.0. As the X-ray photon energy increases, the fraction transmitted becomes smaller quite rapidly, so that equilibrium approximations become worse. At 2 Mev the fraction transmitted is about 96 percent and at 100 Mev it is about 58 percent. In actual practice, equilibrium conditions may be somewhat better than figure 2 indicates, because of the fact that secondary electrons have a distribution in energy ranging from zero to approximately the primary photon energy.

Since the conditions for electronic equilibrium cannot be satisfied above about 2 Mev, the primary radiation exposure (or quantity) can be obtained from the observed ionization only by means of a tedious and uncertain calculation to determine the number and energies of the secondaries. Even then, the ionization at a given point is a measure of the radiation exposure at various positions closer to the source of the secondaries. The average position of production of the detected secondaries is dependent upon the primary radiation

[44] Electronic equilibrium should not be confused with the equilibrium thickness as defined in section 1.16, p. 2. The equilibrium thickness refers to a maximum in the curve of ionization versus depth and implies only that the *ionization* from secondaries originating at that depth equals the *ionization* from secondaries stopped at that depth. Since the ionization per unit depth produced by low-energy electrons is higher than that of high-energy electrons, there are fewer electrons stopped than are produced at the equilibrium thickness. Therefore, electronic equilibrium does not exist.

[45] W. Heitler, Quantum theory of radiation, p. 215, 223 (Oxford University Press, 1936).

energy and the material. The complete solution for the measurement of radiation exposure in roentgens becomes quite complex.

A more logical approach to the measurement of primary X-radiation exposure is the direct measurement of the incident radiation energy per unit area by means of a calorimeter.[46]

The calorimeter measures the incident energy by recording the total energy absorbed. A calculation of the number and type of secondaries is unnecessary and the interpretation is straightforward. This procedure is recommended.

Similarly, the more logical and practical approach to the definition and measurement of dose is in terms of the energy absorbed at a point in a medium. The absorbed energy in ergs per gram can be measured most conveniently and accurately at the present time with an ionization chamber.[47]

Because of the above considerations, the present recommendations disregard completely the roentgen. The recommended unit of radiation exposure for energies between 2 and 100 Mev is watt-second per square centimeter. The recommended unit of radiation intensity is watt per square centimeter. The analogous unit for a dose rate is watt per gram. The recommended magnitude for the dose-rate unit is 1 erg/g/sec.

A summary of the radiation units and their conversion factors is shown in table 6.

TABLE 6. *Conversion factors for radiation units.*[a]

	To convert from (A)	To the unit (B)	Multiply (A) by
Radiation exposure	esu/cm^3	watt-sec/cm^2	[b]5.7×10^{-4}
	watt-sec/cm^2	erg/cm^2	10^7
	effective quanta (Q)/cm^2	erg/cm^2	[c]$1.6\times10^{-6}\times E_0$ (Mev)
Radiation intensity	watt/cm^2	erg/cm^2/sec	10^7
	effective quanta/cm^2/min	watt/cm^2	$2.7\times10^{-15}\times E_0$ (Mev)
Dose	rad[d]	erg/g	100
	watt-sec/g	erg/g	10^7
Dose rate	watt/g	erg/g/sec	10^7

[a] See section 8, Units of measurement, table 5.
[b] This specific factor applies to the esu/cm^3 as measured in an 11.5-cm Lucite cube with a 22.5-Mev operating energy. See appendix B, Secondary standards for measuring X-ray intensities.
[c] See W. Blocker, R. W. Kenney, and W. K. H. Panofsky, Transition curves of 330-Mev bremsstrahlung, Phys. Rev. **79**, 419 (1950).
[d] See section 1.43.

[46] See appendix C, Calorimetric method of determining X-ray intensities.
[47] See section 9.1 (b) and appendix D.

Appendix B. Secondary Standards for Measuring X-ray Intensities

One of the simplest ways to measure X-ray intensities is to observe the ionization produced in a chamber under specified conditions. A shell is usually placed around the chamber for the purpose of shielding it from lower-energy stray radiation. This shell also produces secondary electrons, which may contribute the major portion of the ionization in the chamber. Table 7 lists some of the materials that have been used to surround an ion chamber, with associated references. In several cases, the response of a particular arrangement to X-ray photons has been calculated as a function of the X-ray photon energy. These references have been labeled with a superscript "a."

The majority of the literature has reported the use of a Victoreen thimble chamber encased in a thick wall of low-atomic-number material. The advantages of this arrangement for a material such as Lucite are (1) the ionization

TABLE 7. *Secondary standards*

Description	Reference number
Wall material: Air	
1. Ionization vs. photon energy is calculated assuming equilibrium has been established	[17]
Wall material: Aluminum	
1. Cylinder contains an ion chamber. Ionization vs. photon energy is calculated	[8, 23]
2. Flat ion chamber is placed at depth of 5 cm in aluminum. Ionization vs. photon energy is calculated	[7]
3. Cube, ~10 cm on edge, contains Victoreen thimble chamber at center	[6, 13]
4. Ionization in a flat chamber vs. depth in aluminum observed. Integral under curve represents total absorbed energy	[3, 16]
5. Ionization observed in a thin aluminum wall chamber, which transmits the entire useful beam with very small attenuation. Useful as a continuously recording monitor, but responds to stray radiation	[1, 11]
Wall material: Carbon	
1. Ionization observed in a flat ion chamber placed between two carbon slabs, each 4.5 cm thick. Ionization vs. photon energy is calculated	[15, 19]
2. Cylinder contains an ion chamber. Ionization vs. wall thickness observed at several energies	[17]
3. Ion chamber placed behind a 4-in. wall. Ionization vs. photon energy is calculated	[22]
4. Cylinder with 2-in. wall contains a Victoreen thimble chamber	[18]
5. Ionization in a flat chamber vs. depth in carbon observed. Integral under curve represents total absorbed energy	[3, 16]

TABLE 7. *Secondary standards*—Continued

Description	Reference number
Wall material: Copper	
1. Cylinder contains an ion chamber. Ionization vs. wall thickness observed at several energies	[17]
2. Ionization in a flat chamber vs. depth in copper observed. Integral under curve represents total absorbed energy	[3, 16]
Wall material: Lead	
1. Cylinder with ⅛-in. wall, ⅞-in. outside diameter, 3½ in. long with hollow hemispherical end contains a Victoreen thimble chamber. There are variations in readings due to looseness of fit	[19]
2. Cylinder with ⅛-in. wall, ⅞-in. outside diameter, 4 in. long contains a Victoreen thimble chamber. Open end permits detection of stray radiation. Calculation of response to rectangular intensity spectra is made	[2]
3. Cylinder with ⅛-in. wall, ⅞-in. outside diameter, 2 in. long contains a Victoreen thimble chamber	[20]
4. Cylinder with ¼-in. wall contains a Victoreen thimble chamber	[5, 16, 24]
5. Cylinder contains an ion chamber. Ionization vs. wall thickness observed at several energies	[17]
6. Ionization in a flat chamber vs. depth in lead observed. Integral under curve represents total absorbed energy	[3, 16]
7. Flat sheet, ⅛ in. thick, is placed in front of Victoreen thimble chamber. This was calibrated against a calorimeter for 320-Mev X-rays	[12]
Wall material: Lucite	
1. Cube contains a Victoreen thimble chamber at depth of 4.13 g/cm^2. Ionization vs. photon energy is calculated	[10]
2. 11.5-cm cube contains a Victoreen chamber at center	[19]
3. 8-cm cube contains a Victoreen thimble chamber at center. This is calibrated against a calorimeter for 22-Mev X-rays	[14]
4. Cylinder, 3¾ in. diameter and 5⅛ in. long, contains a Victoreen thimble chamber at center	[1]
5. "Plexiglas" block contains a Victoreen thimble chamber at depth of 4.2 cm	[4]
6. Cylinder with 1.95-cm wall contains Victoreen r-chamber	[21]
Wall material: Magnesium	
1. Cylinder contains an ion chamber. Ionization vs. wall thickness observed at several energies	[17]
Wall material: Water	
1. 8-cm cube contains a Victoreen thimble chamber at center. This is calibrated against a calorimeter for 22-Mev X-rays	[14]

observed is nearly the same as would be observed in tissue of comparable dimensions, and (2) the errors introduced by failure to establish true electron equilibrium (see appendix A) at thicknesses greater than the equilibrium thickness are less for a material of low atomic number than for one of high atomic number. As a result the approximation of 1 esu/cm^3 of ionization representing one "roentgen" can be used for rough comparison of effects from low-energy radiation (where the "roentgen" is acceptable) and from high-energy radiation.

In view of the above facts, the NBS has used a Lucite cube, 11.5 cm on an edge, with a 25-r Victoreen thimble chamber in the center, as a secondary standard for the measurement of X-ray intensities. A number of experiments have been done with this secondary standard and are summarized below.

Figure 3 shows the dimensions of the Lucite shell that was used. These dimensions place the thimble chamber at the equilibrium thickness only for an X-ray spectrum with a peak energy of about 27 Mev. However, since the maxima are broad, the compromise position gives a reading within 10 percent of that at the equilibrium thickness over a range of energies from 10 to 50 Mev, and is useful over the entire range of this Handbook if suitable calibration is made.

For the Victoreen chamber to record 97 percent of the beam intensity, the diameter of the beam at 48 Mev should be at least 3 cm. This is shown in figure 4, which gives a plot of the relative ionization observed when a beam, 2 mm wide by 12 mm high, irradiated different portions of the Lucite block. The beam should be cleared of electrons of energy greater than about 12 Mev, because they may penetrate the Lucite and produce spurious ionization [1].[48]

A comparison has been made among (a) a Lax chamber, (b) a 25-r Victoreen thimble chamber placed in an ⅛-in. lead cap, and (c) a 25-r Victoreen thimble chamber placed at the center of the 11.5-cm Lucite cube [19]. Figure 5 shows the ratio of their responses as a function of the peak energy of the X-ray spectrum.

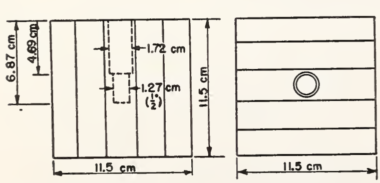


FIGURE 3. *Hydrocarbon cap for Victoreen thimble chamber.*

This cube can be made from 4 or 5 sheets of Lucite, the specific gravity of which should be 1.18 to 1.19. The surfaces should be wiped with ethylene dichloride and pressed together.

[48] The numbers in brackets in appendix B apply to the references listed on p. 34.

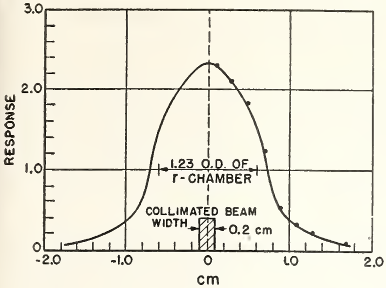


FIGURE 4. Relative response of a 25-r Victoreen thimble chamber in the center of a 11.5-cm Lucite cube plotted as a function of its position with respect to a beam of 48-Mev X-rays, 2 mm wide and 12 mm high.

These data were supplied by J. McElhinney.

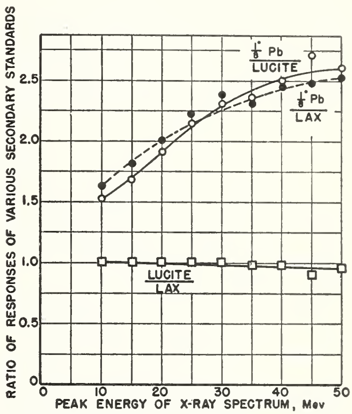


FIGURE 5. Ratio of the ionization recorded in various secondary standards when exposed to X-radiation.

"⅛ in. Pb" refers to a 25-r Victoreen thimble chamber placed in a lead cap ⅛ in. thick. "Lucite" refers to a 25-r Victoreen thimble chamber placed in the center of a 11.5-cm Lucite cube. "Lax" refers to ionization observed in a Lax chamber [15, 19].

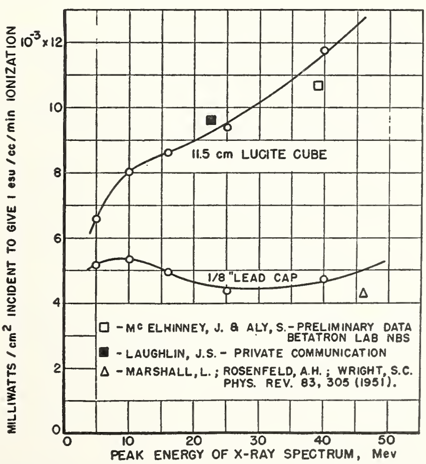


FIGURE 6. *Radiation intensity necessary to produce 1 esu/cm³/min.*

The ionization is measured in an air cavity surrounded in one case by Lucite and in the other by lead. The data are plotted as a function of the peak energy of the X-ray spectrum from an accelerator. The circles represent calculated values, which depend strongly on the roentgen interpretation at these energies. Experimental values are also indicated on the diagram.

By the combined use of (a) the ratios in figure 5, (b) the theoretical response of an ionization chamber in a Lucite cube, and (c) an assumed spectral shape, the number of milliwatts per square centimeter of X-ray intensity necessary to produce 1 esu/cm^3/min of ionization in the chamber was computed and plotted in figure 6. The comparison of the Lucite and lead curves with three experimental points is also given.

For a given-energy accelerator, it is often desirable to use a Lucite block of such thickness as to place the thimble chamber at the position of maximum ionization. The principal reasons for this selection are to give a large ionization, and to have a thickness great enough to shield the chamber from most of the stray electrons accompanying the incident X-rays.

References

[References that include calculations of the response of the secondary standard are indicated by a superscript a; those that show a calibration of the secondary standard with a calorimeter, by superscript b.]

[1] Allis-Chalmers Manufacturing Co., Milwaukee, Wis., Betatron instruction manual.

[a][2] G. C. Baldwin and G. S. Klaiber, X-ray yield curves for γ-n reactions, Phys. Rev. **73**, 1156 (1948).

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[13] L. H. Lanzl and A. O. Hanson, Z dependence and angular distribution of bremsstrahlung from 17-Mev electrons, Phys. Rev. **83**, 959 (1951).

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* Obtainable from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

Appendix C. Calorimetric Method of Determining X-ray Intensities

The calorimetric method has been shown to be applicable with high accuracy to the problem of determining radiation intensities.[49] A lead or other heavily absorbing cylinder is placed in the beam of radiation and its temperature compared by means of thermocouples or thermistors to that of an identical cylinder that is shielded from the radiation. Both cylinders are mounted in evacuated chambers and every precaution is taken to reduce thermal losses by radiation and conduction to a minimum. Care is also taken to absorb as large a fraction as possible of the X-ray beam. The absorbing cylinder is made so long and of such diameter that a negligible amount of radiation is transmitted through the cylinder or is lost by scattering out of the sides. Backscattering, which is small at these energies, is estimated from ionization measurements and a correction is made. Correction is also made for the energy of escaping neutrons. Results accurate to 1 or 2 percent are claimed.

[49] D. W. Kerst and G. A. Price, Phys. Rev. **79,** 725 (1950); J. S. Laughlin and J. W. Beattie, Rev. Sci. Instr. **22,** 572 (1951); J. S. Laughlin, J. W. Beattie, W. J. Henderson, and R. A. Harvey, Am. J. Roentgenol. Radium Therapy Nuclear Med. (in press).

Appendix D. Determination of the Dose Produced in a Medium by X-rays

No standardized procedure has been developed for measuring the energy imparted to a medium by high-energy X-rays. However, application of the Bragg-Gray [50] law will provide measurements that are sufficiently accurate for protection work.

The Bragg-Gray theory has shown that the energy imparted to the gas in a small gas-filled cavity in a medium is directly proportional to the energy that would be dissipated in the medium at that point in the absence of the cavity. This theory results in the relationship

$$E_{\mathrm{med}} = \frac{\rho_{\mathrm{med}}}{\rho_{\mathrm{gas}}} J W = \rho J W, \tag{1}$$

where E_{med} is the energy per cubic centimeter that is imparted to the medium; J is the number of ion pairs per cubic

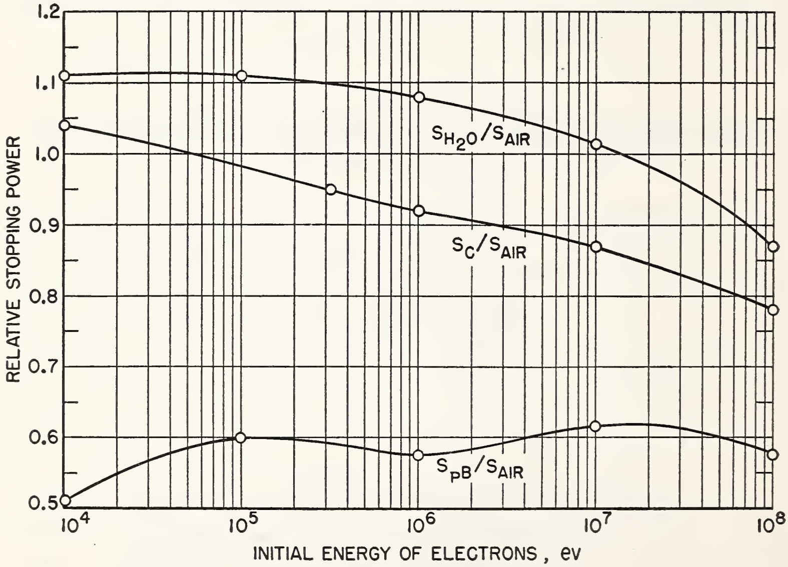


FIGURE 7. *Relative collision losses by electrons as a function of energy.*

The stopping powers, S, are in units of Mev-cm²/g. This figure was taken from T. J. Wang, Nucleonics **7**, No. 2, p. 55 (1950).

[50] See T. J. Wang, Cavity ionization chamber for measurement of absorbed X-radiation energy, Nucleonics **7**, No. 2, p. 55 (1950), for a bibliography and discussion of this relationship.

centimeter produced in the gas; W is the average energy dissipated per ion pair formed, and can be assumed to be 32.2 ev per ion pair; ρ is the ratio of the stopping powers of the medium (ρ_{med} in Mev/cm) and the gas (ρ_{gas} in Mev/cm) for the ionizing particles. W and ρ are each known to within a few percent for the gases and materials of chief importance, and J can be measured to almost any required accuracy. Hence, an ionization measurement permits one to calculate energy absorption in ergs per gram with an absolute error that should not exceed 5 percent.

Figure 7 provides the ratio of stopping powers in Mev-cm^2/g for several common materials (see footnote 50). Figure 8 provides the relationship between ergs per gram in water and esu/cm^3 in air as derived from the Bragg-Gray relationship by Laughlin.[51] The conversion factor is plotted as a function of primary electron energy and includes the effect of the associated secondary electrons.

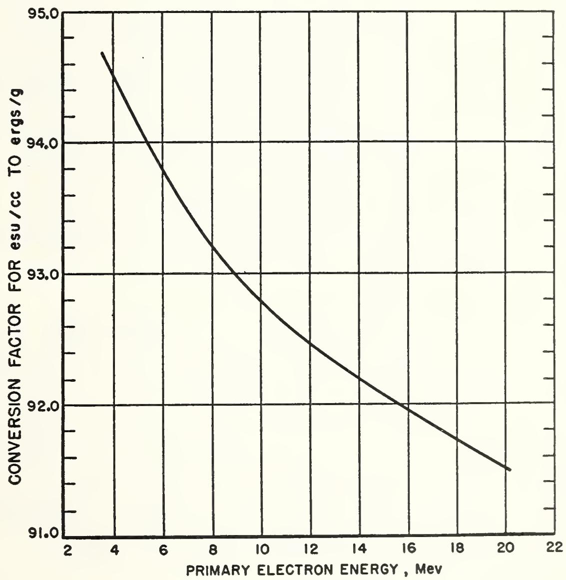
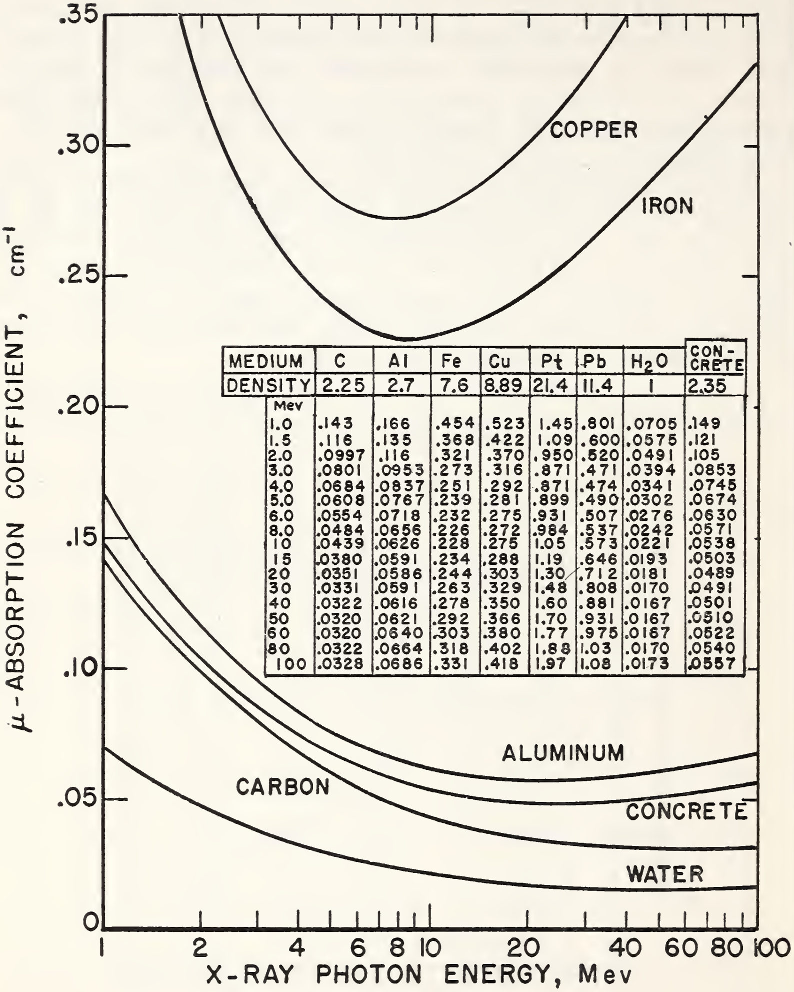


FIGURE 8. *Average energy absorbed per gram of water for each electrostatic unit per cubic centimeter of air ionization in a cavity in water, as a function of the energy of the primary electron.*

This curve was obtained from J. S. Laughlin, et al., Radiology **60**, 165 (1953).

[51] J. S. Laughlin, J. Ovadia, J. W. Beattie, W. J. Henderson, R. A. Harvey, and L. L. Haas, Radiology **60**, 165 (1953).

Appendix E. X-ray Absorption Coefficients for Monoenergetic X-rays



MEDIUM	C	Al	Fe	Cu	Pt	Pb	H_2O	CON-CRETE
DENSITY	2.25	2.7	7.6	8.89	21.4	11.4	1	2.35
Mev								
1.0	.143	.166	.454	.523	1.45	.801	.0705	.149
1.5	.116	.135	.368	.422	1.09	.600	.0575	.121
2.0	.0997	.116	.321	.370	.950	.520	.0491	.105
3.0	.0801	.0953	.273	.316	.871	.471	.0394	.0853
4.0	.0684	.0837	.251	.292	.871	.474	.0341	.0745
5.0	.0608	.0767	.239	.281	.899	.490	.0302	.0674
6.0	.0554	.0718	.232	.275	.931	.507	.0276	.0630
8.0	.0484	.0656	.226	.272	.984	.537	.0242	.0571
10	.0439	.0626	.228	.275	1.05	.573	.0221	.0538
15	.0380	.0591	.234	.288	1.19	.646	.0193	.0503
20	.0351	.0586	.244	.303	1.30	.712	.0181	.0489
30	.0331	.0591	.263	.329	1.48	.808	.0170	.0491
40	.0322	.0616	.278	.350	1.60	.881	.0167	.0501
50	.0320	.0621	.292	.366	1.70	.931	.0167	.0510
60	.0320	.0640	.303	.380	1.77	.975	.0167	.0522
80	.0322	.0664	.318	.402	1.88	1.03	.0170	.0540
100	.0328	.0686	.331	.418	1.97	1.08	.0173	.0557

FIGURE 9. *Absorption coefficient of X-rays in cm^{-1} plotted as a function of X-ray photon energy in million electron volts.*

These data were taken from Gladys White, X-ray attenuation coefficients (unpublished results, 1952). It should be emphasized that the absorption coefficients given in the figure apply to a monoenergetic X-ray or X-rays and not to a continuous distribution of X-rays as obtained from an electron accelerator. The densities of the media given in the table are in units of grams per cubic centimeter.

Appendix F. Theoretical Half-Value Layers of Various Materials for 7.5-Mev X-ray Photons

The half-value layers given in table 8 correspond to an average incident energy of 7.5 Mev, which corresponds approximately to that obtained from a 20-Mev betatron. They were derived from the absorption coefficients of appendix E and represent the thickness necessary to reduce the primary X-ray intensity to one-half of its initial value. They should compare approximately with the half-value layers measured in practice at depths in a substance that are greater than the equilibrium thickness in that substance. The half-value layers found in practice are known to vary slightly with depth.

TABLE 8. *Theoretical half-value layers of various materials for 7.5-Mev X-ray photons*

Material	Thickness	Material	Thickness
	in.		*in.*
Aluminum	4.1	Iron	1.2
Concrete (147 lb/ft^3)	4.6	Lead	0.52
Glass, leaded	1.8	Water	10.9
Glass, plate	5.0		

Appendix G. Characteristics of the X-radiation from a Circular Electron Accelerator

The X-rays from a circular electron accelerator are produced by the interaction of high-energy monoenergetic electrons with a target of thickness x cm and atomic number Z. The main characteristics of the X-radiation are the shape of the X-ray spectra, and the angular distribution of the X-ray intensity about the incident electron direction.

A detailed description of these characteristics is difficult and has been the subject of a series of papers. The following description, which is intended to provide a very general picture of the processes involved in X-ray production in an accelerator, is given in three parts: (1) The X-ray spectra shapes to be expected from an accelerator under idealized conditions are discussed, (2) the useful concept of radiation-length units is described in order to facilitate an understanding of the scientific literature relating to X-ray production, and (3) a summary is given of the available predictions on the angular distribution of the X-rays from an accelerator target.

1. *Shape of the X-ray spectra.* An electron of energy E_0 in traveling through a target will radiate as X-rays a fraction of its energy in the distance dx. The average electron-energy loss per centimeter of path is given by

$$-\frac{dE_0}{dx}=N\int_0^1 k\phi_k d\left(\frac{k}{E_0-\mu}\right), \tag{2}$$

where k is the X-ray photon energy in Mev, μ is the electron rest energy equal to 0.51 Mev, N is the number of atoms per cubic centimeter, and ϕ_k is proportional to the probability for the emission of an X-ray photon of energy k in range $d(k/E_0-\mu)$.

L. I. Schiff [52] has derived the expression for ϕ_k, using the Bethe-Heitler theory. His result is given approximately in the formula

$$k\phi_k d\left(\frac{k}{E_0-\mu}\right)=\frac{8\bar{\phi}E_0(dk)\sin\theta_0 d\theta_0}{\mu^2\left[1+\left(\frac{E_0\theta_0}{\mu}\right)^2\right]^2}\,\Gamma, \tag{3}$$

where

$\bar{\phi}=5.7\times10^{-28}Z^2\ \text{cm}^2.$

θ_0=angle between the incoming-electron direction and the secondary X-ray direction. θ is assumed small.

$\Gamma=[2(1-\epsilon)(\ln\alpha-1)+\epsilon^2(\ln\alpha-1/2)]$, a quantity proportional to the intensity (the number of X-ray photon times k) spectrum in the forward direction.

$\alpha=\frac{\alpha_1\alpha_2}{(\alpha_1^2+\alpha_2^2)^{1/2}};\quad \alpha_1=\left(\frac{2E_0}{\mu}\right)\left(\frac{E_0-k}{k}\right);\quad \alpha_2=\frac{111}{Z^{1/3}}$

$\epsilon=k/E_0.$

The integration over the angle θ_0 results in an intensity spectrum whose shape is very similar (within 10%) to the shape of Γ but whose analytical form is more complicated. No detailed experimental or theoretical examination has been made of the shapes of the intensity spectra of the X-rays from a 100-Mev betatron or synchrotron. Because no other spectrum has been proved to be more exact, and because of the simple form of the forward spectrum (Γ), the spectra obtained from Γ have been tabulated in this Handbook. Table 9 supplies values of $E_0^2\Gamma/k$ for various E_0's. This

[52] L. I. Schiff, Phys. Rev. 83, 252 (1951).

quantity gives the relative X-ray spectrum in terms of numbers of photons of each photon energy that would be radiated per high-energy electron.

TABLE 9. *Relative numbers of photons of various energies in terms of $E_0^2\Gamma/k$ as a function of k*

X-ray photon energy (*k*) in Mev	Electron energy, E_0, in Mev									
	5.51	6.51	8.51	10.51	12.51	14.51	15.51	16.51	18.51	20.51
2	45.3	69.3	130	208	304	418	481	550	700	869
4	10.6	21.7	50.1	86.2	130	183	213	245	316	396
6	------	1.36	22.8	46.6	74.7	108	126	147	191	241
8	------	------	1.73	25.2	47.1	71.4	84.8	99.1	131	167
10	------	------	------	2.10	28.0	49.1	60.1	71.4	95.9	123
12	------	------	------	------	2.47	31.0	41.6	52.0	73.0	95.5
14	------	------	------	------	------	2.84	21.7	34.1	55.3	75.5
16	------	------	------	------	------	------	------	3.22	37.3	58.8
18	------	------	------	------	------	------	------	------	3.59	40.6
20	------	------	------	------	------	------	------	------	------	3.97
	22.51	24.51	25.51	26.51	28.51	30.51	35.51	40.51	45.51	505.1
2	1056	1261	1370	1484	1725	1984	2712	3554	4510	5579
4	485	583	635	690	806	931	1284	1693	2160	2683
6	298	360	393	428	503	583	811	1077	1380	1721
8	207	251	275	300	354	412	577	771	993	1243
10	154	188	206	226	267	312	439	590	763	958
12	120	147	162	177	210	246	349	471	611	770
14	96.6	119	132	144	171	201	286	387	504	638
16	78.6	98.7	109	120	143	168	240	326	426	540
18	62.6	82.1	91.7	101	122	144	205	279	366	464
20	43.9	66.5	76.3	85.9	105	124	179	243	319	405
22	4.34	47.3	59.6	70.4	89.8	108	157	214	281	358
24	------	4.72	34.0	50.6	74.4	93.9	140	191	251	319
26	------	------	------	5.10	54.0	78.5	125	172	226	288
28	------	------	------	------	5.47	57.3	111	156	205	261
30	------	------	------	------	------	5.85	97.2	142	187	238
32	------	------	------	------	------	------	78.9	129	172	219
34	------	------	------	------	------	------	46.5	116	159	203
36	------	------	------	------	------	------	------	99.5	146	189
38	------	------	------	------	------	------	------	74.3	134	176
40	------	------	------	------	------	------	------	7.83	119	164
42	------	------	------	------	------	------	------	------	98.5	152
44	------	------	------	------	------	------	------	------	59.0	138
46	------	------	------	------	------	------	------	------	------	121
48	------	------	------	------	------	------	------	------	------	91.4
50	------	------	------	------	------	------	------	------	------	9.61

Table 9 continued on page 42.

TABLE 9. *Relative numbers of photons of various energies in terms of $E_0^2\Gamma/k$ as a function of k*—Continued

X-ray photon energy (k) in Mev	Electron energy, E_0, in Mev				
	60.51	70.51	80.51	90.51	100.51
5	3070	4217	5546	7056	8749
10	1418	1969	2610	3343	4167
15	877	1229	1641	2115	2648
20	613	865	1163	1507	1896
25	460	653	882	1148	1450
30	362	516	700	914	1158
35	296	422	573	750	953
40	250	355	481	631	802
45	215	305	413	541	689
50	187	267	361	472	600
55	153	238	320	417	530
60	11.5	212	288	374	474
65		176	262	340	429
70		13.4	236	311	392
75			199	286	361
80			15.3	262	335
85				222	312
90				17.1	287
95					245
100					19.0

The numbers of X-ray photons from table 9 are plotted as curve 1 in figure 10 for a thin tungsten ($Z=74$) target as a function of k for a betatron operating at an energy of 16 Mev. Since the total energy of the electrons in this betatron is 16.5 Mev, the maximum value of k is 16 Mev.

It should be noted that the quantity usually plotted in a standard reference is $k\phi_k/E_0\overline{\phi}$ (which is $8E_0\Gamma/\mu^2$) as a function of $k/(E_0-\mu)$. This plot is the X-ray intensity spectrum shown as curve 2 of figure 10.

2. *Radiation-length unit.* A convenient quantity in X-ray theory is ϕ_{rad}, which is proportional to the probability of energy by radiation, of an electron, per centimeter of path. This probability is defined by the equation

$$-\frac{dE_0}{dx}=NE_0\phi_{\text{rad}}, \text{ where } \phi_{\text{rad}}=\frac{1}{E_0}\int_0^1 k\phi_k d\left(\frac{k}{E_0-\mu}\right). \quad (4)$$

For high energies ϕ_{rad} is given approximately by ϕ^*_{rad}, where

$$\phi^*_{\text{rad}}=4\overline{\phi}\log(183Z^{-1/3})\,\text{cm}^2. \quad (5)$$

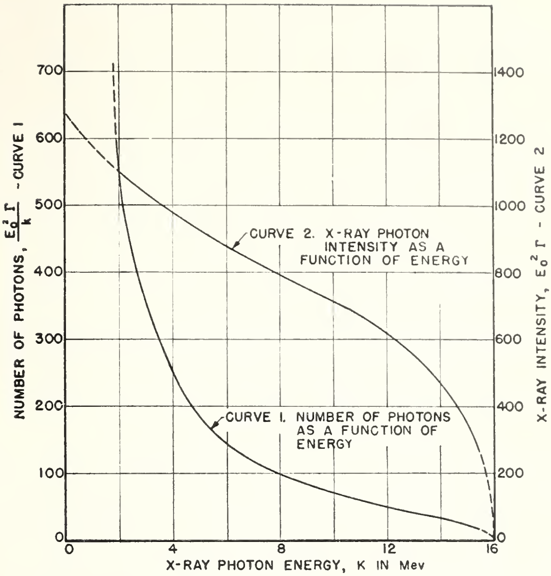


FIGURE 10. *X-ray photon spectrum (curve 1) and intensity spectrum (curve 2) for thin-target X-rays from a 16-Mev betatron.*

Therefore, for convenience, assume at all energies $\phi_{\text{rad}} = K\phi^*_{\text{rad}}$, where K is a correction factor, which is of the order of unity and is very little dependent on Z or E_0, as is shown in table 10. Then

$$-dE_0 = NE_0 K\phi^*_{\text{rad}}\, dx = E_0 K d\,[N\phi^*_{\text{rad}} x] = E_0 K dX, \tag{6}$$

where X is a distance measured conveniently in units of a radiation length, X_0, where

$$X_0 = \frac{1}{N\phi^*_{\text{rad}}} \text{ cm.}$$

Radiation-length units in centimeters can be converted to grams per square centimeter in order to obtain a smooth function of the atomic number. The result, ρX_0, is plotted as a function of the atomic number in figure 11. ρ is the density in grams per cubic centimeter.

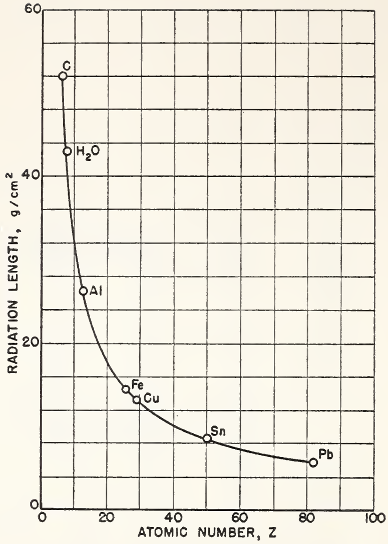


FIGURE 11. *Radiation lengths for various materials in grams per square centimeter as a function of the atomic number.*

These data were taken from W. Heitler, Quantum theory of radiation (Oxford University Press, 2d ed., 1944).

TABLE 10. *Radiation probability correction factor, K* [a]

Medium	Energy (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

[a] J. D. Lawson, Brit. J. Appl. Phys. **3**, 214 (1952); B. Rossi and K. Greisen, Revs. Mod. Phys. **13**, 256 (1941).

The usefulness of the radiation-length unit can be appreciated partially from equation 6, which shows that the fractional energy lost by an electron by radiation per radiation length of target is almost independent of target material and electron energy.

3. *Angular distribution of the X-ray intensity.* Schiff [53] has shown that the angular distribution of the X-rays from an accelerator target is determined by the multiple scattering of the electron beam in the target. Therefore, the energy lost by radiation by electrons will appear as photons emitted with an angular distribution determined by the electron multiple-scattering distribution, $R(\theta,X)$. This can be expressed by rewriting equation 6 as follows:

$$-dE_0 = E_0 K dX = E_0 \int R(\theta,X)\, 2\pi\theta d\theta dX. \tag{7}$$

If one substitutes the appropriate function for $R(\theta,X)$ and integrates from $X=0$ to t, then one obtains

$$-dE_0 = E_0 R(\theta)\, 2\pi\theta d\theta, \tag{8}$$

where $R(\theta)$ is the fractional energy radiated per unit solid angle by electrons throughout the thickness t radiation lengths of the target.

Lawson [54] and Lanzl and Hanson [55] summarize the work that defines $R(\theta)$. A convenient formula, suggested by Muirhead, et al,[56] is

$$R(\theta) = \left[-Ei \left\{ \frac{-(E\theta)^2 \ln(183Z^{-1/3})}{1510.8t} \right\} + Ei \left\{ \frac{-(E\theta)^2}{1.787\mu^2} \right\} \right], \tag{9}$$

where Ei is the exponential integral function.[57] This reduces at $\theta=0$ to the forward intensity, R_0, given by

$$R_0 = \frac{E_0^2 K}{440\pi} \left[\ln \left\{ \frac{1510.8t}{\mu^2} \ln(183Z^{-1/3}) \right\} - 0.577 \right], \tag{10}$$

where E is in Mev, θ is in radians, and t is in radiation lengths (t must be less than 0.1 radiation length to satisfy conditions of calculations).[58]

A plot of $R(\theta)/R_0$ for tungsten ($Z=74$) for three target thicknesses is given in figure 12. These distributions should be comparable to those found experimentally, unless, in practice, a particular accelerator produces X-rays at several operating energies, at parasitic targets, or from multiple electron traversals through the X-ray target.

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[53] L. I. Schiff, Phys. Rev. **70**, 87 (1946).
[54] J. D. Lawson, Phil. Mag. **43**, 306 (1952).
[55] L. H. Lanzl and A. O. Hanson, Phys. Rev. **83**, 959 (1951).
[56] Muirhead, Spicer, and Lichtblau, Proc. Phys. Soc. (London) **65**A, 59 (1952).
[57] Exponential integral functions Ei are tabulated in National Bureau of Standards Tables of Sine, Cosine, and Exponential Integrals, vols. 1 and 2 (MT5 and MT6, Government Printing Office, Washington 25, D. C.).
[58] See footnote 55.

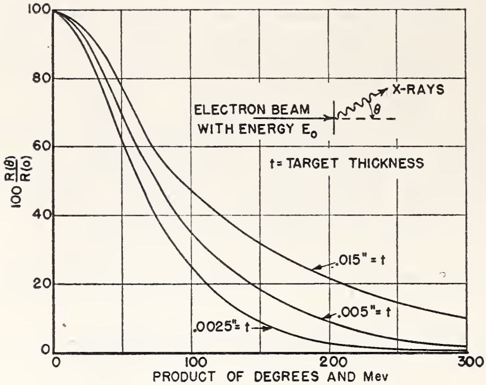

FIGURE 12. *Angular distribution for betatron target radiation (tungsten target).*

Ratio of the X-radiation intensity at the angle θ to the intensity at $\theta=0$ for three thicknesses of the target. The abscissa scale supplies the angle θ after the value of Mev-degree has been divided by the kinetic energy of the electrons striking the X-ray target.

Appendix H. Neutron Production Data

TABLE 11. *Common photoneutron threshold energies and data regarding the resulting radioactivities* [a]

Elements	Threshold	Half-life	Electron (−) or positron (+) energy
	Mev		*Mev*
Carbon, C^{12}	18.7	[b] 20.5 m	+0.99
Nitrogen, N^{14}	10.7	10.1 m	+1.24
Oxygen, O^{16}	15.6	118 s	+1.68
Magnesium, Mg^{24}	16.2	11.95 s	+2.82
Aluminum, Al^{27}	14.4	6.3 s	+2.80
Silicon, Si^{28}	16.8	4.9 s	+3.50
Phosphorus, P^{31}	12.3	2.18 m	+3.50
Sulfur, S^{32}	14.8	3.18 s	+3.87
Potassium, K^{39}	13.2	7.5 m	+2.53
Calcium, Ca^{40}	15.9	1.0 s	+
Iron, Fe^{54}	13.8	8.9 m	+
Copper, Cu^{63}	10.9	9.9 m	+2.83
Copper, Cu^{65}	10.2	12.8 h	+
Zinc, Zn^{70}	9.2	52.0 m	−0.86
Bromine, Br^{79}	10.7	6.4 m	+2.30
Bromine, Br^{81}	10.2	18.5 m	−2.00
Selenium, Se^{82}	9.8	17.0 m	−1.50
Zirconium, Zr^{90}	11.9	80.1 h	+1.07
Silver, Ag^{107}	9.5	24.5 m	+2.04
Antimony, Sb^{121}	9.25	17.0 m	+
Praeseodymium, Pr^{141}	9.4	3.6 m	+2.5
Tantalum, Ta^{181}	7.7	8.0 h	−0.7
Gold, Au^{197}	8.0	5.55 d	−0.3

[a] These data were obtained from National Bureau of Standards Circular 499, Nuclear data (Sept. 1, 1950) and Supplements 1, 2, and 3.
[b] s=seconds, m=minutes, h=hours, d=days.

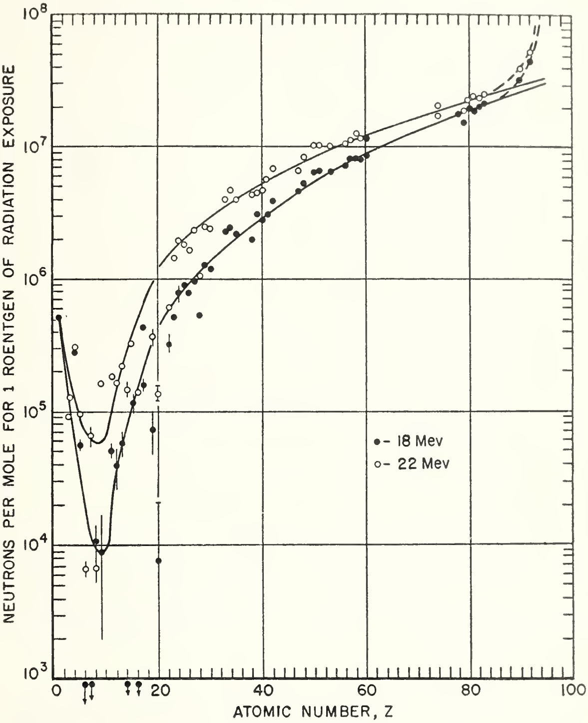

FIGURE 13. *Neutron yields in neutrons per mole for 1 roentgen of primary X-ray beam exposure (measured in a thick-walled Victoreen ionization chamber).*

The neutron yields are plotted as a function of the atomic number of the irradiated material. The data is from G. A. Price and D. W. Kerst, Phys. Rev. **77,** 806 (1950). Similar measurements using 50-Mev X-rays are reported by G. C. Baldwin and F. R. Elder, Phys. Rev. **78,** 76 (1950).

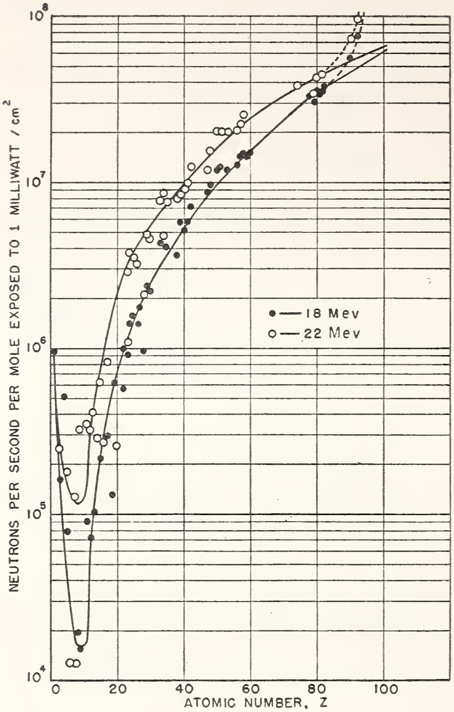

FIGURE 14. *Neutron yields in neutrons per second per mole for 1 milliwatt per square centimeter of primary beam intensity.*

The neutron yields are plotted as a function of the atomic number of the irradiated material and were derived from data of G. A. Price and D. W. Kerst, Phys. Rev. **77,** 806 (1950).

Appendix I. Concrete Attenuation Data

The thickness requirements for concrete protective barriers can be computed for the X-rays from an accelerator operating in the range from 5 to 100 Mev. These requirements are deduced from ionization measurements that have been made behind various thicknesses of concrete placed in the primary X-ray beam from the 50-Mev betatron at the National Bureau of Standards.

The information necessary to compute barrier thicknesses on the axis of the accelerator X-ray beam is the maximum X-ray beam intensity at 1 m from the X-ray target (in watts per square centimeter), the accelerator operating energy, and the target-to-occupied-space distance. The procedure is then as follows:

(1) The X-ray beam intensity at the occupied space can be computed from the intensity at 1 m from the target, assuming the inverse-square-law decrease of intensity with distance and assuming no intervening barrier.

(2) The X-ray intensity at the occupied space and the accelerator operating energy define the maximum dose rate (in ergs per gram per minute) that a person would receive in the X-ray beam intensity in question. The maximum dose rate can be obtained from figure 16, which supplies the ergs/g/min for 1 watt/cm^2 of X-ray intensity as a function of concrete thickness and accelerator operating energy. By defining in this manner the maximum dose rate, one can compute the maximum dose a person would receive during a 40-hr week behind the barrier and at the position in question.

The maximum dose rate as obtained above can also be compared with the maximum permissible dose rate.[59] The maximum permissible dose for 1 week is 30 ergs/g. If one assumes a 40-hr week and an X-ray-intensity constant in time, then the maximum permissible dose rate is approximately 0.0125 erg/g/min. The concrete-barrier thickness that reduces the dose rate to this maximum permissible level can be deduced directly from figure 16. The required concrete thicknesses obtained in this manner are given in table 12.

TABLE 12. *Concrete-barrier requirements*

Distance from target to occupied space	Assumed X-ray intensity at 3 ft from X-ray target	Required concrete barrier thickness			
		6 Mev	10 Mev	20 Mev	30 to 38 Mev
ft	*Milliwatts/cm²*	*in.*	*in.*	*in.*	*in.*
12.5	0.5	61	68	81	82
	2.0	------	79	91	92
	10.0	------	------	------	------
25	0.5	52	59	69	70
	2.0	61	68	81	82
	10.0	------	------	92	93
50	0.5	44	50	58	59
	2.0	52	59	69	70
	10.0	62	68	82	83
100	0.5	36	41	48	49
	2.0	44	50	58	59
	10.0	53	60	70	71
200	0.5	28	31	37	38
	2.0	36	41	48	49
	10.0	45	51	60	61
400	0.5	20	22	26	26
	2.0	28	31	37	38
	10.0	37	42	49	50

[59] See section 1.29.

The following comments might be helpful to those interested in more of the conclusions obtainable from the data of figures 15 and 16:

(1) The data should be applicable for any practical target-to-barrier distance.

(2) Narrow-beam attenuation calculations in the energy range up to 100 Mev indicate that the character of the curves does not change much between 30 and 100 Mev. Therefore, the 30- and 38-Mev curves in figures 15 and 16 can be used as approximately correct up to 100 Mev.

(3) The data were originally obtained as ratios of ionization-chamber readings behind the barrier to those in a Lucite

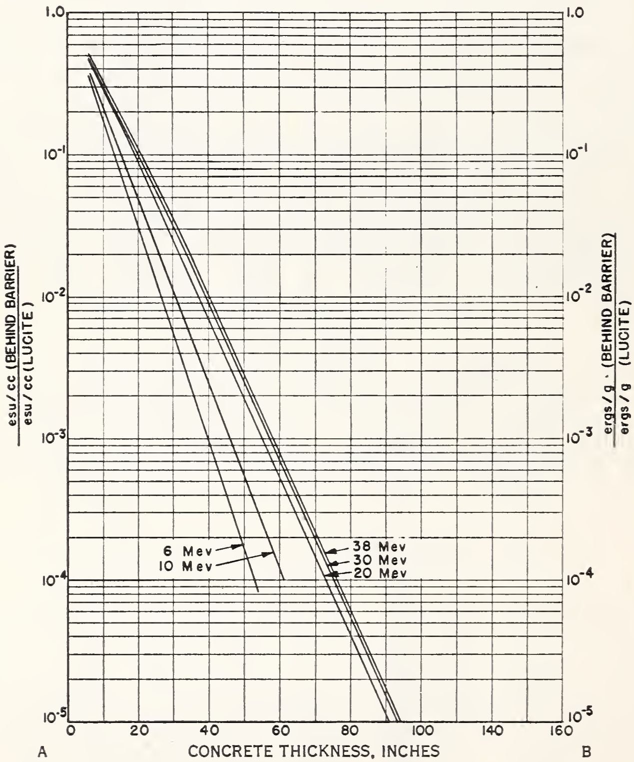

FIGURE 15. *Attenuation in concrete at betatron energies of 6, 10, 20, 30, 38 Mev.*

Density of concrete, 147 lb/ft³. Scale A: The esu/cm³ detected in an ionization chamber behind various thicknesses of concrete, per esu/cm³ detected in a thimble chamber imbedded in an 11.5-cm Lucite cube at the same position without barrier, is plotted for various betatron energies. Scale B: The ratio of maximum tissue dose received with and without a concrete barrier calculated from scale A assuming the same conversion of 93 ergs/g for 1 esu/cm³. These data are taken from results to be published by F. Kirn and R. Kennedy of the National Bureau of Standards.

cube in the direct beam. These data are provided in scale A of figure 15.

(4) The ionization behind the barrier was converted to an approximate dose value by the factor 93 ergs/g per 1 esu/cm^3 of ionization, or 0.93 rad per 1 esu/cm^3. These conversion factors are only approximately correct; they were used to obtain the numerator of the ordinate scale B values of figure 16.

(5) The ionization in a 25-r thimble chamber placed in the center of an 11.5-cm cube of Lucite in front of the concrete barrier defines the primary X-ray beam intensity that is incident on the concrete barrier. This ionization reading

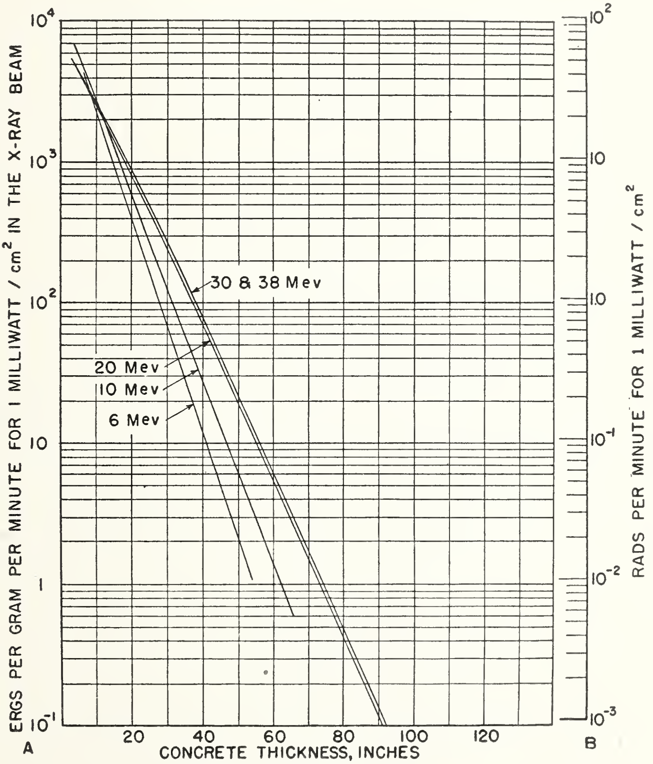

FIGURE 16. *Attenuation in concrete at betatron energies of 6, 10, 20, 30, 38 Mev.*

Density of concrete, 147 lb/ft^3. Scale A: The absorbed ergs/g/min behind various thicknesses of concrete for a beam intensity of 1 milliwatt/cm^2 at the same position is plotted for various betatron energies. The energy absorbed is calculated from data of figure 15, assuming 93 ergs/g for 1 esu/cm^3. Scale B: The dose received in rads for the same conditions as scale A.

was converted to dose in the middle of an 11.5-cm cube of Lucite by the factor of 93 ergs/g per esu/cm^3. Also, it can be converted to primary X-ray intensity units of watts per square centimeter by the factor shown in figure 6. These factors were used to obtain the denominator of the ordinate scale values of figures 15 and 16.

Submitted for the National Committee on Radiation Protection.

Lauriston S. Taylor, *Chairman.*

Washington, July 10, 1953.

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