SAFETY STANDARD FOR NON-MEDICAL X-RAY AND SEALED GAMMA-RAY SOURCES

Part I. General

Handbook 93

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Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

Safety Standard For Non-Medical X-Ray and Sealed Gamma-Ray Sources

Part I. General

By

Subcommittee 1, General Provisions and Methods and Materials Protection, of the ASA Z54 Sectional Committee

Under the Sponsorship of the National Bureau of Standards

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Notice

THE FOLLOWING CORRECTIONS HAVE BEEN MADE IN THIS REPRINTING

Page 26, Figure 5 has been completely replaced with a new figure. The legend remains the same.

Page 27, Figure 6a has been completely replaced with a new figure. The legend remains the same.

Page 43, Footnote "d" has been added to the table.

Page 44, Footnote "e" has been added to the table.

Page 52, Figure 19 has been completely replaced with a new figure. A new paragraph has been added to the legend.

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Foreword

X-ray and sealed gamma-ray sources are used extensively in industry for the inspection, testing, and analysis of a wide variety of objects and materials. X radiation is also emitted as an unwanted by-product from devices such as electron tubes operating at potentials as low as 10 kv. It is therefore essential that adequate measures be taken to protect persons who work with or are near such radiation sources, as well as the general public, against excessive exposure to the radiation.

The present Handbook provides recommended safety standards developed for this field by Sectional Committee Z54, "Industrial Use of X-Rays and Radiation," of the American Standards Association, under the sponsorship of the National Bureau of Standards. Its text has been approved by ASA as an American Standard. In 1946 the Committee issued American War Standard Z54.1, "Safety Code for the Industrial Use of X-Rays." The present Handbook is a revision of a part of this standard.

The National Bureau of Standards is authorized by the Congress to cooperate with other governmental agencies and private organizations in the establishment of standard practices. The work of ASA Sectional Committee Z54 is an outstanding example of such cooperation. The Bureau is pleased to have the continuing opportunity to increase the usefulness of NBS-sponsored American Standards by publishing them as NBS Handbooks.

This Handbook presents basic protection recommendations pertaining to x- and sealed gamma-ray sources for nonmedical applications. Subsequent publications of other subcommittees will present recommendations relating to specific types of x- and gamma-ray sources or to special problems. Their recommendations will supplement these basic recommendations to achieve the same standard of protection, through special means, for the particular types or uses of sources.

A. V. Astin, *Director*.

Preface

Standards for maximum permissible exposure to ionizing radiation are established by the National Committee on Radiation Protection and Measurement, and by the International Commission on Radiological Protection. The American Standards Association Z54 Sectional Committee utilizes these basic standards and other appropriate data applicable to non-medical radiation protection problems in the formulation of safety standards. Such data include the recommendations of the Federal Radiation Council for the guidance of Federal Agencies as approved by the President.

The scope and membership of the Z54 Sectional Committee at the time of the action taken on this Standard were as follows:

Scope:

Safety standards for the manufacture, installation, operation, use, and maintenance of industrial equipment which may give off radiations from radioactive materials or x-rays.

Membership:

Chairman, Scott W. Smith, National Bureau of Standards
Secretary, Henry G. Lamb, American Standards Association

American College of Radiology	G. C. Henny, R. H. Morgan, F. O. Coe,* R. R. Newell.*
American Conference of Government Industrial Hygienists	D. E. VanFarowe, D. A. Holaday.*
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Electronic Industries Association	J. T. Brothers, N. Anton.*
Health Physics Society	H. Mermagen.

Industrial Medical Association	F. Borrelli.
International Association of Government Labor Officials	M. Kleinfeld, O. Kooyman.*
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Joint Electron Device Engineering Council	C. Y. Bartholomew.
National Association of Mutual Casualty Companies	C. R. Williams, W. E. Shoemaker.*
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National Safety Council	H. W. Speicher, J. T. Siedlecki.*
Radiological Society of North America	H. W. Jacox.
Society for Non-Destructive Testing	A. F. Cota.
Underwriters' Laboratories, Inc	L. H. Horn, G. E. Schall.*
U.S. Atomic Energy Commission	W. D. Claus.
U.S. Department of Labor, Bureau of Labor Standards	J. P O'Neill.
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U.S. Department of the Navy, Bureau of Naval Weapons	E. L. Criscuolo, J. C. Johnston.*
U.S. Department of the Navy, Bureau of Ships, Code 708C	C. L. Frear.
U.S. Public Health Service	H. E. Ayer.
Members-at-large	C. B. Braestrup, G. Ferlazzo.

Nine working subcommittees have been established. The reports of the subcommittees are approved by the main committee before publication. The subcommittees are as follows:

1. General Provisions and Methods and Materials of Protection
2. Health Provisions and Monitoring
3. X-ray Protection for 2,000-kv Installations and Lower
4. X-ray Protection for Installations Above 2,000 kv
5. Gamma-Ray Sources for Industrial Applications
6. Electrical and Fire Protection
7. X-ray Diffraction, Fluorescence Analysis and Microradiography
8. Sealed Beta-Ray Sources
9. Contamination Levels of Industrial Materials

The present Handbook was prepared by the Subcommittee 1, General Provisions and Methods and Materials of Protection. Its membership is as follows: C. B. Braestrup, Chairman; C. E. Coner, R. H. Duguid, and the chairmen of the other subcommittees.

The classification of installations as Exempt, Enclosed, and Open Protective Installations is made in recognition of the fact that some installations may economically be made independent of limitations on operating procedures, while the use, size, and arrangement of others place a practical

*Alternate.

limit on the amount of built-in protection that can be provided economically. The classification is an indication of the degree of personnel control required to achieve protection.

Many of the shielding data of this Handbook have been taken from National Bureau of Standards Handbook 73, Protection Against Radiations From Sealed Gamma Sources, and Handbook 76, Medical X-Ray Protection Up to Three Million Volts. This Handbook has also drawn freely from other sources such as *Radiation Protection* by C. B. Braestrup and H. O. Wyckoff (Chas. C Thomas, Publisher) and *Manual of Industrial Radiation Protection Part II, Model Code of Safety Regulations* (International Labour Office, Geneva 1959).

Scott W. Smith, *Chairman*,
ASA Z54 Sectional Committee.

Contents

Safety Standard for the Non-Medical Use of X-Ray and Sealed Gamma-Ray Sources

1. Scope

1.1. This Handbook is intended to serve as a guide toward the safe use of x-ray and sealed gamma-ray sources for non-medical purposes and of equipment emitting x rays serving no useful purpose. Its main objectives are to reduce needless exposure of persons to radiation and to ensure that no one receives more than the maximum permissible dose. These objectives are achieved by the use of appropriate equipment, ample structural shielding and most important, safe operating procedures.

1.2. Those recommendations containing the word "shall" identify requirements that are necessary to meet the standards of protection of this Handbook. Those using the word "should" indicate advisory recommendations that should be applied when practicable.

2. Classification of Protective Installations

Basically any installation which is so constructed and operated as to meet the Maximum Permissible Dose Equivalent requirements is acceptable. However, if this were the only requisite, the assumptions as to the use of the equipment and degree of occupancy might be subject to widely divergent interpretations. In order to ensure certain minimum standards of protection without needless expenditures, it has been found advisable to divide installations into different classes. Their basic requirements are given below. (See paragraph 3 for selection of class, 6.6 for specific tests, and 7 for operating limitations.)

2.1. **Exempt Protective Installation.** An installation shall be so classified when it conforms with all of the following requirements:

2.1.1. The source and all objects exposed thereto are within a permanent enclosure, within which no person is permitted to remain during irradiation.

2.1.2. Reliable interlocks are provided to prevent access to the enclosure during irradiation (see 5.5.2).

2.1.3. If the enclosure is of such a size or is so arranged that the operator cannot readily determine whether the enclosure is unoccupied, there shall be provided:

2.1.3.1. Audible or visible warning signals within the enclosure which must be actuated before irradiation can be started.

2.1.3.2. Suitable means of exit, so that any person who accidentally may be shut in can leave the enclosure without delay, or

2.1.3.3. Effective means within the enclosure for preventing or quickly interrupting the irradiation, and which cannot be reset from outside the enclosure.

2.1.4. The exposure at any accessible region 2 in. (5 cm) from the outside surface of the enclosure cannot exceed 0.5 mR in any one hour. (The distance 2 in. is chosen as being the minimum *practical* distance from the barrier at which the exposure may be measured. The limit of 0.5 mR in one hour assures with reasonable probability that under practical conditions of occupancy and use, the requirements of paragraph 2.1.5 would be met.)

2.1.5. No person, either within the controlled area or in the environs of the installation, is exposed to more than the maximum permissible dose equivalent.

2.2. **Enclosed Protective Installation.** An installation shall be so classified when it conforms with all the following requirements:

2.2.1. The source and all objects exposed thereto are within a permanent enclosure, within which no person is permitted to remain during irradiation.

2.2.2. Reliable interlocks are provided to prevent access to the enclosure during irradiation (see 5.5.2).

2.2.3. If the enclosure is of such a size or is so arranged that the operator cannot readily determine whether the enclosure is unoccupied, there shall be provided:

2.2.3.1. Audible or visible warning signals within the enclosure which must be actuated before irradiation can be started.

2.2.3.2. Suitable means of exit, so that any person who accidentally may be shut in can leave the enclosure without delay, or

2.2.3.3. Effective means within the enclosure for preventing or quickly interrupting the irradiation, and which cannot be reset from outside the enclosure.

2.2.4. The exposure at any accessible and occupied region 1 ft (30 cm) from the outside surface of the enclosure does not exceed 10 mR in any one hour. For x-ray installations, this exposure limitation shall be met for any of the specified ratings of the x-ray tube.

2.2.5. The exposure at any accessible and normally unoccupied region 1 ft (30 cm) from the outside surface of the enclosure does not exceed 100 mR in any one hour. For x-ray installations, this exposure limitation shall be met for any of the specified ratings of the x-ray tube. (The distance 1 ft is chosen as being a practical distance from the barrier for making measurements. The use of 100 mR in one hour assumes reasonable probability that, under practical conditions of occupancy and use, paragraph 2.2.6 can be met. It may be assumed also that the radiation source and beam direction are positioned and oriented only to serve a useful purpose.)

2.2.6. No person, either within the controlled area or in the environs of the installation, is exposed to more than the maximum permissible dose equivalent.

2.3. **Open Protective Installations.** An Open Protective Installation is one which, due to operational requirements, cannot be provided with the inherent degree of protection specified for either Exempt or Enclosed Protective Installations. An installation shall be so classified when it conforms with all of the following requirements or the special protection requirements established for non-radiographic applications (see 3.3):

2.3.1. The source and all objects exposed thereto are within a conspicuously posted perimeter that limits the area in which the exposure can exceed 100 mR in any 1 hour.

2.3.2. No person has access to the area within the perimeter nor may remain in the area during irradiation. Positive means for preventing access, such as locked barriers shall be provided, particularly during periods of unattended irradiation.

2.3.3. No person, either within a controlled area or in the environs of the installation, is exposed to more than the maximum permissible dose equivalent.

2.3.4. A knowledgeable person is in attendance or the equipment is made inaccessible.

3. Selection of Class of Protective Installation

New radiation facilities shall be constructed to meet the requirements of one of the three classes of protective installations described in section 2. The classes differ in their relative dependence on inherent shielding, operating restrictions, and supervision to secure the required degree of protection.

Each class has certain advantages and limitations; these are indicated in sections 3.1, 3.2, and 3.3.

3.1. **Exempt Protective Installation.** This class provides the highest degree of inherent safety because the protection does not depend on compliance with any operating limitations. This type also has the advantage of not requiring restrictions in occupancy outside the enclosure; the built-in shielding is generally sufficient to meet the maximum permissible dose requirements for the environs.

However, the low allowable exposure level (0.5 mR in 1 hour) for this class of installation necessitates a higher degree of inherent shielding. For radiation sources of lower energies, and for smaller enclosures, such as cabinets, the initial extra cost of the increased shielding is usually insignificant compared with the operational advantages.

At higher energies, as in the megavolt region with high workloads, the required additional shielding will usually make the use of this class extremely expensive compared with the Enclosed Protective Installation. For instance, in the case of cobalt 60, the required concrete thickness of the primary barrier for the *Exempt* type may have to be about a foot greater than for the *Enclosed* type.

3.2. **Enclosed Protective Installations.** This class usually offers the greatest advantages for fixed installations with low use and occupancy factors. This is particularly true for high-energy sources where the reduction in shielding may result in significant savings. The shielding requirements are considerably lower than for the Exempt Protective Installation, as much as 4.3 HVL less, yet, the inherent protection is such that the possibility of significant overexposure is remote. With proper supervision, this class offers a degree of protection similar to the Exempt Installation.

3.3. **Open Protective Installations.** This class shall be selected only if operational requirements prevent the use of either of the other classes. For radiography, its use should be limited mainly to mobile and portable equipment where fixed shielding cannot be used. Fluoroscopy shall be done only by remote observation, such as by closed circuit television.

The operational requirements of other types of installations may necessitate use of this class. In this group may be such applications as process control, thickness and level gages, experimental diffraction apparatus, etc. The special

protection requirements for such installations will be included in pending reports of other subcommittees.

The protection of personnel and the public depends almost entirely on strict adherence to safe operating procedures. With this adherence, Open Protective Installations may provide a degree of protection similar to the other classes.

4. Plans for Radiation Installations

4.1. **Review by Qualified Expert.** The structural shielding requirements of any new installation, or of an existing one in which changes are contemplated, should be reviewed by a qualified expert early in the planning stage.

4.2. **Information to be Supplied to Expert.** The expert should be provided with available data concerning the type, the kilovoltage or energy, milliamperage or output in Rhm, the contemplated use of the source, the expected workload, and use factors, the structural details of the building and the type of occupancy of all areas which might be affected by the installation.

Data for the determination of protective barrier thicknesses may be found in the appendices of this Handbook. See section 5 for structural details.

4.3. **Approval of Plans by Expert.** Final shielding plans, and all pertinent specifications should be approved by the expert before construction begins.

4.4. **Effect of Distance on Shielding Requirements.** Shielding requirements generally may be reduced by locating the installation at a distance from occupied areas. (See tables 7, 9, and 10 in appendices D and E for minimum safe distances.)

4.5. **Direction of Useful Beam.** The cost of shielding may be reduced significantly by arranging the installation so that the useful beam is directed toward occupied areas as little as possible. (There is, of course, no objection to directing the useful beam at occupied areas provided there is adequate protection.)

4.6. **Cross Section of Beam.** Devices which permanently restrict the direction and cross section of the useful beam may reduce the area requiring primary barriers.

4.7. **Multiple Sources of Radiation.** Where persons are likely to be exposed to radiation from more than one source simultaneously, or at different times, the protection associated with each source shall be increased so that the total dose received by any one person from all sources shall not exceed the maximum permissible dose.

4.8. **Radiation Energy, Output, and Workload.** The shielding for each occupied area should be determined on the basis of the expected maximum kilovoltage, or energy, ma or Rhm, workload, use factor, and occupancy factor affecting it. Consideration should be given to the possibility that these may increase in the future. It may be more economical to provide a higher degree of protection initially than to add to it later.

4.9. **Shielding for Films and Low-Level Counting Rooms.** Attention should be given to the shielding of areas used for the storage of undeveloped films and of rooms for measuring low-activity radioactive materials. (Undeveloped fast x-ray film may be damaged by exposures totaling somewhat less than 1 mR, depending upon film type and radiation energy. See table 11. As the shielding requirement for film may be appreciably greater than for personnel, it is usually more economical to store the film in a lead protective enclosure than to place all of the lead in the room barriers.)

5. Structural Details of Protective Barriers

Any material will provide the required degree of shielding, if of sufficient thickness. At lower radiation energies, materials of high atomic number provide the attenuation with the least barrier weight.

5.1. **Quality of Protective Material.** All shielding materials shall be of assured quality, uniformity and permanency.

5.2. **Lead Barriers.**

5.2.1. Lead barriers shall be mounted in such a manner that they will not cold-flow because of their own weight and shall be protected against mechanical damage.

5.2.2. Lead sheets at joints should be in contact with a lap of at least one-half inch or twice the thickness of the sheet, whichever is the greater.

5.2.3. Welded or burned lead seams are permissible, provided the lead equivalent of the seams is not less than the minimum requirement.

5.3. **Joints Between Different Materials or Structures.**

5.3.1. Joints between different kinds of protective materials shall be constructed so that the overall protection of the barrier is not impaired.

5.3.2. Joints at the floor and ceiling shall be constructed so that the overall protection is not impaired. (See figs. 1 and 2 for examples.)

5.4. **Shielding of Openings in Protective Barriers.** In the planning of an installation, careful consideration should be

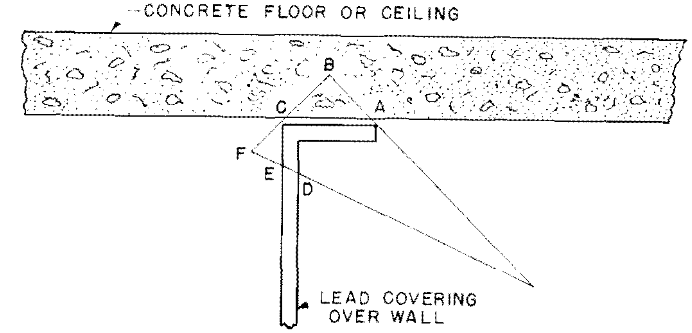

Figure 1. *Example of a wall joint.*

The sum of radiations through all paths *ABCF* and *DEF* to the point *F* shall be not more than the maximum permissible exposure. The framework supporting the lead wall is here considered to be of relatively x-ray transparent material.

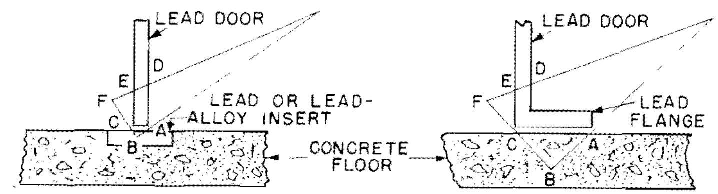

Figure 2. *Example of door baffle.*

The sum of radiations through all paths *ABCF* and *DEF* to the point *F* shall not be more than the maximum permissible exposure. The supporting structure for the lead door is here considered to be a framework of relatively x-ray transparent material.

given to reducing the number and size of all perforations of protective barriers and openings into protected areas. Protection for all such openings shall be provided by means of suitable protective baffles.

5.4.1. **Perforations.** Provision should be made to ensure that nails, rivets, or screws which perforate lead barriers shall be covered to give protection equivalent to that of the unperforated barrier.

5.4.2. **Openings for Pipes, Ducts, Conduits, Louvers, etc.** Holes in barriers for pipes, ducts, conduits, louvers, etc., shall be provided with baffles to insure that the overall protection afforded by the barrier is not impaired. These holes should be located outside the range of possible orientations of the useful beam.

5.4.3. **Doors and Observation Windows.** The lead equivalent of doors and observation windows of exposure rooms, cubicles, and cabinets shall not be less than that required for the walls or barrier in which they are located.

5.5. **General Protection Requirements for Doors into Protected Areas.**

5.5.1. **Location of Doors.** Where practical, doors into exposure rooms should be so located, that the operator has control of access to the room.

5.5.2. **Interlock Switches for Doors.** All doors and panels opening into an exposure room or cabinet (except those which can be opened or removed only with tools) shall be provided with interlocking switches preventing irradiation unless the door or panel is closed.

5.5.3. **Resumption of Operation.** If the operation of any radiation source has been interrupted by the opening of a door or panel to a Protective Installation, it shall not be possible to resume operation by merely closing the door or panel in question. To resume operation, it shall be necessary, in addition, to reset manually a suitable device located near the operator's station.

5.5.4. **Escape, or Interruption of Irradiation, from Inside Exposure Room.** Whenever practicable, the exposure room shall include at least one door which may be opened from the inside. When such a door is not included, suitable means shall be provided to quickly interrupt irradiation from inside the room. The means of accomplishing this shall be explained to all personnel and a sign explaining its use shall be conspicuously posted inside the exposure room. Preferably, the beam should not be directed toward the door or interrupting means.

5.5.5. **Threshold Baffle for Door Sill.** A door baffle or threshold may be required for installations operating above 125 kvp, if the discontinuity can be struck by the useful beam. (See figure 2 for example that fulfills the baffle requirement.)

5.5.6. **Lap of Door Jamb.** The protective lead covering of any door leading to an exposure room or cabinet shall overlap that of the door jamb and lintel so as to reduce the radiation passing through clearance spaces to the allowable limit for the door itself.

6. Radiation Protection Surveys and Inspections

6.1. **Survey of New Installations.** Before a new installation is placed in routine operation a radiation protection survey shall be made by a qualified expert.

6.2. **Changes in Existing Installations.** A radiation protection resurvey or reevaluation by a qualified expert shall be made when changes have been made in shielding, operation, equipment or occupancy of adjacent areas, and these changes may have adversely affected radiation protection. A qualified expert should be consulted in case of doubt.

6.3. **Report of Radiation Protection Survey.** No existing installation shall be assumed to conform with the provisions of this standard unless a radiation protection survey has been made by a qualified expert and a report of the survey has been placed on file at the installation.

6.4. **Elimination of Hazards.** The radiation hazards that may be found in the course of a survey shall be eliminated before the installation is used routinely.

6.5. **Retention of Survey Reports.** Reports of all radiation protection surveys shall be retained together with a record of the action taken with respect to the recommendations they contain.

6.6. **Radiation Protection Survey Procedures.** A radiation protection survey shall include the following procedures:

6.6.1. **Installation Inspection.** The installation shall be inspected to verify or determine the present and expected occupancy of the adjacent areas; the operation of audible or visible warning signals, interlocks, mechanical or electrical restrictions of the positioning of the radiation source, delay switches and other devices that have a bearing on radiation protection.

6.6.2. **Radiation Measurements.** Radiation exposure shall be measured in all adjacent areas that can be occupied. The measurements shall be made under practical conditions of operation that will result in the greatest exposure at the point of interest. X-ray apparatus should be operated at the maximum kilovoltage and at its maximum milliamperage for continuous operation at that voltage.

6.6.3. **Personnel Monitoring.** The adequacy of the personnel monitoring procedures shall be determined for Enclosed and Open Protective Installations. (Personnel monitoring is not required for Exempt Protective Installations but may be desirable where persons have to enter the radiation enclosure.)

6.6.4. **Contents of Radiation Protection Survey Report.** A report of a radiation protection survey shall include:

6.6.4.1. Identification of the radiation source and installation by suitable means, e.g., serial number, room number, and building number or name.

6.6.4.2. The identity and Rhm of a gamma source, and the potential and current at which an x-ray tube was operated during the test.

6.6.4.3. The location of the source and the orientation of the useful beam with relation to each exposure measurement.

6.6.4.4. Exposure rates in all adjacent occupied areas. The locations of the measurements shall be suitably identified, if necessary, by appropriate drawings.

6.6.4.5. A description of the existing mechanical and electrical limiting devices that restrict the orientation of the useful beam and the position of the source.

6.6.4.6. A statement indicating the appropriate classification of the installation.

6.6.4.7. A statement of the restrictions, if any, that shall be placed on the weekly workload, degree of occupancy and the time that the useful beam may be directed at any barrier.

6.6.4.8. If an installation is found not to comply with this standard, it shall be stated what action must be taken to ensure compliance; if a resurvey will be required, it should be so stated.

6.6.5. **Inspections.** All radiation shields, interlocking switches and other safety devices shall be inspected periodically as scheduled by the radiation supervisor. (See par. 7.2.)

6.6.5.1. Inspection shall be made by a competent person but not necessarily by a qualified expert.

6.6.5.2. Defective shields and barriers shall be promptly repaired and the inspection shall be repeated to determine whether the original degree of protection has been restored. If there is doubt about the adequacy of the repair, a qualified expert shall be consulted.

6.6.5.3. Inspection of protective devices is not a substitute for a radiation protection survey.

7. Operating Procedures

7.1. **Restrictions According to Classification.**

7.1.1. **Exempt Protective Installations.** No restrictions shall be imposed on the mode of operation of the equipment.

7.1.2. **Enclosed Protective Installations.**

7.1.2.1. Since the safe operation of an Enclosed Protective Installation is based on the normal operating conditions specified in the applicable radiation protection survey report, the equipment shall be operated only within the indicated limits.

7.1.2.2. When the operating conditions have changed so that there is a probability that the exposure of any person may be increased, a radiation protection resurvey or evaluation shall be conducted. In case of doubt, a qualified expert should be consulted.

7.2. **Control of Personnel.** The employer or his representative shall designate a competent employee as the Radiation Protection Supervisor. This employee shall be qualified by training or experience to carry out his duties as indicated below:

7.2.1. Insuring that all Enclosed and Open Protective Installations are operated within the limitations of the appropriate radiation protection survey reports.

7.2.2. The instruction of personnel in safe working practices and the nature of injuries resulting from overexposure to radiation.

7.2.3. Investigating any case of abnormal exposure to personnel to determine the cause and to take remedial action.

7.2.4. Assuring that interlock switches, warning signals and signs are functioning and located where required.

7.3. **Radiation Safety Instructions.** Radiation safety instructions should be posted and furnished to each radiation worker in writing.

7.4. **Personnel Monitoring**

7.4.1. Personnel monitoring shall be required for all workers involved in the use of radiation apparatus in Open and Enclosed Protective Installations.

7.4.2. Personnel monitoring shall be required for each individual for whom there is a reasonable probability of receiving a radiation dose in any one calendar quarter in excess of 25 percent of the applicable MPDE per calendar quarter. (See table 1, appendix B.) This limit does not include medical exposures.

7.4.3. A qualified expert should be consulted on the establishment of personnel monitoring systems.

Appendix A. Definitions

Terms in this standard will be used in accordance with the following brief definitions:

Shall denotes that the ensuing recommendation is necessary or essential to meet the currently accepted standards of protection.

Should, is recommended, indicates advisory recommendations that are to be applied when practicable.

Absorbed dose. Energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. The unit of absorbed dose is the *rad*. (When the meaning is clear, this term may be shortened to *dose*.)

Activity. The number of atoms decaying per unit of time.

Attenuation. Decrease in exposure rate caused by the passage of radiation through material.

Barrier. (See *protective barrier*.)

Concrete equivalent. The thickness of concrete of density 2.35 g/cc (147 lb/ft^3) affording the same attenuation, under specified conditions, as the material in question.

Contamination (radioactive). Deposition of radioactive material in any place where it is not desired, and particularly in any place where its presence can be harmful. The harm may be in vitiating the validity of an experiment or a procedure, or in actually being a source of danger to persons.

Controlled area. A defined area in which the occupational exposure of personnel to radiation or to radioactive material is under the supervision of an individual in charge of radiation protection. (This implies that a controlled area is one that requires control of access, occupancy, and working conditions for radiation protection purposes.)

Curiage. The number of curies (kilocuries, millicuries, microcuries).

Curie (c). A unit of activity defined as the activity of a quantity of any radioactive nuclide in which the number of disintegrations per second is 3.700×10^{10}.

Dose. See *absorbed dose* and *dose equivalent*. [28].

Dose equivalent (DE). Dose equivalent is the product of absorbed dose D, quality factor (QF), dose distribution factor (DF), and other necessary modifying factors. (DE)=D (QF) (DF) . . .

NOTE: The term RBE dose has been used in the past, in both radiobiology and radiation protection. This term is now reserved for radiobiology only and is replaced by Dose Equivalent (DE) for radiation protection.

Quality Factor (QF). The linear-energy-transfer-dependent factor by which absorbed doses are to be multiplied to obtain for radiation protection purposes, a quantity that expresses on a common scale for all ionizing radiations, the irradiation incurred by exposed persons.

Dose Distribution Factor (DF). The factor used to express the modification of biological effect due to nonuniform distribution of internally deposited isotopes.

Dose rate. Dose per unit time.

Exposure. The exposure of x or gamma radiation at a certain place is a measure of the radiation that is based upon its ability to produce ionization in air. The unit of exposure is the *roentgen*.

Exposure rate. Exposure per unit time.

Exempt protective installation. An x- or gamma-ray installation which conforms with all the requirements of paragraph 2.1. (See *Protective installation*.)

Enclosed protective installation. An x- or gamma-ray installation which conforms with all the requirements of paragraph 2.2. (See *Protective installation*).

Half-value layer (HVL). Thickness of an absorber required to attenuate a beam of radiation to one-half.

Installation. A radiation source, with its associated equipment, and the space in which it is located. (See *Protective installation*; *Exempt protective installation*; *Enclosed protective installation*; *Open protective installation*.)

Interlock. A device for precluding access to an area of radiation hazard either by preventing entry or by automatically removing the hazard.

Lead equivalent. The thickness of lead affording the same attenuation, under specified conditions, as the material in question.

Leakage radiation. (See *Radiation*.)

Maximum permissible dose equivalent (MPDE). The maximum dose equivalent that the body of a person or specific parts thereof shall be permitted to receive in a stated period of time. For the radiations considered here, the dose equivalent in rems may be considered numerically equal to the absorbed dose in rads and the exposure in roentgens numerically equal to the absorbed dose in rads. (See table 1, appendix B.)

Monitoring. Periodic or continuous determination of the exposure rate in an area (area monitoring) or the exposure received by a person (personnel monitoring) or the measurement of contamination levels.

Occupancy factor (T). The factor by which the workload should be multiplied to correct for the degree or type of occupancy of the area in question.

Occupied area. An area that may be occupied by persons.

Open protective installation. An x- or gamma-ray installation which conforms with all the requirements of paragraph 2.3. (See *Protective installation*.)

Protective barrier. Barrier of attenuating material used to reduce radiation hazards.

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

Secondary protective barrier. Barrier sufficient to attenuate stray radiation to the required level.

Protective Source Housing. Enclosure for sealed gamma sources, which limits the leakage radiation to a specified level. It shall conform to the following requirements:

(a) with the shutter closed or the source in the "off" position:

(1) the average exposure rate at 5 cm from the surface shall not exceed 20 mR per hour, and the maximum exposure rate shall not exceed 100 mR per hour;

(2) the average exposure rate at 100 cm from the source shall not exceed 2 mR per hour, and the maximum exposure rate shall not exceed 10 mR per hour;

(b) remote means shall be provided for bringing the source into its exposure and shielded positions.

Protective Tube Housing. The housing which surrounds the x-ray tube itself, or the tube and other parts of the x-ray apparatus (for example, transformer) shall be so constructed that the leakage radiation at a distance of 100 cm from the target cannot exceed 1 roentgen in 1 hr, when the tube is operated at any of its specified ratings.

Qualified expert. A person having the knowledge and training necessary to measure ionizing radiations and to advise regarding radiation protection, for example, persons certified in this field by the American Boards of Radiology, Health Physics, or Industrial Hygiene.

Radiation protection supervisor. Person directly responsible for radiation protection. It is his duty to insure that all procedures are carried out in compliance with pertinent established rules, including recommendations contained in this Handbook.

Radiation protection survey. Evaluation of the radiation hazards in and around an installation. It customarily includes a physical survey of the arrangement and use of the equipment and measurements of the exposure rates under expected operating conditions.

Radiation (ionizing radiation). Electromagnetic radiation (x-ray or gamma-ray photons or quanta), or corpuscular radiation (alpha particles, beta particles, electrons, positrons, protons, neutrons, and heavy particles) capable of producing ions.

(1) **Primary radiation.**

(a) **X rays.** Radiation coming directly from the target of the x-ray tube. Except for the useful beam, the bulk of this radiation is absorbed in the tube housing.

(b) **Beta and gamma rays.** Radiation coming directly from the radioactive source.

(2) **Secondary radiation.** Radiation other than the primary radiation, emitted by irradiated matter.

(3) **Scattered radiation.** Radiation that, during passage through matter, has been deviated in direction and usually has also had its energy diminished.

(4) **Useful beam.** That part of the primary and secondary radiation which passes through the aperture, cone, or other device for collimation.

(5) **Leakage radiation.** All radiation, except the useful beam, coming from the tube or source housing.

(6) **Stray radiation.** Radiation other than the useful beam. It includes leakage radiation and secondary radiation.

Rad. Unit of absorbed dose. 1 rad is 100 ergs/g.

Rem. Unit of dose equivalent (DE).

Rhm. Roentgens per hour at 1 m from the effective center of the source. (This distance is usually measured to the nearest surface of the source as its effective center generally is not known.)

Roentgen (R). Unit of exposure of x- or gamma-radiation. One roentgen is an exposure of x-radiation or gamma-radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 esu of quantity of electricity of either sign.

Sealed source. Radioactive material that is encased in, and is to be used in, a container in a manner intended to prevent leakage of the radioactive material.

Source. Discrete amount of radioactive material or radiation producing equipment.

Scattered radiation. (See *Radiation.*)

Secondary radiation. (See *Radiation.*)

Secondary protective barrier. (See *Protective barrier.*)

Stray radiation. (See *Radiation.*)

Survey. (See *Radiation protection survey.*)

Specific gamma-ray constant (Γ). Specific gamma-ray constant [28] (specific gamma-ray output) of a radioactive nuclide is the exposure rate produced by the unfiltered gamma rays from a point source of a defined quantity of that nuclide at a defined distance. The unit of specific gamma-ray constant is the roentgen per millicurie hour at 1 cm.

Tenth value layer (TVL). Thickness of an absorber required to attenuate a beam of radiation to one-tenth.

Use factor (U). The fraction of the workload during which the useful beam is pointed in the direction under consideration.

Useful beam. (See *Radiation*.)

User. A person, organization, or institution having administrative control over one or more installations or mobile sources.

Workload. A measure in suitable units of the amount of use of radiation equipment. For the purpose of this standard the workload is expressed in milliampere-minutes per week for x-ray sources and roentgens per week at 100 cm from the source for gamma-ray sources.

Appendix B. Maximum Permissible Dose Equivalent Values

TABLE 1. *Maximum permissible dose equivalent values* [d]

[The indicated values are for the limited scope of this standard. See Addendum to H59, April 15, 1958 for more complete information] [24]

	Average weekly dose [a]	Maximum 13-week dose	Maximum yearly dose	Maximum accumulated dose [b]
	rem [c]	*rem* [c]	*rem* [c]	*rem* [c]
Controlled areas—				
Whole body gonads, blood-forming organs, and lens of eye	0.1	3		5(N-18)
Skin of whole body		[e] 10	[e] 30	
Hands and forearms, head, neck, feet, and ankles		25	75	
Environs—				
Any part of body	.01		0.5	

Notes:

N = Age in years and is greater than 18.

[a] For design purposes only.

[b] When the previous occupational exposure history of an individual is not definitely known, it shall be assumed that he has already received the full dose permitted by the formula 5(N-18).

Persons who were exposed in accordance with the former maximum permissible weekly dose of 0.3 rem and who have accumulated a dose higher than that permitted by the formula shall be restricted to a maximum yearly dose of 5 rem.

[c] The dose equivalent in rems may be assumed to be equal to the exposure in roentgens.

[d] Exposure of patients for medical and dental purposes is not included in the maximum permissible dose equivalent.

[e] See Am. J. Roen. 84, 152 (1960). [21]

Appendix C. Occupancy and Use Factors

TABLE 2. *Occupancy factors (T)*

[For use as a guide in planning shielding where adequate occupancy data are not available.]

Full occupancy (*T*=1)
Control space and waiting space, darkrooms, workrooms, shops, offices, and corridors large enough to hold desks, rest and lounge rooms routinely used by occupationally exposed personnel, living quarters, children's play areas, occupied space in adjoining buildings.
Partial occupancy (*T*=1/4)
Corridors too narrow for desks, utility rooms, rest and lounge rooms not used routinely by occupationally exposed personnel, elevators using operators, unattended parking lots.
Occasional occupancy (*T*=1/16)
Closets too small for future occupancy, toilets not used routinely by occupationally exposed personnel, stairways, automatic elevators, outside areas used only for pedestrians or vehicular traffic.

TABLE 3. *Use factors* (U)

[For use as a guide in planning shielding when complete data are not available.]

Installation use	Exempt all uses	Enclosed	
		Collimated sources	Open sources
Floor	1	1	1
Walls	1	1/4	1
Ceiling	1	1/16	1

Appendix D. Determination of Gamma-Ray Protective Barrier Thicknesses

The thickness of protective barrier necessary to reduce the gamma rays from a sealed gamma source to the maximum permissible level depends upon the energy of the radiation, design of the source housing, beam diameter, scattered radiation from irradiated objects, the use factor (fraction of the time during which the radiation is incident on the barrier), distance from the source to occupied areas, degree and nature of occupancy, type of installation, and the material of which the barrier is constructed.

Table 4 gives data on radioactive gamma-ray sources of interest for industrial purposes, including the energy of the gamma rays emitted. Tables 5 through 8 give shielding requirements for several commonly used types of source. Occasionally, conditions are not covered by the tables and it will then be necessary to resort to computation of the barrier requirements by using the transmission curves in various materials, figures 3 through 16.

Table 4. *Gamma-ray sources*

Radioisotope	Atomic number	Half-life	Gamma-ray energy	Specific gamma-ray constant
	Z		*Mev*	*R/curie hr at 1 m* [a]
Cesium 137	55	27y	0.662	0.32
Chromium 51	24	28d	0.323	[c] 0.018
Cobalt 60	27	5.2y	1.17, 1.33	1.3
Gold 198	79	2.7d	0.412	0.23
Iridium 192	77	74d	0.136, 1.065	[c] 0.5
Radium 226	88	1622y	0.047 to 2.4	[b] 0.825
Tantalum 182	73	115d	0.066 to 1.2	[c] 0.6

[a] These values assume that gamma-ray absorption in the source is negligible. Value in R/curie hr at 1 m can be converted to R/millicurie hr at 1 cm by multiplying by 10.
[b] This value assumes that the source is sealed within a 0.50-mm thick platinum capsule.
[c] These values are less certain and in some cases are estimates.

Table 5A. *Cobalt 60 shielding requirements for controlled areas* [a]

WUT [b]	Curies [c] approx.	Distance from source to occupied areas (ft)										
80,000	2000	5	7	10	14	20	28	40				
40,000	1000		5	7	10	14	20	28	40			
20,000	500			5	7	10	14	20	28	40		
10,000	250				5	7	10	14	20	28	40	
5,000						5	7	10	14	20	28	40
2,500							5	7	10	14	20	28
1,250								5	7	10	14	20
625									5	7	10	14
310										5	7	10

Type of barrier	Approx. HVL (cm)	Approx. TVL (cm)	Thickness of lead (cm)										
Primary	1.20	4.0	22.5	21.3	20.1	18.9	17.7	16.5	15.3	14.1	12.9	11.7	10.5
Secondary:													
Leakage [d] 0.1%	1.20	4.0	10.5	9.3	8.2	7.1	6.0	4.7	3.4	2.0	0.6	0	0
0.05%	1.20	4.0	9.3	8.2	7.1	6.0	4.7	3.4	2.0	0.6	0	0	0
Scatter [e] 30°	1.02	3.40	12.15	11.10	10.10	9.05	8.00	7.00	6.00	4.95	3.95	2.95	1.95
45°	0.87	2.90	9.65	8.75	7.90	7.00	6.15	5.25	4.35	3.50	2.65	1.75	0.90
60°	0.75	2.50	7.65	6.90	6.15	5.40	4.65	3.90	3.15	2.4	1.65	0.9	0.25
90°	0.43	1.45	3.60	3.15	2.70	2.30	1.85	1.40	1.00	0.60	0.25	0.03	0
120°	0.20	0.65	1.45	1.25	1.05	0.85	0.65	0.45	0.30	0.15	0.05	0	0
150°	0.14	0.45	0.90	0.75	0.65	0.50	0.10	0.25	0.15	0.08	0.02	0	0

[a] For a weekly design level of 100 mR; add one tenth-value layer (TVL) for regions in the environs to reduce radiation to 10 mR/week.
[b] W=workload in R/week at 1 m, U=use factor, T=occupancy factor.
[c] Assumes use factor (U) and occupancy factor (T) are equal to one.
[d] Refers to leakage radiation of source housing; may be ignored if less than 2.5 mR/hr at 1 m in "on" position.
[e] For large field (20 cm diam) and a source-phantom distance of 40 to 60 cm. This includes scattering from the collimator and from the phantom. (From Braestrup and Wyckoff [1].)

TABLE 5B. *Cobalt 60 sheilding requirements for controlled areas* [a]

WUT [b]	Curies [c] approx.	Distance from source to occupied areas (ft)										
80,000	2000	5	7	10	14	20	28	40				
40,000	1000		5	7	10	14	20	28	40			
20,000	500			5	7	10	14	20	28	40		
10,000	250				5	7	10	14	20	28	40	
5,000						5	7	10	14	20	28	40
2,500							5	7	10	14	20	28
1,250								5	7	10	14	20
625									5	7	10	14
310										5	7	10

Type of barrier	Approx. HVL (in.)	Approx. TVL (in.)	Thickness of concrete (density 147 lb/cu ft) (in.)										
Primary	2.6	8.6	47.5	45.1	42.7	40.3	37.8	35.4	32.9	30.5	28.0	25.6	23.1
Secondary:													
Leakage [d] 0.1%	2.6	8.6	23.1	20.7	18.3	15.6	12.9	10.2	7.3	4.4	1.4	0	0
0.05%	2.6	8.6	20.7	18.3	15.6	12.9	10.2	7.3	4.4	1.4	0	0	0
Scatter [e] 30°	2.5	8.2	30.6	28.1	25.7	23.2	20.6	18.2	15.8	13.3	10.9	8.4	5.9
45°	2.4	8.0	27.0	24.6	22.2	19.8	17.4	15.0	12.6	10.2	7.8	5.4	3.0
60°	2.3	7.6	24.0	21.7	19.4	17.1	14.8	12.3	10.0	7.7	5.4	3.0	0.5
90°	1.8	6.2	16.9	15.0	13.2	11.4	9.6	7.8	6.0	4.1	2.1	0.1	0
120°	1.7	5.8	15.0	13.3	11.6	9.9	8.2	6.5	4.7	3.0	1.2	0	0
150°	1.5	5.0	12.5	11.0	9.6	8.1	6.6	5.1	3.7	2.2	0.8	0	0

[a] For a weekly design level of 100 mR; add one tenth-value layer (TVL) for regions in the environs to reduce radiation to 10 mR/week.
[b] *W*=workload in R/week at 1 m, *U*=use factor, *T*=occupancy factor.
[c] Assumes use factor (*U*) and occupancy factor (*T*) are equal to one.
[d] Refers to leakage radiation of source housing; may be ignored if less than 2.5 mR/hr at 1 m in "on" position.
[e] For large field (20 cm diam) and a source-phantom distance of 40 to 60 cm. This includes scattering from the collimator and from the phantom. (From Braestrup and Wyckoff [1].)

TABLE 6A. *Cesium 137 sheilding requirements for controlled areas* [a]

WUT [b]	Curies [c] approx.	Distance from source to occupied areas (ft)										
24,000	2000	5	7	10	14	20	28	40				
12,000	1000		5	7	10	14	20	28	40			
6,000	500			5	7	10	14	20	28	40		
3,000	250				5	7	10	14	20	28	40	
1,500	125					5	7	10	14	20	28	40
750							5	7	10	14	20	28
375								5	7	10	14	20

Type of barrier	Approx. HVL (cm)	Approx. TVL (cm)	Thickness of lead (cm)										
Primary	0.65	2.1	10.5	9.9	9.3	8.6	8.0	7.4	6.7	6.1	5.5	4.8	4.1
Secondary:													
Leakage [d] 0.1%	0.65	2.1	4.2	3.5	2.9	2.3	1.6	1.0	0.4	0	0	0	0
0.05%	0.65	2.1	3.5	2.9	2.3	1.6	1.0	0.4	0	0	0	0	0
Scatter [e] 35°	0.45	1.5	5.3	4.9	4.4	3.9	3.5	3.0	2.6	2.2	1.7	1.3	0.8
56°	0.38	1.3	4.1	3.7	3.3	2.9	2.5	2.1	1.7	1.4	1.0	0.7	0.4
90°	0.22	0.7	2.0	1.8	1.6	1.3	1.1	0.9	0.7	0.5	0.4	0.2	0.1
119°	0.13	0.4	1.0	0.9	0.8	0.7	0.6	0.5	0.3	0.2	0.2	0.1	0.03

[a] For a weekly design level of 100 mR; add one tenth-value layer (TVL) for regions in the environs to reduce to 10 mR/week.
[b] *W*=workload in R/week at 1 m, *U*=use factor, *T*=occupancy factor.
[c] Assumes use factor (*U*) and occupancy factor (*T*) are equal to one.
[d] Refers to leakage radiation of source housing; may be ignored if less than 2.5 mR/hr at 1 m in "on" position.
[e] For large field (20 cm diam) and a source-scatterer distance of 50 cm. This includes only scattering from an obliquely positioned flat scatterer.

TABLE 6B. *Cesium 137 shielding requirements for controlled areas* [a]

WUT [b]	Curies [c] approx.	Distance from source to occupied areas (ft)										
24,000	2000	5	7	10	14	20	28	40				
12,000	1000		5	7	10	14	20	28	40			
6,000	500			5	7	10	14	20	28	40		
3,000	250				5	7	10	14	20	28	40	
1,500	125					5	7	10	14	20	28	40
750							5	7	10	14	20	28
375								5	7	10	14	20

Type of barrier	Approx. HVL (in.)	Approx. TVL (in.)	Thickness of concrete (in.)										
Primary	1.9	6.2	34.1	32.2	30.2	28.3	26.3	24.4	22.4	20.6	18.7	16.8	14.8
Secondary:													
Leakage [d] 0.1%	1.9	6.2	14.8	12.9	11.0	9.1	7.0	4.9	2.0	0	0	0	0
0.05%	1.9	6.2	12.9	11.0	9.1	7.0	4.9	2.8	0	0	0	0	0
Scatter [e] 35°	1.8	6.1	23.4	21.6	19.8	18.0	16.2	14.4	12.5	10.7	8.8	7.0	5.1
56°	1.5	4.9	18.8	17.3	15.8	14.3	12.8	11.3	9.8	8.4	6.9	5.5	4.0
90°	1.4	4.7	16.3	14.9	13.5	12.0	10.6	9.2	7.8	6.4	5.0	3.7	1.9
119°	1.3	4.4	14.9	13.6	12.3	11.0	9.6	8.3	7.0	5.7	4.3	3.0	1.3

[a] For a weekly design level of 100 mR; add one tenth-value layer (TVL) for regions in the environs to reduce to 10 mR/week.
[b] W=workload in R/week at 1 m, U=use factor, T=occupancy factor.
[c] Assumes use factor (U) and occupancy factor (T) are equal to one.
[d] Refers to leakage radiation of source housing; may be ignored if less than 2.5 mR/hr at 1 m in "on" position.
[e] For large field (20 cm diam) and a source-scatterer distance of 50 cm. This includes only scattering from an obliquely positioned flat scatterer.

TABLE 7. *Relation between distance and millicurie-hours for an exposure of 0.1 R from an unshielded source*

Millicurie-hours	Distance to source: Radium	Cobalt 60	Cesium 137	Iridium 192	Gold 198
	ft	*ft*	*ft*	*ft*	*ft*
10	0.9	1.2	0.6	0.7	0.5
30	1.6	2.1	1.0	1.3	0.9
100	3.0	3.8	1.9	2.3	1.6
300	5.1	6.5	3.2	4.0	2.7
1,000	9.4	11.9	5.8	7.4	5.0
3,000	16.3	20.5	10.1	12.7	9.0
10,000	30.1	37.6	18.5	23.2	15.8

TABLE 8. *Protection requirements (in centimeters of lead) for various gamma-ray sources*

Millicurie-hours	Radium TVL[a]=5.5 cm lead			Cobalt 60 TVL[a]=4.1 cm lead			Cesium 137 TVL[a]=2.2 cm lead		
	Thickness of lead required to reduce radiation to 100 mR [b] at a distance of –								
	1 ft	3.2 ft	6.5 ft	1 ft	3.2 ft	6.5 ft	1 ft	3.2 ft	6.5 ft
100	4.0	0	0	5.0	0.7	0	1.1	0	0
300	6.2	1.5	0	7.0	2.8	0	2.1	0	0
1,000	8.9	3.6	1.1	9.1	4.9	2.5	3.3	1.1	0
3,000	11.3	5.8	3.1	11.0	6.8	4.4	4.3	2.1	0.8
10,000	14.1	8.5	5.5	13.1	8.9	6.5	5.4	3.2	1.9
30,000	16.7	11.0	7.8	15.0	10.8	8.4	6.4	4.2	2.9
100,000	19.5	13.7	10.5	17.2	12.9	10.5	7.5	5.3	4.0

Millicurie-hours	Iridium 192 TVL[a]=2.0 cm lead			Gold 198 TVL[a]=1.1 cm lead		
	Thickness of lead required to reduce radiation to 100 mR [b] at a distance of–					
	1 ft	3.2 ft	6.5 ft	1 ft	3.2 ft	6.5 ft
100	0.8	0	0	0.4	0	0
300	1.4	0.1	0	0.9	0	0
1,000	2.2	0.7	0.1	1.5	0.3	0
3,000	3.1	1.4	0.6	2.1	0.9	0.2
10,000	4.0	2.1	1.2	3.0	1.4	0.8
30,000	5.0	3.0	2.0	[illegible]	2.0	1.3
100,000	6.2	4.0	2.8	5.3	2.9	1.9

[a] Approximate value obtained with large attenuation.
[b] Add one tenth-value layer (TVL) to reduce radiation to 10 mR.

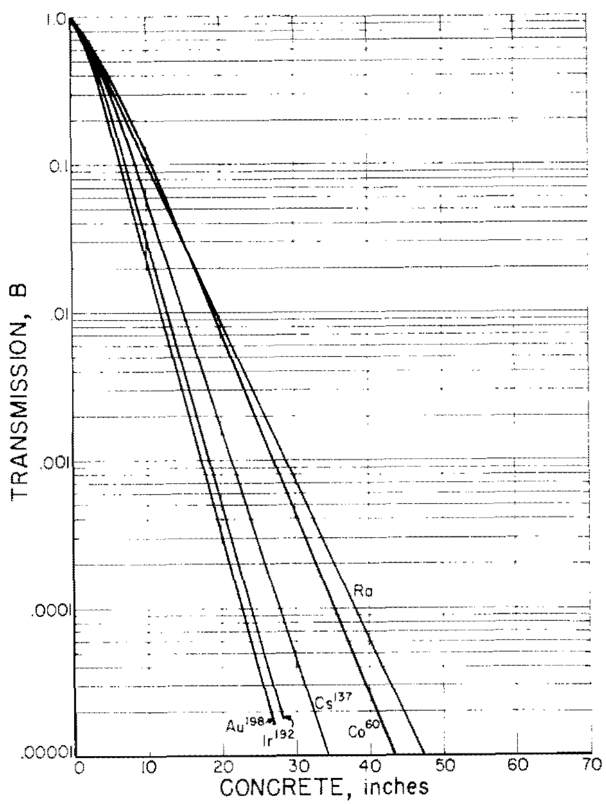

FIGURE 3. *Transmission through concrete (density 147 lb/ft^3) of gamma rays from radium [14]; cobalt 60, cesium 137, gold 198 [7]; iridium 192 [15].*

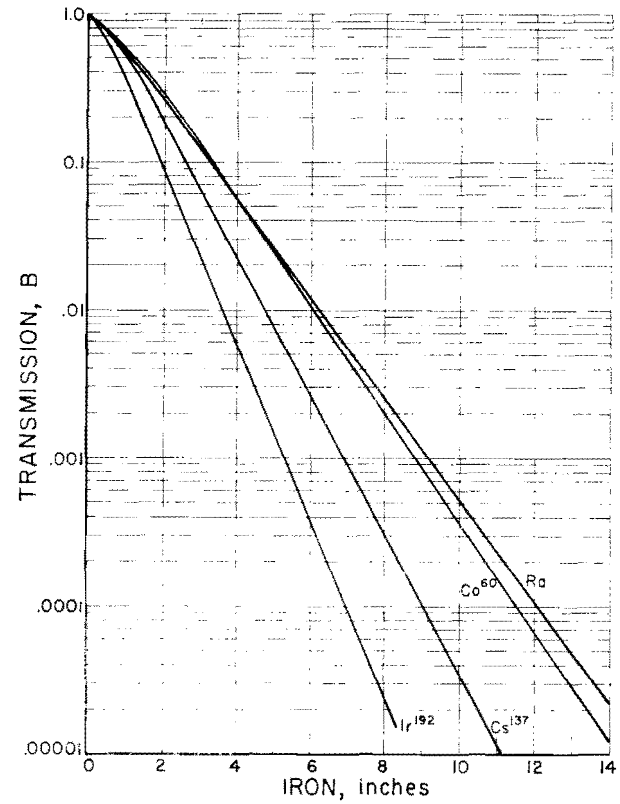

FIGURE 4. *Transmission through iron of gamma rays from radium [14]; cobalt 60, cesium 137 [7]; iridium 192 [15].*

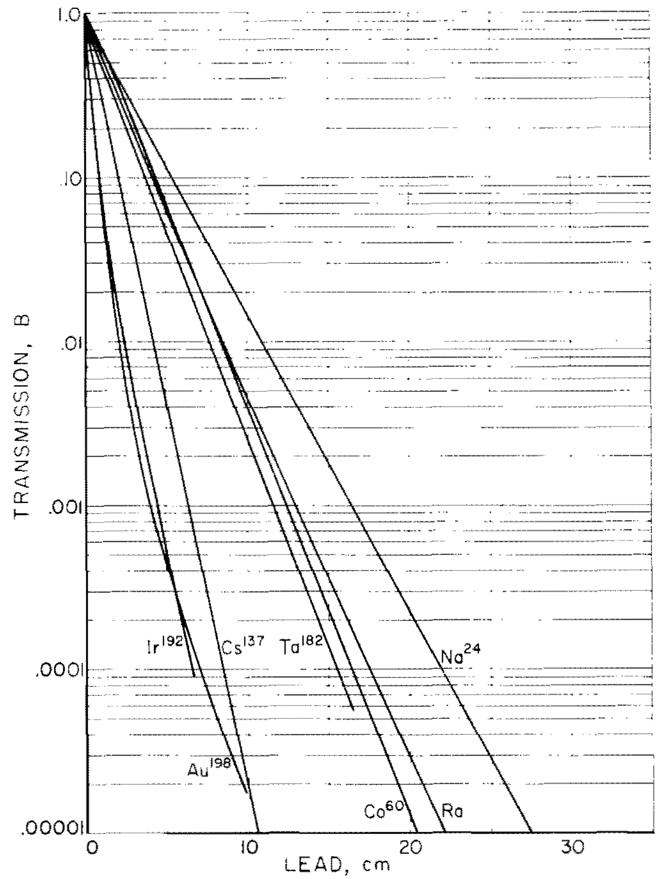

FIGURE 5. *Transmission through lead of gamma rays from radium [14]; cobalt 60, cesium 137, gold 198 [7]; iridium 192 [15]; tantulum 182 and sodium 24 [29].*

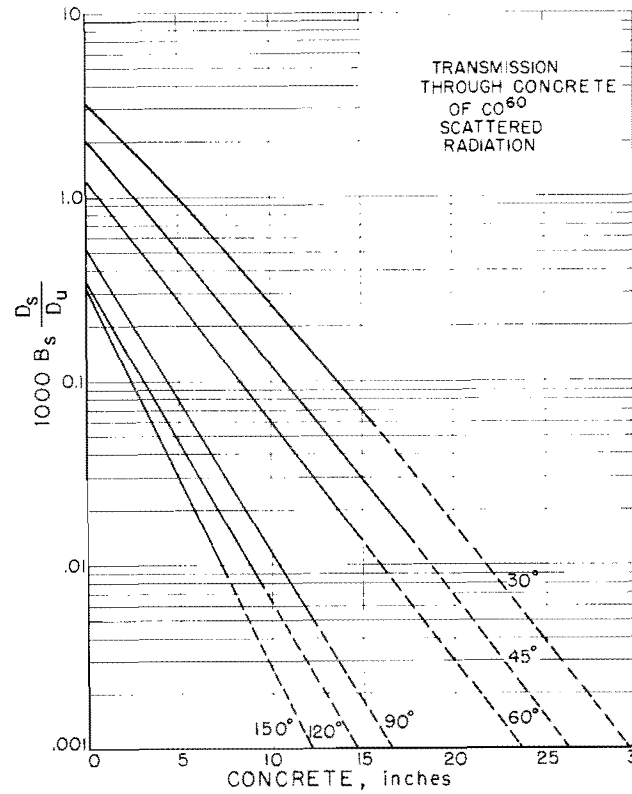

FIGURE 6a. *Transmission through concrete (density 147 lb/ft³) of cobalt 60 scattered radiation from cylindrical Masonite phantom, 20-cm diam field at 1 m from source [10].*

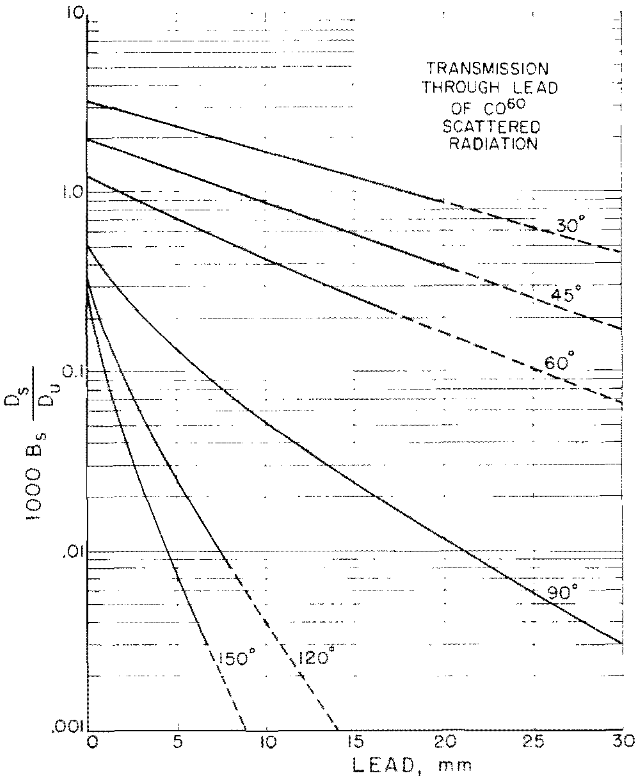

FIGURE 6b. *Transmission through lead of cobalt 60 scattered radiation from cylindrical Masonite phantom, 20-cm diam field at 1 m from source [10].*

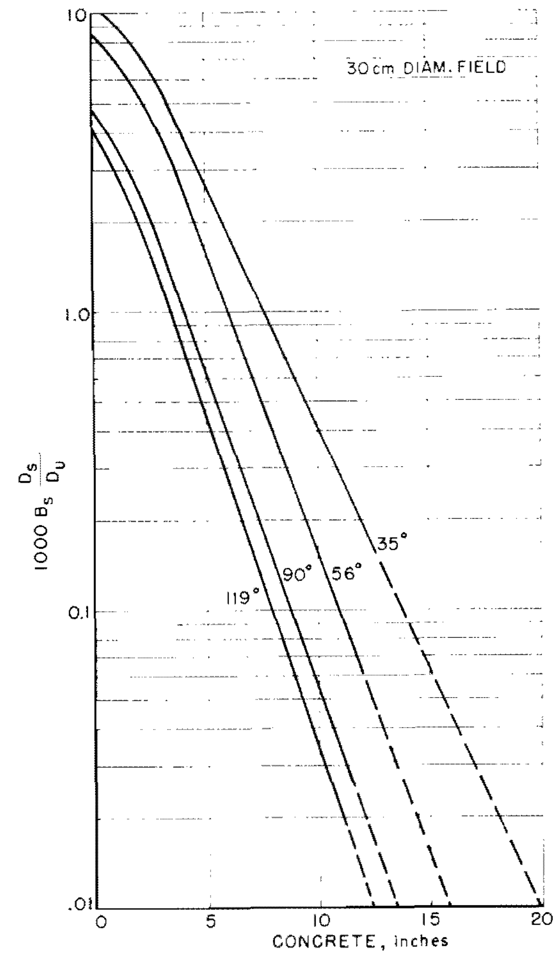

FIGURE 7a. *Transmission through concrete (density 147 lb/ft³) of cesium 137 radiation scattered at the indicated angles from an oblique concrete barrier [4].*

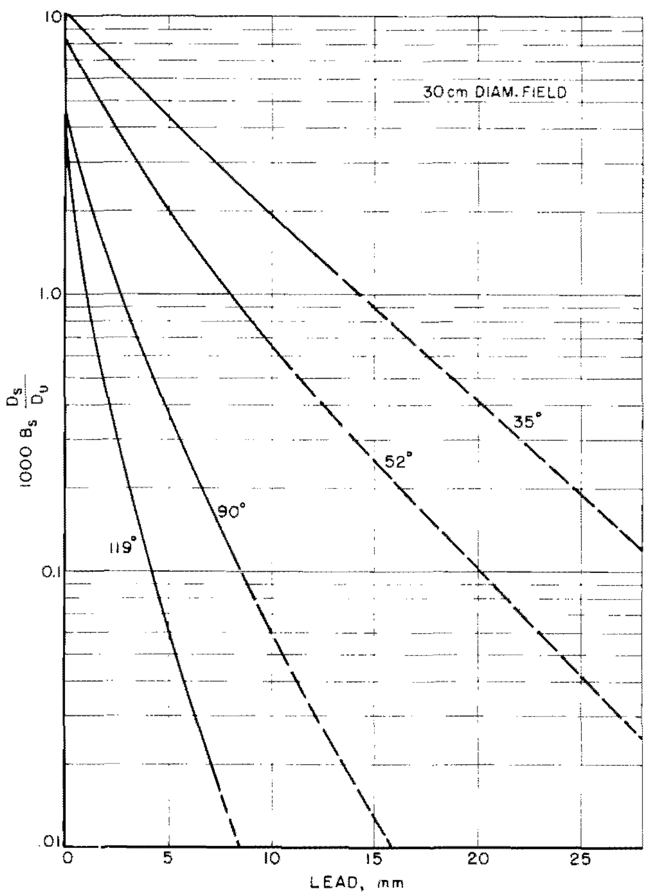

FIGURE 7b. *Transmission through lead of cesium 137 radiation scattered at the indicated angles from an oblique concrete barrier [4].*

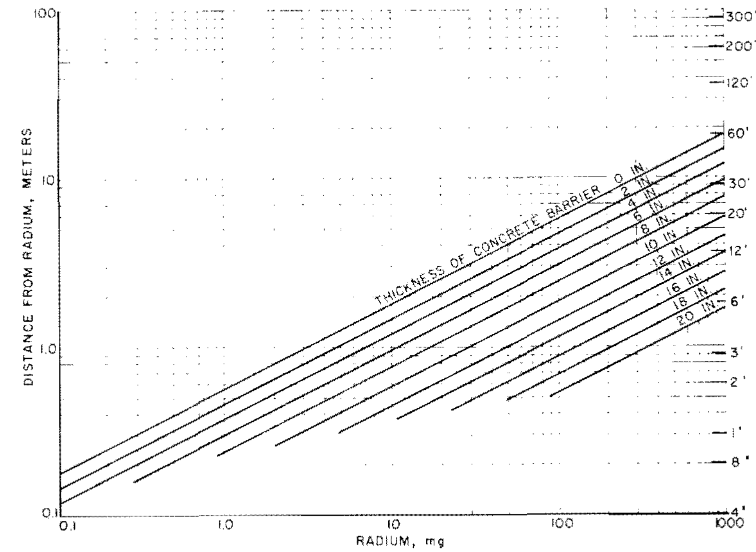

FIGURE 8. *Relation between amount of radium, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 hr.*

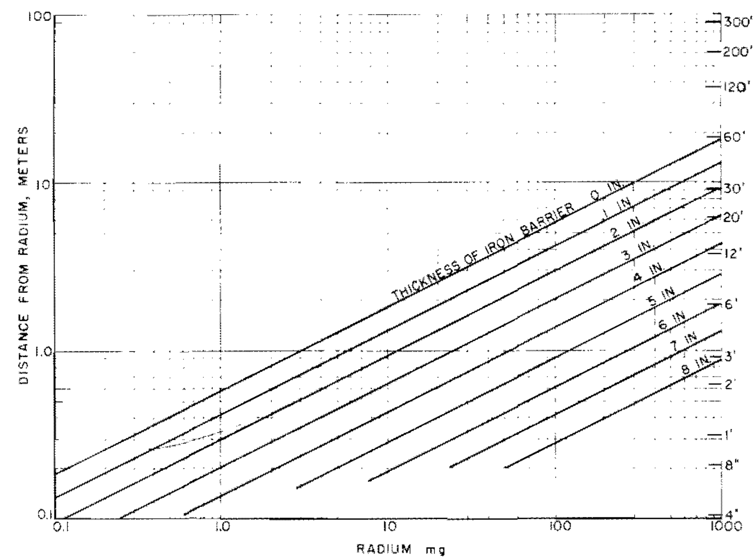

FIGURE 9. *Relation between amount of radium, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 hr.*

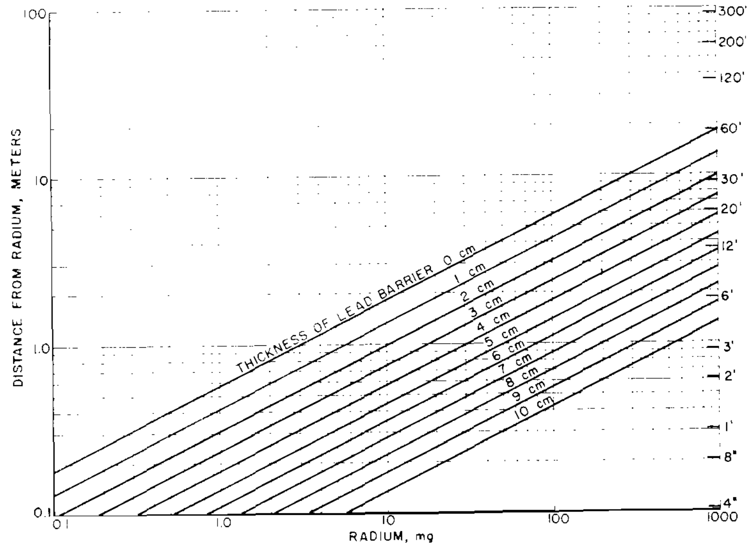

Figure 10. *Relation between amount of radium, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 hr.*

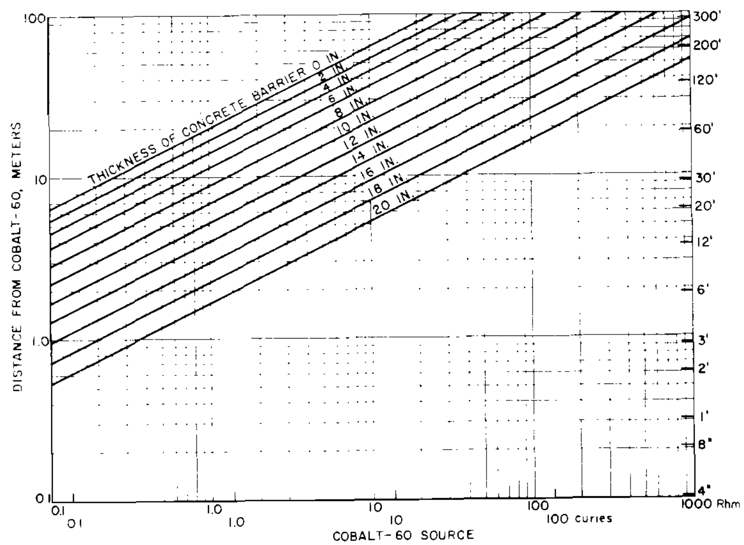

Figure 11. *Relation between amount of cobalt 60 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 hr.*

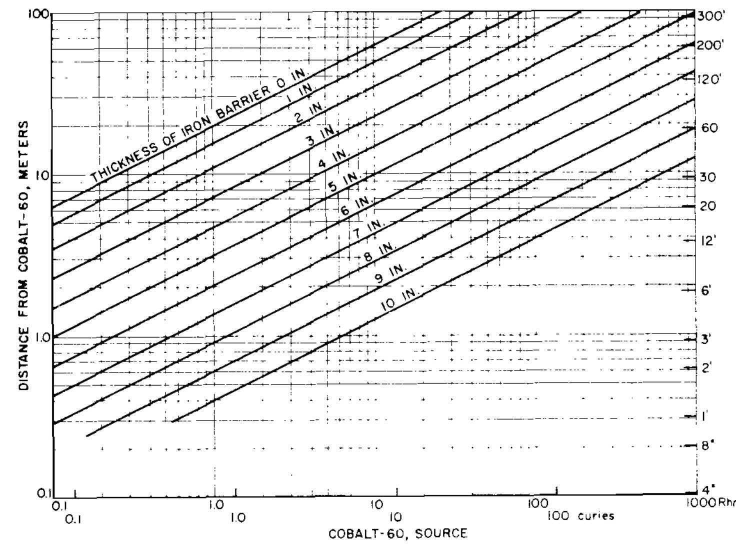

Figure 12. *Relation between amount of cobalt 60 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 hr.*

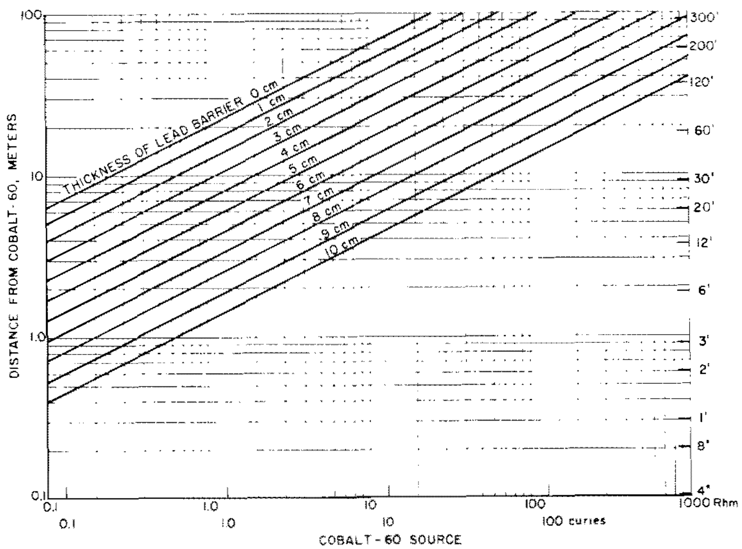

FIGURE 13. *Relation between amount of cobalt 60 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 hr.*

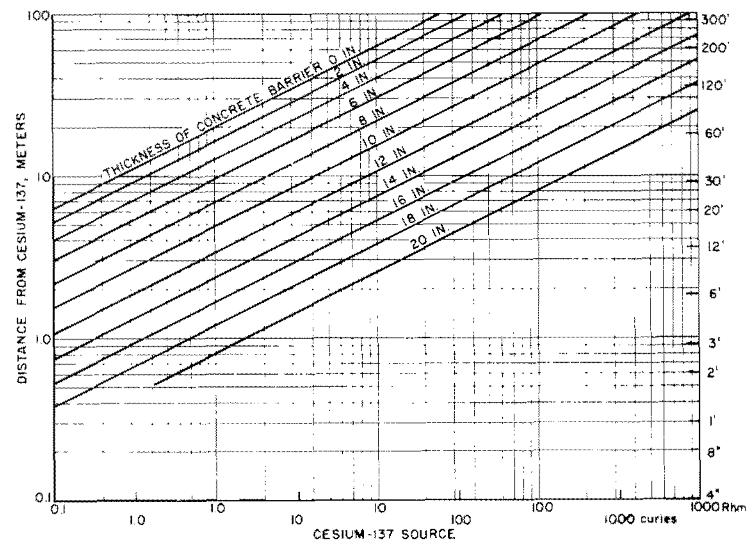

FIGURE 14. *Relation between amount of cesium 137 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 hr.*

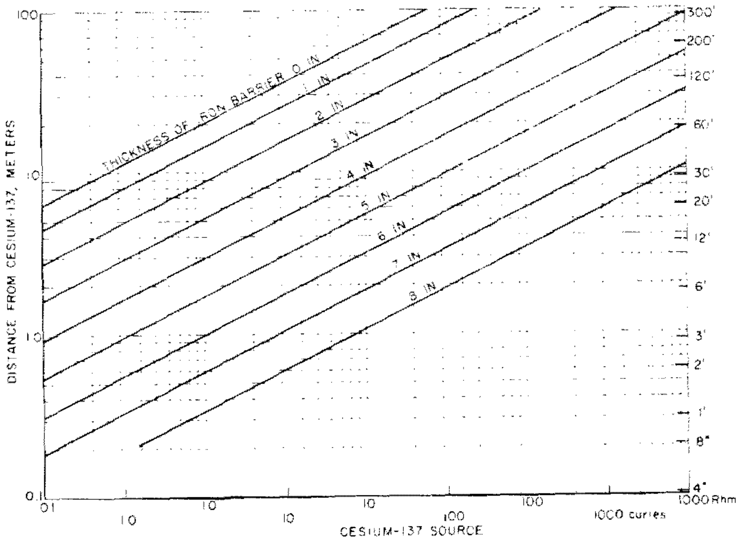

FIGURE 15. *Relation between amount of cesium 137 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 hr.*

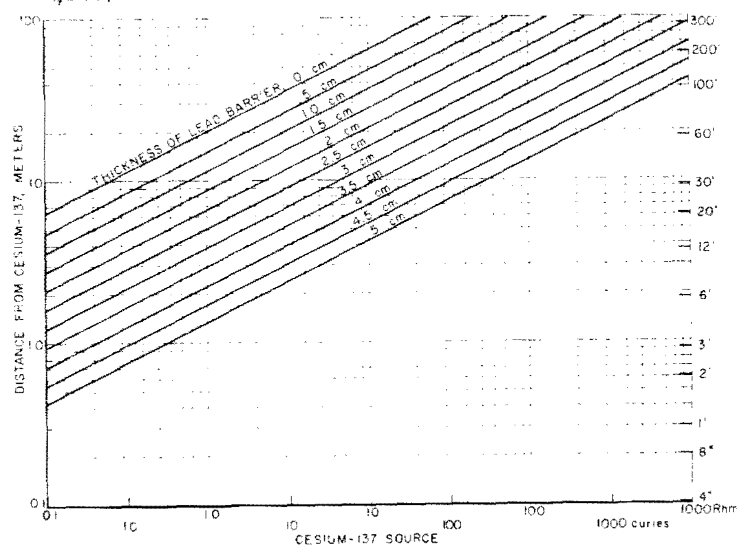

FIGURE 16. *Relation between amount of cesium 137 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 hr.*

Appendix E. Tables of General X-Ray Information

TABLE 9. *Distance protection (in feet) against useful beam in controlled areas*

[For design purposes only, the maximum permissible exposure is taken to be 100 mR/wk.]

Kilovoltage	50	70	100	250	1,000	2,000
X-ray output (K_0) (R/ma-min at 1 m)	0.05	0.1	0.4	2	20	280
WUT[a]	Distance in feet					
2	3	5	9	20	60	200
4	5	7	13	28	76	270
7	6	9	17	37	105	335
8	7	10	19	40	115	350
12	8	12	23	47	130	415
15	9	13	25	52	145	450
30	12	17	35	69	190	550
50	15	22	44	85	230	650
60	16	24	47	92	240	700
125	22	33	62	120	320	850
150	24	35	66	130	335	880
200	27	38	75	140	375	950
250	30	42	80	155	400	1,000
500	40	55	100	200	500	1,150
600	42	58	107	210	530	1,200
800	47	65	120	235	570	1,275
1,000	50	70	130	250	600	1,350
2,000	62	85	165	310	720	1,500
2,500	69	90	175	330	760	1,575
4,000	75	102	200	370	850	1,700
10,000	95	130	250	480	1,030	1,950
40,000	125	180	350	640	1,300	2,350

[a] *W*=workload in milliampere-minutes per week.
U=use factor.
T=occupancy factor.

TABLE 10. *Distance protection (in feet) against useful beam in areas outside of controlled areas (environs)*

[For design purposes only, the maximum permissible exposure is taken to be 10 mR/wk.]

Kilovoltage	50	70	100	250	1,000	2,000
X-ray output (K_0) (R/ma-min at 1 m)	0.05	0.1	0.4	2	20	280
WUT [a]	Distance in feet					
2	11	15	30	50	160	480
4	15	20	38	77	220	590
7	18	25	50	95	255	690
8	20	27	52	100	270	720
12	23	31	60	116	310	800
15	25	35	65	127	340	850
30	32	45	85	165	430	1,000
50	38	55	102	195	510	1,150
60	40	59	110	210	530	1,200
125	53	78	140	265	670	1,400
150	56	84	150	280	700	1,450
200	62	95	165	310	750	1,550
250	65	102	175	330	800	1,600
500	85	130	220	400	940	1,800
600	90	145	232	420	990	1,850
800	100	150	250	460	1,050	1,920
1,000	110	160	270	490	1,100	2,000
2,000	135	200	330	570	1,250	2,150
2,500	145	210	345	600	1,300	2,200
4,000	165	240	375	650	1,400	2,300
10,000	210	300	460	750	1,550	2,550
40,000	280	390	580	900	1,750	2,850

[a] *W*=workload in milliampere-minutes per week.
U=use factor.
T=occupancy factor.

TABLE 11. *Shielding for radiographic films*

[b][Indicated thicknesses required to reduce radiation to 1 mR [c] for a weekly workload of 1,000 ma-min at 100 kvp, 400 ma-min at 125 kvp, or 200 ma-min at 150 kvp]

Storage time	Type of barrier	Distance from tube to stored films											
		7 ft (2.13 m)			10 ft (3.05 m)			14 ft (4.26 m)			20 ft (6.10 m)		
		Lead		Concrete [a]	Lead		Concrete [a]	Lead		Concrete [a]	Lead		Concrete [a]
		mm	*in.*	*in.*	*mm*	*in.*	*in.*	*mm*	*in.*	*in.*	*mm*	*in.*	*in.*
1 hour	Primary	2.0	3/32	6.1	1.8	1/16	5.4	1.5	1/16	4.8	1.3	1/16	4.1
1 day	Primary	2.7	3/32	8.0	2.5	3/32	7.4	2.2	3/32	6.7	2.0	3/32	6.0
1 week	Primary	3.4	1/8	9.6	3.1	1/8	8.9	2.8	1/8	8.2	2.6	3/32	7.6
1 month	Primary	3.8	5/32	10.9	3.6	5/32	10.2	3.3	1/8	9.6	3.1	1/8	8.9
1 hour	Secondary	0.3		1.1	0.2		0.6						
1 day	Secondary	.9	1/32	2.9	.7	1/32	2.3	0.5		1.7	0.3		1.1
1 week	Secondary	1.4	1/16	4.4	1.2	1/16	3.7	1.0	1/32	3.1	.7	1/32	2.4
1 month	Secondary	1.9	1/16	5.7	1.6	1/16	5.0	1.4	1/16	4.4	1.2	1/16	3.7

[a] NOTE. Concrete thicknesses approximate.
[b] NOTE. For other workloads, add or subtract appropriate number of HVL.
[c] NOTE. Undeveloped fast x-ray film may be damaged by exposures totaling somewhat less than 1 mR depending upon film type and radiation energy. Such film may require the addition of one tenth-value layer to the protective barriers specified in the table.

TABLE 12. *Half-value layer*

[Approximate half-value layers *obtained at high filtration* for the indicated tube potentials under broad-beam conditions]

Attenuating material	hvl for various tube potentials												
	50 kvp	70 kvp	100 kvp	125 kvp	150 kvp	200 kvp	250 kvp	300 kvp	400 kvcp	500 kvcp	1,000 kvcp	2,000 kvcp	3,000 kvcp
Lead (mm)	0.05	0.18	0.24	0.27	0.3	0.5	0.8	1.3	2.2	3.6	8.0	12.0	15.0
Concrete (in.)	.2	.5	.7	.8	.9	1.0	1.1	1.2	1.3	1.4	1.8	2.45	2.95
Concrete (cm)	.51	1.27	1.8	2.0	2.3	2.5	2.8	3.0	3.3	3.6	4.6	6.2	7.5

NOTE.—One tenth-value layer is equivalent to 3.33 half-value layers.

TABLE 13. *Secondary barrier requirements for leakage radiation from protective tube housings for controlled areas*

[Add 3.3 hvl for environs]

Distance from target in feet	Operating time in hours per week					
	2	5	10	15	25	40
	Number of half-value layers					
3	4.6	5.9	6.9	7.5	8.2	8.9
4	3.8	5.1	6.1	6.7	7.4	8.1
5	3.2	4.5	5.5	6.1	6.8	7.4
6	2.6	3.9	4.9	5.5	6.3	7.0
7	2.2	3.5	4.5	5.1	5.8	6.5
8	1.8	3.1	4.1	4.7	5.4	6.1
9	1.5	2.8	3.7	4.3	5.1	5.8
10	1.2	2.5	3.5	4.0	4.8	5.5
12	0.6	1.9	2.9	3.5	4.3	4.9
15	0	1.3	2.3	2.9	3.6	4.3
20		0.5	1.5	2.0	2.8	3.5
30			0.3	0.9	1.6	2.3

TABLE 14. *Densities of commercial building materials*

Material	Density range	Density of average sample
	g/cc	*g/cc*
Brick	1.6 to 2.5	1.9
Granite	2.60 to 2.70	2.63
Limestone	1.87 to 2.69	2.30
Marble	2.47 to 2.86	2.70
Sand plaster	---- ----	1.54
Sandstone	1.90 to 2.69	2.20
Siliceous concrete	2.25 to 2.40	2.35
Tile	1.6 to 2.5	1.9

NOTE.—Concrete and cinder blocks vary too much to be listed.

See also reference [12].

TABLE 15. *Commercial lead sheets*

Thickness		Approximate weight
mm	*in.*	*lb/ft*²
0.79	1/32	2
1.00	5/128	2½
1.19	3/64	3
1.58	1/16	4
1.98	5/64	5
2.38	3/32	6
3.17	1/8	8
4.76	3/16	12
6.35	1/4	16
8.50	1/3	20
10.1	2/5	24
12.7	1/2	30
16.9	2/3	40
25.4	1	60

Appendix F. X-Ray Shielding Tables for Controlled Areas and Environs [1]

TABLE 16a. *Industrial x-ray shielding requirements for controlled areas* [a] [1]

[b] *WUT*	Distance from tube to occupied area *ft*										
40,000	5	7	10	14	20	28	40				
20,000		5	7	10	14	20	28	40			
10,000			5	7	10	14	20	28	40		
5,000				5	7	10	14	20	28	40	
2,500					5	7	10	14	20	28	40
1,250						5	7	10	14	20	28
625							5	7	10	14	20
310								5	7	10	14
155									5	7	10

Potential	Approximate [c] HVL	Approximate [c] TVL	Type of barrier	Thickness of lead [d] *mm*										
kv	*mm*	*mm*												
100	0.2	0.7	Prim.	3.2	2.9	2.7	2.4	2.2	1.9	1.7	1.4	1.2	1.0	0.8
			Sec.	2.1	1.8	1.6	1.4	1.2	1.0	0.8	0.6	0.4	0.2	0.1
150	0.3	1.0	Prim.	4.1	3.8	3.5	3.3	3.0	2.7	2.4	2.1	1.8	1.6	1.3
			Sec.	2.6	2.3	2.0	1.8	1.5	1.2	0.9	0.7	0.5	0.3	0.1
200	0.5	1.7	Prim.	6.4	5.9	5.4	4.9	4.4	3.9	3.4	3.0	2.6	2.3	2.0
			Sec.	4.1	3.7	3.1	2.6	2.2	1.8	1.4	1.1	0.8	0.5	0.2
250	0.9	3.0	Prim.	11.3	10.4	9.5	8.6	7.7	6.8	6.0	5.2	4.4	3.6	2.8
			Sec.	6.4	5.7	5.0	4.2	3.5	2.8	2.2	1.6	1.2	0.8	0.3
300	1.7	5.6	Prim.	21.6	19.8	18.0	16.3	14.6	13.0	11.4	9.8	8.3	6.8	5.5
			Sec.	12.0	10.4	8.9	7.5	6.3	5.2	4.2	3.2	2.3	1.5	0.6

[a] For a design level of 100 mR/week. Add one tenth-value layer (TVL) for environs to reduce radiation to 10 mR/week.
[b] W=workload in ma-min/week. U=use factor. T=occupancy factor. T is equal to one for controlled areas and may be less than one for environs.
[c] These values are obtained at high filtration.
[d] The indicated values for mm lead are for pulsating potentials; for constant potentials, 15 to 25 percent larger thicknesses of lead may be required.

TABLE 16b. *Industrial x-ray shielding requirements for controlled areas* [a] [1]

[b] *WUT*				Distance from tube to occupied area *ft*										
40,000				5	7	10	14	20	28	40				
20,000					5	7	10	14	20	28	40			
10,000						5	7	10	14	20	28	40		
5,000							5	7	10	14	20	28	40	
2,500								5	7	10	14	20	28	40
1,250									5	7	10	14	20	28
625										5	7	10	14	20
310											5	7	10	14
155												5	7	10
Potential	Approximate [c] HVL	Approximate [c] TVL	Type of barrier	Thickness of concrete (density 147 lb/ft ^{3}) [d], [e] *in.*										
kv	*in.*	*in.*												
100	0.6	2.0	Prim.	9.2	8.6	8.0	7.3	6.6	6.0	5.5	4.6	4.0	3.3	2.8
			Sec.	6.6	5.8	5.2	4.6	1.0	3.4	2.8	2.3	1.8	1.3	0.8
150	0.9	3.0	Prim.	13.3	12.4	11.5	10.6	9.7	8.9	8.1	7.2	6.5	5.8	5.1
			Sec.	9.1	8.2	7.3	6.4	5.5	4.6	3.7	2.9	2.2	1.7	1.2
200	1.1	3.6	Prim.	16.9	15.8	14.8	13.7	12.7	11.6	10.6	9.6	8.5	7.5	6.5
			Sec.	12.1	10.9	9.8	8.7	7.6	6.6	5.6	4.6	3.6	2.6	1.6
250	1.1+	3.8	Prim.	19.3	18.0	16.8	15.6	14.4	13.2	12.0	10.8	9.6	8.4	7.2
			Sec.	12.6	11.4	10.3	9.2	8.1	7.0	6.0	5.0	4.0	3.0	2.0
300	1.2	4.0	Prim.	21.7	20.5	19.3	18.1	16.9	15.7	14.5	13.3	12.1	10.9	9.7
			Sec.	13.4	12.2	11.0	9.8	8.8	7.8	6.8	5.8	4.8	3.8	2.8

[a] For a design level of 100 mR/week. Add one tenth-value layer (TVL) for environs to reduce radiation to 10 mR/week.
[b] W=workload in ma-min/week, U=use factor, T=occupancy factor. T is equal to one for controlled areas and may be less than one for environs.
[c] These values are obtained at high filtration.
[d] For other densities, ρ, the tabular values should be multiplied by $\frac{147}{\rho}$.
[e] The indicated values for inches of concrete are for pulsating potentials; for constant potentials, 5 to 15 percent larger thicknesses of concrete may be required.

TABLE 17. *Average shielding requirements for 1-mv x-ray installations* [a] [1]

Type of barrier	UT [b]	Distance from tube to occupied area: 7 ft (2.14m) Lead mm	7 ft Lead in. [c]	7 ft Lead psf [d]	7 ft Concrete in.	7 ft Concrete psf [d]	10 ft (3.05m) Lead mm	10 ft Lead in. [c]	10 ft Lead psf [d]	10 ft Concrete in.	10 ft Concrete psf [d]	14 ft (4.28m) Lead mm	14 ft Lead in. [c]	14 ft Lead psf [d]	14 ft Concrete in.	14 ft Concrete psf [d]	20 ft (6.10m) Lead mm	20 ft Lead in. [c]	20 ft Lead psf [d]	20 ft Concrete in.	20 ft Concrete psf [d]	30 ft (9.15m) Lead mm	30 ft Lead in. [c]	30 ft Lead psf [d]	30 ft Concrete in.	30 ft Concrete psf [d]
For controlled areas: Primary	1	130	5.1	300	32	390	120	4.7	280	30	370	115	4.5	270	28½	350	105	4.1	240	26½	330	100	3.9	230	25	310
	¼	115	4.5	270	28½	350	105	4.1	240	26½	330	100	3.9	230	25	310	90	3.5	200	23	280	85	3.3	200	21½	260
	1/16	100	3.9	230	25	310	90	3.5	210	23	280	85	3.3	200	21½	260	75	3.0	180	19½	240	70	2.8	170	18	220
For environs: Primary	1	160	6.3	270	38	470	145	5.7	330	36	440	140	5.5	320	34½	420	130	5.1	300	32½	400	125	4.9	290	31	380
	¼	140	5.5	320	31½	420	130	5.1	300	32½	400	125	4.9	290	31	380	115	4.5	270	29	360	110	4.3	250	27½	340
	1/16	125	4.9	290	31	380	115	4.5	270	29	360	110	4.3	250	27½	340	100	3.9	230	25½	310	90	3.5	210	24	290
	1/64	110	4.3	250	27½	340	100	3.9	230	25½	310	90	3.5	210	24	290	80	3.2	190	22	270	75	3.0	170	20½	250
	1/256	90	3.5	210	21	290	80	3.2	190	22	270	75	3.0	170	20½	250	65	2.6	150	18½	230	60	2.4	140	17	210

[a] For design levels of 100 mR/week for controlled areas and 10 mR/week for environs, and for a weekly workload of 4000 ma-min.
[b] U=use factor, T=occupancy. T is equal to one for controlled areas, and may be less than one for environs.
[c] Approximately.
[d] Pounds per square foot computed from mm of lead or in. of concrete and a concrete density of 2.35 g/cc (147 lb/ft ^{3}).

Table 18. *Average shielding requirements for 2-Mv x-ray installations* [a] [1]

Type of barrier	UT[b]	Distance from tube to occupied area: 7 ft (2.14 m)					10 ft (3.05 m)					14 ft (4.28 m)					20 ft (6.10 m)					30 ft (9.15 m)				
		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete	
		mm	in.[c]	psf[d]	in.	psf[d]	mm	in.[c]	psf[d]	in.	psf[d]	mm	in.[c]	psf[d]	in.	psf[d]	mm	in.[c]	psf[d]	in.	psf[d]	mm	in.[c]	psf[d]	in.	psf[d]
For controlled areas: Primary	1	235	9.3	550	50	610	225	8.9	520	47	580	210	8.3	490	45	550	200	7.9	470	42	520	185	7.3	430	40	490
	1/4	210	8.3	490	45	550	200	7.9	470	42	520	185	7.3	430	40	490	175	6.9	440	37	460	160	6.3	370	35	430
	1/16	185	7.3	430	40	490	175	6.9	410	37	460	160	6.3	370	35	430	150	5.9	350	32	390	135	5.3	320	30	370
For environs: Primary	1	280	11.1	650	58	710	265	10.5	620	55	670	255	10.1	590	53	650	240	9.5	560	50	610	230	9.1	540	48	590
	1/4	255	10.1	590	53	650	240	9.5	560	50	610	235	9.1	540	48	590	215	8.5	500	45	550	205	8.1	480	43	530
	1/16	230	9.1	540	48	590	215	8.5	500	45	550	205	8.1	480	43	530	190	7.5	440	40	490	180	7.1	420	38	470
	1/64	205	8.1	480	43	530	190	7.5	440	40	490	180	7.1	420	38	470	165	6.5	380	35	430	155	6.1	360	33	400
	1/256	180	7.1	420	38	470	165	6.5	380	35	430	155	6.1	360	33	400	140	5.5	330	30	370	130	5.1	300	28	340

[a] For design levels of 100 mR/week for controlled areas and 10 mR/week for environs, and for a weekly workload of 2000 ma-min.
[b] U=use factor, T=occupancy factor. T is equal to 1 for controlled areas, and may be less than 1 for environs.
[c] Approximately.
[d] Pounds per square foot computed from mm of lead or in. of concrete and a concrete density of 2.35 g/cc (117 lb/ft³).

Table 19. *Primary barrier thickness of concrete for multimegavolt installations* [1]

	Tube potential	Concrete thickness required for WUT[a] and distances from target to occupied area of........ (WUT)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
		1600	10	3.05	20	6.10	40	12.2	80	21.4						
		100	5	1.52	10		20		40		80					
		100			5		10		20		40		80			
		25					5		10		20		40		80	
		6							5		10		20		40	
		1½									5		10		20	
	Mev		in.	psf[b]	in.	psf[b]	in.	psf[b]	in.	psf[b]	in.	psf[b]	in.	psf[b]	in.	psf[b]
Controlled area	6		42	510	34	420	26	320	18	220	11	135	2	25	0	
	10		49	600	40	490	31	380	21	260	12	145	3	40	0	
	20		59	720	48	590	37	450	26	320	15	185	4	50	0	
	40-180		61	750	50	610	40	490	29	360	17	210	4	50	0	
Environs	6		55	670	48	590	40	490	32	390	23	280	15	180	8	100
	10		64	780	55	670	46	560	37	450	28	340	18	220	9	110
	20		77	940	66	810	56	690	45	550	34	420	23	280	12	150
	40-180		79	970	68	830	58	710	47	580	36	440	25	310	13	160

[a] W=weekly workload in esu/cc (lucite) at 1 m; U=use factor; T=occupancy factor. T is equal to 1 for controlled areas, and may be less than 1 for environs.
[b] Assuming a density of 117 lb/ft³. psf=pounds per square foot of wall area.

Table 20. *Primary barrier thickness of lead for multimegavolt installations* [1]

		Lead thickness required for WUT[a] and distances from target to occupied area of														
		(WUT)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
	Tube potential	1600	10	3.05	20	6.10	40	12.2	80	24.4						
		400	5	1.52	10		20		40		80					
		100			5		10		20		40		80			
		25					5		10		20		40		80	
		6							5		10		20		40	
		1½									5		10		20	
	Mev		in.	psf[b]	in.	psf[b]	in.	psf[b]	in.	psf[b]	in.	psf[b]	in.	psf[b]	in.	psf[b]
Controlled areas	10		6.7	400	5.5	330	4.2	250	2.9	170	1.7	100	0.4	21	0	0
	86-176		5.7	340	4.6	270	3.6	210	2.5	150	1.4	80	0.4	21	0	0
Environs	10		8.9	530	7.6	450	6.3	370	5.1	300	3.8	230	2.5	150	1.3	80
	86-176		7.5	440	6.4	380	5.3	310	4.3	250	3.2	190	2.1	120	1.1	70

[a] W=weekly workload in esu/cc (lucite) at 1 m; U=use factor; T=occupancy factor. T is equal to 1 for controlled areas, and may be less than 1 for environs.

[b] psf=pounds per square foot of wall area.

Appendix G. Determination of X-Ray Protective Barrier Thicknesses

The thickness of protective barrier necessary to reduce the exposure rate from any x-ray machine to the maximum permissible level depends upon the quality of the radiation, the quantity being produced in some chosen period of time, the distance from the tube to the occupied area, the degree and nature of the occupancy, the type of area, and the material of which the barrier is constructed. Tables 16 through 20, appendix E, give the thicknesses of lead required under a wide variety of conditions which are commonly met. Occasionally conditions may be encountered which are not covered by the tables. The necessary barrier thickness may then be computed by the use of eqs 1 to 5 and the curves shown in figures 17 to 21 of this appendix.

Computation of Primary Protective Barrier Thicknesses

By definition, primary protective barriers protect against the radiation of the useful beam. It has been found experimentally that the transmission of x rays through thick barriers is closely related to the peak operating potential of the x-ray tube. The filtration added to the useful beam in an x-ray machine is always small in comparison with the attenuation afforded by the barrier, and hence the barrier thickness required at a given kilovoltage is essentially independent of any changes in half-value-layer caused by added filtration in the machine. Thus, it is sufficient, for the purposes of protection calculations, to establish transmission curves specified in kilovolts under conditions of minimum added filtration. It has also been found that at any given kilovoltage and with minimum added filtration the exposure rate produced by any x-ray machine is nearly a constant when expressed in terms of roentgens per milliampere-minute at a distance of 1 m.

Figures 17 through 21 show the exposure rate measured in roentgens per milliampere-minute at a distance of 1 m from the target of the x-ray tube which would be transmitted through barriers of various thicknesses. The ordinate of the figures, given the symbol K, is the transmitted exposure per milliampere-minute at a reference distance of 1 m. The abscissa is the thickness of absorbing material required to give the desired value of K. Families of curves are shown for various kilovoltages and absorbing materials. In order to calculate the required barrier thickness for any set of

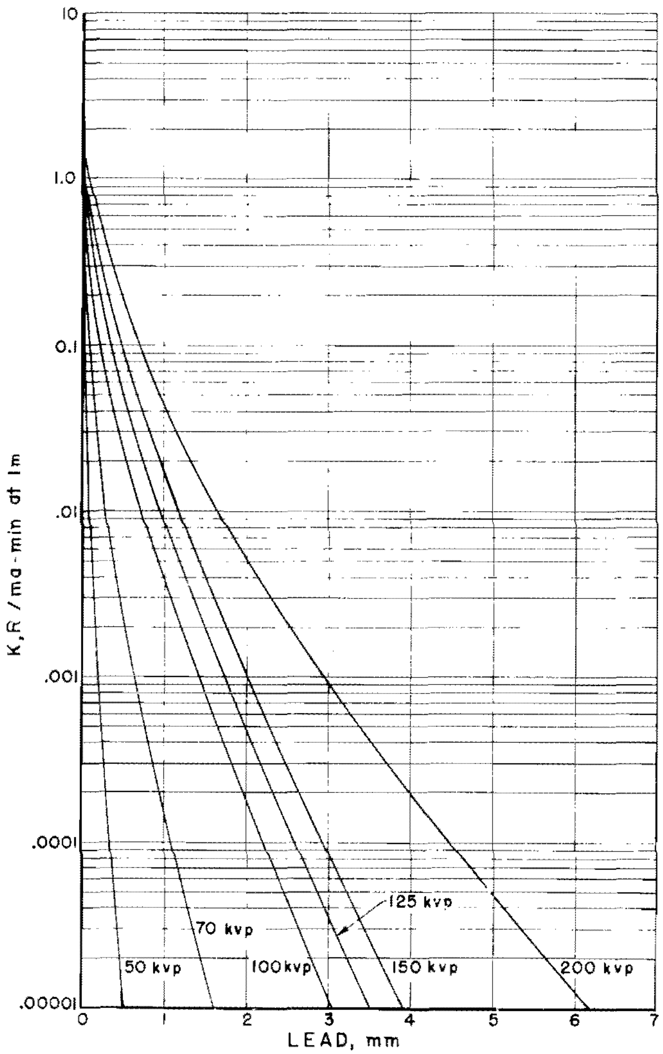

FIGURE 17. *Attenuation in lead of x rays produced by potentials of 50- to 200-kv peak.*

The measurements were made with a 90° angle between the electron beam and the axis of the x-ray beam and with a pulsed waveform. The curves at 50 and 70 kvp were obtained by interpolation and extrapolation of available data (Braestrup, 1944) [2]. The filtrations were 0.5 mm of aluminum for 50, 70, 100, and 125 kvp, and 3 mm of aluminum for 150 and 200 kvp [26].

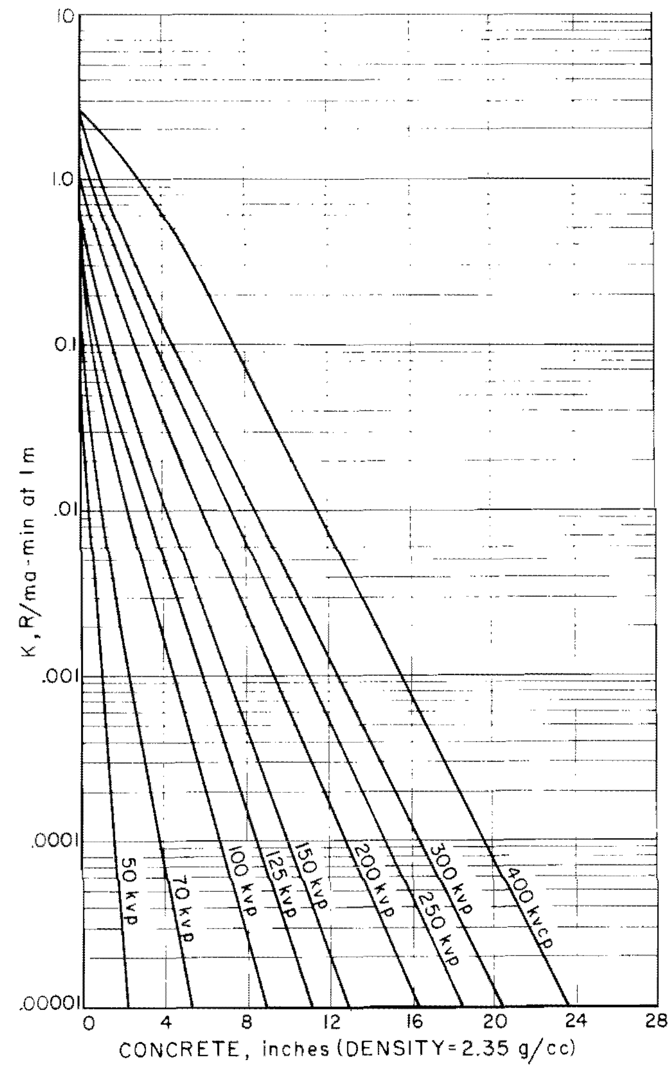

FIGURE 18. *Attenuation in concrete of x rays produced by potentials of 50 to 400 kv.*

The measurements were made with a 90° angle between the electron beam and the axis of the x-ray beam. The curves for 50 to 300 kvp are for a pulsed waveform. The filtrations were 1 mm of aluminum for 70 kvp, 2 mm of aluminum for 100 kvp, and 3 mm of aluminum for 125 to 300 kvp (Trout et al., 1955 and 1956) [11]. The 400-kvcp curve was interpolated from data obtained with a constant potential generator and inherent filtration of approximately 3 mm of copper (Miller and Kennedy, 1955) [8] [26].

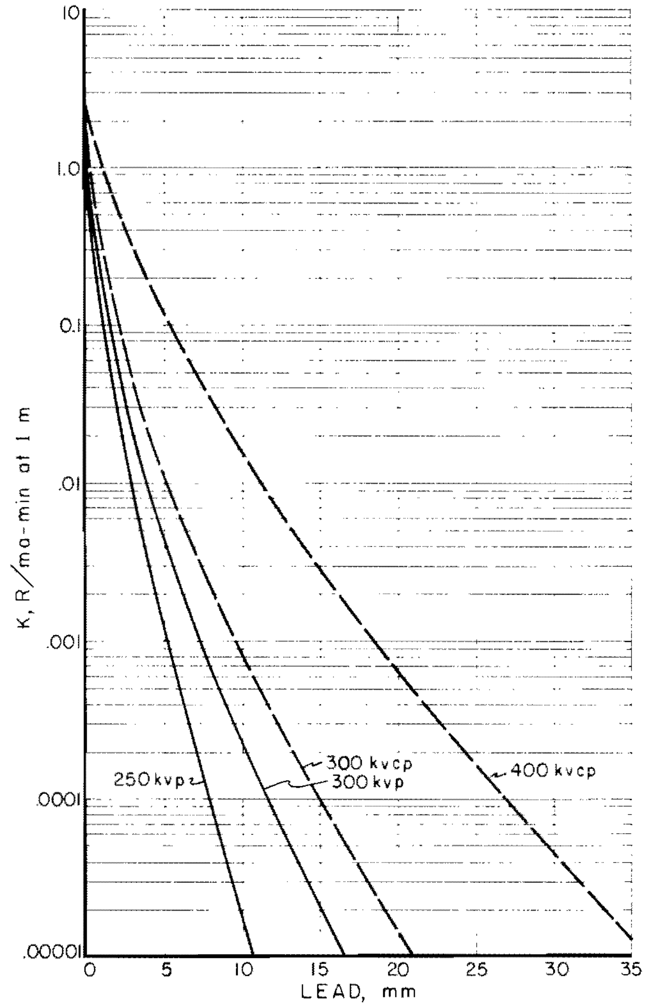

FIGURE 19. *Attenuation in lead of x rays produced by potentials of 250 to 400 kv.*

The measurements were made with a 90° angle between the electron beam and the axis of the x-ray beam. The 250-kvp curve is for a pulsed waveform and a filtration of 3 mm of aluminum (Braestrup, 1944) [2]. The 400-kvcp curve was obtained with a constant potential generator and inherent filtration of approximately 3 mm of copper (Miller and Kennedy, 1955) [8]. The 300-kvp curve is for pulsed waveform and 3 mm of aluminum (Trout et al., 1959) [11] [26].

The 300-kvcp curve is interpolated and extrapolated from the broad beam data obtained with constant potential (Miller and Kennedy, 1955 [8]).

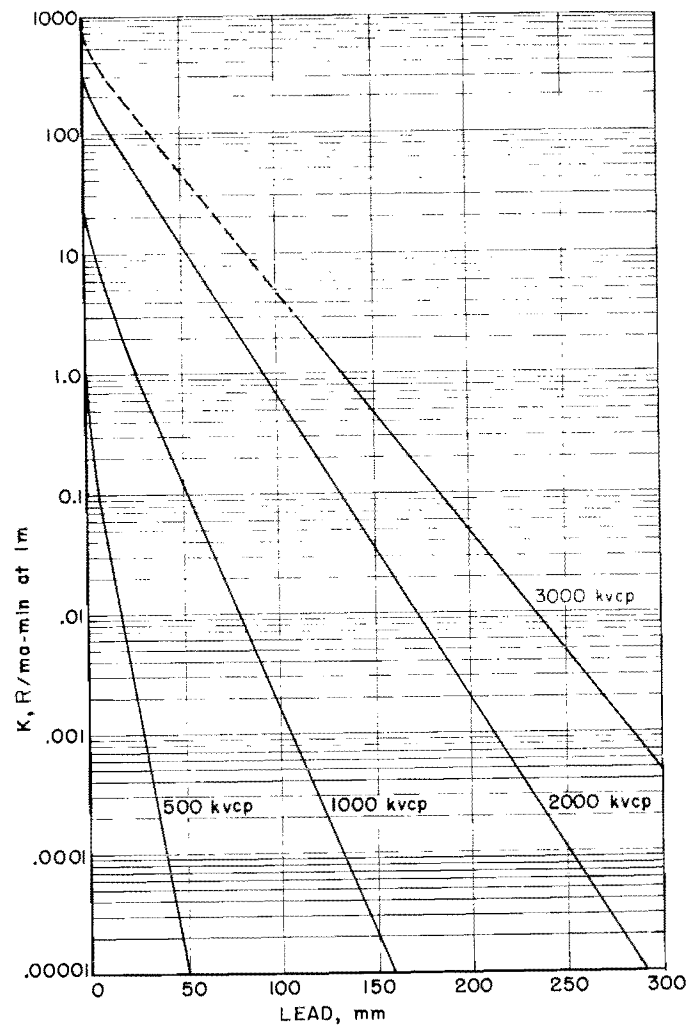

FIGURE 20. *Attenuation in lead of x rays produced by potentials of 500- to 3,000-kv constant potential.*

The measurements were made with a 0° angle between the electron beam and the axis of the x-ray beam and with a constant potential generator. The 500- and 1,000-kvcp curve were obtained with filtration of 2.88 mm of tungsten, 2.8 mm of copper, 2.1 mm of brass, and 18.7 mm of water (Wyckoff et al., 1948) [13]. The 2,000-kvcp curve was obtained by extrapolating to broad-beam conditions (E.E. Smith) the data of Evans et al., 1952 [3]. The inherent filtration was equivalent to 6.8 mm of lead. The 3,000-kvcp curve has been obtained by interpolation of the 2,000-kvcp curve given herein, and the data of Miller and Kennedy, 1956 [9].

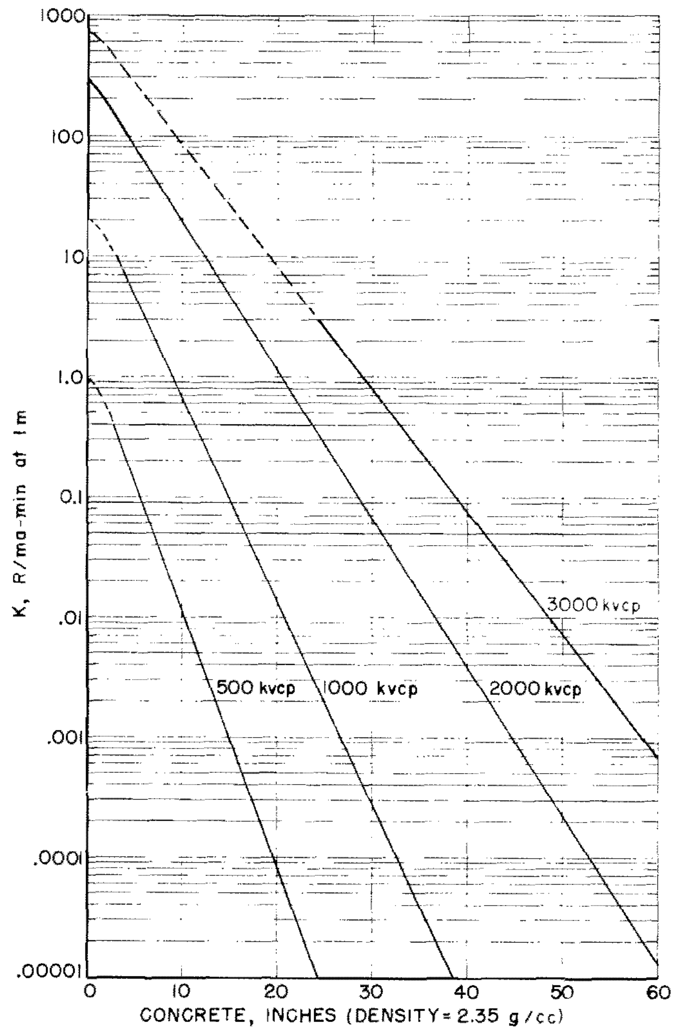

FIGURE 21. *Attenuation in concrete of x rays produced by potentials of 500- to 3,000-kv constant potential.*

The measurements were made with a 0° angle between the electron beam and the axis of the x-ray beam and with a constant potential generator. The 500- and 1,000-kvcp curves were obtained with filtration of 2.8 mm of copper, 2.1 mm of brass, and 18.7 mm of water (Wyckoff et al., 1948) [13]. The 2,000-kvcp curve was obtained by extrapolating to broad-beam conditions (E.E. Smith) the data of Evans et al., 1952 [3]. The inherent filtration was equivalent to 6.8 mm of lead. The 3,000-kvcp curve has been obtained by interpolation of the 2,000-kvcp curve given herein, and the data of Kirn and Kennedy, 1954 [5].

parameters, it is only necessary to determine the allowed value of K and then to find the corresponding thickness on the appropriate kilovoltage curve for the barrier material which is to be used.

The value of K will depend first of all on the maximum permissible dose which is to be used. *For design purposes only*, this may be taken to be 100 mR/week for controlled areas and 10 mR/week for environs. Secondly, it will depend upon the workload (W), use factor (U), occupancy factor (T), and the distance (d) from the target to the area of interest. The smaller the product of WUT and the greater the distance, the larger the permitted value of K. Larger WUT values and shorter distances will result in smaller values for K.

The relation between these variables may be expressed by the equation.

$$K=\frac{Pd^2}{WUT}, \tag{1}$$

where

P = Maximum permissible dose equivalent
 0.1 R/week for controlled areas
 0.01 R/week for environs

d = distance in meters. (If distance in feet is used, this becomes $d/3.28$.)

W = workload in ma-min/week. (This should, insofar as possible, be averaged over a period of at least several months and preferably a year.)

U = use factor.

T = occupancy factor. (See table 3 of appendix C for suggested values.)

Example:

Find the primary protective barrier thickness necessary to protect a controlled area 32.8 ft from the target of an x-ray machine operating at a maximum energy of 100 kvp. The wall in question has a use factor of 1/4, the workload is estimated to average 1,000 ma-min/week, and the occupancy factor of the area to be protected is 1.

$P=0.1$ r week
$d=32.8/3.28=10$
$W=1{,}000$
$U=1/4$
$T=1.$

Therefore,

$$K = \frac{0.1 \times 100}{1{,}000 \times 1/4 \times 1} = 0.04$$

Reference to figures 17 and 18 shows that the required barrier thickness is 1½ in. of concrete or 0.4-mm lead.

Attention should be given at this point to the amount of protection which may be supplied by the structural materials of the wall. Often these appreciably attenuate the radiation and can be considered as fulfilling at least part of the barrier requirements. Unfortunately, there are few detailed attenuation data for these materials [12], but to a first approximation, their concrete equivalents may be calculated on the basis of density alone. Concrete equivalent in inches is equal to the density of the material in question multiplied by the thickness of the material in inches and divided by 2.35. When these materials are of higher atomic number than concrete, this approximation tends to underestimate the concrete equivalent (i.e., to lead to somewhat more protection than is needed). Table 14 in appendix D lists some common building materials and the ranges of their densities.

For example, we may assume in the problem just given that there is already 1.0 in. of sand plaster in the wall. Reference to table 14 shows that this material has an average density of 1.54, making a concrete equivalent of 0.65 in. already present. The remaining protection requirement of 0.85 in. of concrete is shown in table 12, appendix D, to be just slightly more than 1 hvl for 100 kvp highly filtered radiation. Thus, the addition of 0.3 mm of lead would amply take care of the situation.

Computation of Secondary Protective Barriers

Again by definition, secondary protective barriers are those exposed only to leakage and scattered radiation. Obviously, the use factor for these radiations is always one. Since these radiations may be of considerably different qualities, their barrier requirements must be computed separately. Furthermore, as the qualities and other factors differ greatly under various combinations of circumstances, there is no single method of computation that is always wholly satisfactory. However, *for first approximations*, the following rules may be used as guides.

Leakage radiation:

The number of hvl's required in the secondary barrier for leakage radiation alone depends upon: (1) the operating potential of the tube; (2) the weekly operating time of the tube; (3) the distance from the tube to the occupied area; (4) the nature and degree of occupancy; and (5) whether the area in question is a controlled area. The maximum amount of leakage radiation allowed through a tube housing is 1 R at 1 m in any 1 hr. Thus, the workload is measured only in terms of the average number of hours of actual operating time per week. The radiation by passage through the tube housing has already attained a hvl which depends only on the tube potential. Table 12 in appendix D gives representative hvl thicknesses for lead and concrete for various kilovoltages. Table 13 gives the number of hvl's necessary to reduce the exposure rate to the required degree for various weekly operating times and various distances for both controlled areas and environs. The required barrier thickness for leakage radiation alone may be found simply by determining the number of hvl's necessary to reduce the exposure rate to the permissible level for the given distance and operating time and multiplying this number by the thickness of the hvl of lead or concrete for the given kilovoltage. As mentioned before, if building materials other than concrete are used, the necessary thickness may be computed on the basis of their concrete equivalents.

Scattered radiation:

The amount and energy of the scattered radiation depend on a large number of factors. These include the incident exposure rate, the cross-sectional area of the beam at the irradiated object, the absorption in the object, the angle of scattering and the operating potential of the x-ray tube. However, in shielding design certain simplifications can be made. For x rays generated at potentials below 500 kv, Compton scattering does not greatly degrade the photon energy and the scattering object also acts as an absorber for the lower energy photons. For design purposes the 90° scattered radiation generated from a useful beam produced at a potential of less than 500 kv may be assumed to have the same average energy as the useful beam. Consequently, the transmission curve for the useful beam may be used in determining necessary barrier thickness. In the supervoltage range, the 90° scattered radiation is, to a first approximation, equal in energy distribution to x rays generated by potentials of 500 kv regardless of the kilovoltage of the useful beam. Therefore, in the supervoltage range, the 500 kvcp transmission curve may be used in the calculation of the secondary barrier thickness. It has been shown that the amount of 90° scattered radiation is approximately 0.1 percent of that incident upon the scatterer. Thus, a K value 1,000 times greater may be allowed for scattered radiation than for that of the useful beam. However, the exposure rate at a fixed distance increases with the x-ray kilovoltage. Therefore, in order to use the 500 kvcp curve for the scattered radiation, K must be decreased by a factor of 20 for 1,000 kvcp radiation, by 120 for 2,000 kvcp, and by 300 for 3,000 kvcp.

Equation (1) may, therefore, be used for the computation of secondary barriers subject to the following modifications:

(a) For scattered radiation from useful beams generated at 500 kvcp or below.

$$K=\frac{1{,}000\times P\times d^2}{WT} \quad \text{(Use curve for kv of useful beam).} \quad (2)^1$$

(b) For scattered radiation from useful beams generated at 1,000 kvcp.

$$K=\frac{1{,}000\times P\times d^2}{20\,WT} \quad \text{(Use 500 kvcp curve).} \quad (3)^2$$

(c) For scattered radiation from useful beams generated at 2,000 kvcp.

$$K=\frac{1{,}000\times P\times d^2}{120\,WT} \quad \text{(Use 500 kvcp curve).} \quad (4)^2$$

(d) For scattered radiation from useful beams generated at 3,000 kvcp.

$$K=\frac{1{,}000\times P\times d^2}{300\,WT} \quad \text{(Use 500 kvcp curve).} \quad (5)^2$$

[1] If a 50-cm FSD is used divide K by 4.
[2] If a 70-cm FSD is used divide K by 2.

If the barrier thicknesses for leakage and scattered radiations are found to be approximately the same, 1 hvl should be added to the larger one to obtain the required total secondary barrier thickness. If the two differ by a large enough factor (this situation is assumed to exist if there is a difference of at least 3 hvl's), the thicker of the two will be adequate.

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