

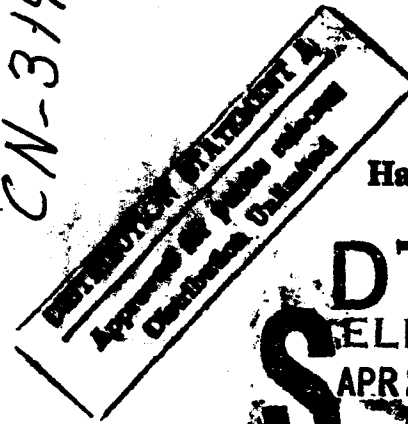
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X-RAY PROTECTION

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

# X-RAY PROTECTION

Recommendations of the  
National Committee on Radiation Protection



**DTIC QUALITY INSPECTED 3**

**National Bureau of Standards Handbook 60**

**Issued December 1, 1955**

**(Supersedes Handbook 41)**

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## ADDENDUM TO NATIONAL BUREAU OF STANDARDS HANDBOOK 60

The NCRP has recently (*Radiology*, February 1957) revised the recommendations in NBS Handbook 59 on the maximum permissible radiation dose. Distinction is made between controlled areas (areas where the exposure of persons is under the supervision of a radiation safety officer) and regions outside of controlled areas.

The revised recommendations, as interpreted for NBS Handbook 60, mean that the maximum permissible weekly dose remains 0.3 r for all ages of occupational workers, but not to exceed an average yearly dose of 5 r. Therefore, the shielding should be designed for a weekly dose not to exceed 0.1 r in controlled areas. For regions outside of controlled areas, the shielding should be designed for a weekly exposure not to exceed 0.01 r after taking into account the appropriate occupancy factors, use factors, and workloads.

In order to meet the new recommendations, and until a more extensive modification of H60 can be completed, it is suggested that the following changes be incorporated in H60, issued December 1, 1955.

Pages IV and 2: Definition of MPD modified in line with NCRP recommendations (*Radiology*, February 1957).

6, 2.4.f: "One-fifth" changed to "one-tenth".

6, 2.5.b: "Permissible dose" changed to "0.1 r".

7, 3.5.a: (1) "one-fourth the MPD" changed to "0.03 r/week".

(2) "one-half the MPD" changed to "0.05 r/week".

Tables 2 and 3:

Experimental information (Smith and Kennedy, *Radiology* 64, 114 (1955); and later unpublished information) indicates that the kilovoltage actually used in diagnostic equipment is somewhat lower than that given in tables 2 and 3. If present techniques are continued, the values of the tables will provide adequate shielding to comply with the revised permissible level for controlled areas.

Tables 2, 3, 5, 6, 8, and 9:

(1) Add  $1\frac{1}{2}$  HVL for controlled areas, 5 HVL outside controlled areas to each of the tabular barrier thicknesses. (See table 11.)

(2) Delete from footnotes the sentence "For living quarters the product of workload and occupancy factor shall be multiplied by 4 for computing the protective barriers."

Page 30\*, eq (1): Replace 0.03 with 0.01 for controlled areas, and with 0.001 outside controlled areas.

31\*, eq (2): Replace 7 with 2.5 for controlled areas, and with 0.25 outside controlled areas.

31, eq (3): Replace 0.35 with 0.1 for controlled areas, and with 0.01 outside controlled areas.

31, eq (4): Replace 0.023 with 0.007 for controlled areas, and with 0.0007 outside controlled areas.

34, tables 12 and 13: Add  $1\frac{1}{2}$  HVL for controlled areas and 5 HVL outside controlled areas to each of the tabular values.

\*Only the changes in the equations have been indicated. Of course, earlier terms in section 19 will also require modification.

FEBRUARY 1957.

## Preface

This Handbook supersedes National Bureau of Standards Handbook 41, "Medical X-ray Protection up to Two Million Volts" prepared by the National Committee on Radiation Protection in 1949.

Because a great many copies of Handbook 41 have been distributed and are now in use, wherever possible each section of this new Handbook bears the same number as the corresponding section of H41. Where major changes have been made for the present Handbook, these are indicated with an asterisk. The section on electrical protection has been omitted from this revision because it does not fall within the scope of the Handbook. The word "medical" has been deleted from the present title as many of the recommendations and suggestions can be used equally well for industrial applications. This Handbook is complete in itself and reference by the reader to H41 is unnecessary.

Although these recommendations are intended primarily for the protection of the radiation worker and the public rather than the patient, the increasing use of ionizing radiations makes it necessary for the medical profession to exercise great caution and restraint in the use of these agents. Current methods and practices should be reviewed to see if the same result could be obtained with less radiation. In particular, the beam of radiation reaching the patient should be only as large in cross section as is necessary—especially in fluoroscopy. The gonads and eyes should be protected whenever possible either by limiting the size of the beam or by local shielding.

The use of student technicians as radiographic subjects for training purposes should be minimized. The student's body or any part thereof shall not be exposed to more than the maximum permissible weekly dose (see definition of **Maximum permissible dose**).

Dermatologists and radiologists should avoid as much as possible the use of radiation for the treatment of benign conditions of persons occupationally exposed to radiation. It should be the duty of the physician, when prescribing radiation treatment, to ascertain if the patient is occupationally exposed to radiation.

The maximum permissible weekly dose used in this Handbook is 0.3 r as recommended in the report of the National Committee on Radiation Protection published as National Bureau of Standards Handbook 59.

Changes in X-ray-equipment design, availability of more complete attenuation and scattering data, and a more complete analysis of the work load, use factor, and occupancy factor may necessitate future revisions of these recommendations. The structural details and recommended barrier thicknesses are shown as a guide in the planning of an installation. Other methods may be used provided the permissible weekly dose is not exceeded for any occupied areas after allowances are made for the degree of occupancy.

The National Committee on Radiation Protection (originally known as the Advisory Committee on X-ray and Radium Protection) was formed in 1929 upon the recommendation of the International Commission on Radiological Protection. The Committee is sponsored by the National Bureau of Standards and governed by representatives of participating organizations. Eleven subcommittees have been established, each 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 Dental Association: R. J. Nelsen.  
American Industrial Hygiene Association: E. C. Barnes and J. H. Sterner.  
American Medical Association: P. C. Hodges.  
American Radium Society: T. P. Eberhard and E. H. Quimby.  
American Roentgen Ray Society: T. C. Evans and R. R. Newell.  
National Bureau of Standards: L. S. Taylor, Chairman, M. S. Norloff, Editorial Secretary, and S. W. Raskin, Secretary.  
National Electrical Manufacturers Association: J. A. Reynolds and E. D. Trout.  
Radiological Society of North America: G. Failla and R. S. Stone.  
U. S. Air Force: S. E. Lifton, Maj.  
U. S. Army: E. A. Lodmell, Col.  
U. S. Atomic Energy Commission: J. C. Bugher and K. Z. Morgan.  
U. S. Navy: C. F. Behrens, Rear Adm.  
U. S. Public Health Service: H. L. Andrews and E. G. Williams.  
Representatives-at-large: Shields Warren, J. L. Weatherwax, and H. B. Williams.

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), H. H. Rossi.
- 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.
- Subcommittee 10. Regulation of Radiation Exposure, L. S. Taylor.
- Subcommittee 11. Incineration of Radioactive Waste, G. W. Morgan.

The present Handbook was prepared by the Subcommittee on X-rays up to Two Million Volts. Its membership is as follows:

H. O. WYCKOFF, Chairman	R. R. NEWELL
C. B. BRAESTRUP	S. W. SMITH
T. P. EBERHARD	E. D. TROUT
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# X-ray Protection

## I. General

### 1. Definitions

Because the correct interpretation of a statement frequently depends upon the precise meaning given to one or more critical terms, the following definitions are given for certain words and phrases as they are used in this Handbook. The list is not intended to be a complete glossary of radiation terms. Every effort has been made to insure agreement with the definitions of the same terms as used in other Handbooks of this series.

**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.

**Aluminum equivalent.** The thickness of aluminum affording the same attenuation, under specified conditions, as the material in question.

**Attenuation.** The decrease in the dose rate of radiation in passing through a material.

**Barrier.** See protective barrier.

**Concrete equivalent.** The thickness of concrete based on a density of 2.35 g/cm<sup>3</sup> (147 lb/ft<sup>3</sup>) affording the same attenuation, under specified conditions, as the material in question.

**Dose.** The quantity of radiation in roentgens at a given point, measured in air. The expression "measured in air" has a definite meaning in radiology, namely that the measurement is made at a given point in the radiation field without the presence of the human body or substitute scattering material.

**Dose rate.** Dose per unit time.

**Film badge.** Appropriately packaged X-ray-sensitive film for detecting radiation received by persons. It is usually dental-film size, and worn or carried on the person.

**Filter.** Material placed in the useful beam to absorb preferentially the less penetrating radiations.

**Added filter.** Filter added to the inherent filter.

**Inherent filter.** Filtration introduced by the wall of the X-ray tube and any permanent tube enclosure.

**Total filter.** Sum of inherent and added filters.

**Half-value layer (HVL).** The thickness of attenuating material necessary to reduce the dose rate of any X-ray beam to one-half its original value. For use in this Handbook the half-value layer shall be the half-value layer in the region of the dose rate considered.

**Kilovolts constant potential (kvcp).** The potential in kilovolts of a constant voltage generator.

**Kilovolts peak (kvp).** The crest value of the potential wave in kilovolts. When only one-half of the wave is used, the value refers to that of the useful half of the wave.

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

**Maximum permissible dose (MPD).** Dose of ionizing radiation that, in the light of present knowledge, is not expected to cause detectable bodily injury to a person at any time during his lifetime. Permissible external radiation levels for long-term *occupational* exposure and for occasional exposure are discussed in detail in the report of the Subcommittee on Permissible Dose from External Sources (*National Bureau of Standards Handbook 59*). For the limited scope of the present Handbook, the following rules based on the aforementioned report are applicable.

(a) For persons between 18 and 45 years of age, whose entire body, or major portion thereof, is exposed solely to X- or gamma rays from external sources for an indefinite period of years, the maximum permissible total weekly dose shall be 0.3 r measured in air at the point of highest weekly dose in the region occupied by the person. For persons 45 years of age or older, similarly exposed, the corresponding maximum permissible total weekly dose shall be double the above-stated value.

(b) For persons 18 years of age or older whose hands and forearms (or feet and ankles) are exposed solely to X- or gamma rays from external sources for an indefinite period of years, the maximum permissible weekly dose to these regions shall be 1.5 r. It shall be definitely understood that total weekly dose means the sum of weekly doses resulting from whole-body and local exposures, whether they take place simultaneously or in succession.

(c) For persons under 18 years of age who are exposed nonoccupationally to radiation in the course of their normal activities, protective measures shall be taken to make sure that they receive no more than 1.5 r/year.

Note: Because the exposure of persons under 18 years of age may be averaged over a whole year, the methods of computation outlined in the present Handbook will be adequate for their protection in most cases. However, for living quarters, the product of workload and occupancy factor shall be multiplied by 4 for computing the protective barriers.

**Milliroentgen (mr).** A submultiple of the roentgen equal to one-thousandth ( $\frac{1}{1000}$ ) of a roentgen.

**Monitoring.** Periodic or continuous determination of the dose rate in an occupied area (area monitoring) or of the dose received by a person (personnel monitoring).

**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. (See table 10 for degree of occupancy.)

**Occupied area.** An area that may be occupied by persons or radiation-sensitive materials.

**Pocket chamber.** A condenser ionization chamber designed to be worn in the pocket and used for monitoring. An auxiliary charging and reading device is necessary.

**Pocket dosimeter.** A pocket ionization chamber containing its own electrometer. An auxiliary charging device is usually necessary.

**Protection survey.** Evaluation of the radiation hazards in an installation. It customarily includes a physical survey of the arrangement and use of equipment, and measurements of the dose rates of radiation under expected conditions of use. (See section 2.4.)

**Protective apron.** Apron made of attenuating materials used to reduce radiation hazards.

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

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

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

**Protective glove.** Glove made of attenuating materials used to reduce radiation hazards.

**Protective tube housing.** An X-ray-tube enclosure that provides radiation protection.

**Diagnostic-type protective tube housing.** One that reduces the leakage radiation to at most 0.10 r/hr at a distance of 1 m from the tube target when the tube is operating at its maximum continuous rated current for the maximum rated voltage.

**Therapeutic-type protective tube housing.** One that reduces the leakage radiation to at most 1.0 r/hr at a distance of 1 m from the tube target and 1.0 r/min at any point on

the surface of the housing when the tube is operating at its maximum continuous rated current for the maximum rated voltage.

**Qualified expert.** A person suited by training and experience to perform dependable radiation surveys, to oversee radiation monitoring, to estimate the degree of radiation hazard, and to advise regarding radiation hazards.

**Radiation.** Energy propagated through space. In this Handbook, radiation is X-rays and high-speed electrons up to 2 Mev; but is not sound or radio waves, or visible, infrared, or ultraviolet light.

**Leakage (direct) radiation.** All radiation coming from within the tube housing, except the useful beam.

**Primary radiation.** Radiation coming directly from the target of the X-ray tube. Except for the useful beam, most of this radiation is absorbed in the tube housing.

**Scattered radiation.** Radiation that, during passage through a substance, has been deviated in direction. It may also have been modified by an increase in wavelength. It is one form of secondary radiation.

**Secondary radiation.** Radiation emitted by any matter being irradiated with X-rays.

**Stray radiation.** Radiation not serving any useful purpose. It includes leakage and secondary radiation.

**Useful beam.** See **useful beam**.

**Radiation field.** Region in which energy is being propagated.

**Radiation hazard.** Any situation where persons might be exposed to radiation in excess of the maximum permissible dose.

**Radiation survey.** See **protection survey**.

**Roentgen (r).** 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 esu of quantity of electricity of either sign.

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

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

**Workload (W).** The working activity of a machine measured in milliamperere minutes per week.

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

**X-ray installation.** The area of radiation hazard under the administrative control of the person or organization possessing an X-ray source.

## 2. Planning, Surveys, and Inspections

\*2.1.<sup>1</sup> The structural shielding requirements of any new installation, or an existing one in which changes are contemplated, should be discussed with a qualified expert early in the planning stage.

a. The expert should be provided with available data concerning the type, use, and kilovoltage of the machine to be installed in each room; the expected workload; the structural details of the building; and the type of occupancy of all areas that might be affected by this installation. *If no other information is available*, the suggested workloads, use factors, and occupancy factors included in the pertinent sections of this Handbook should be used. Some structural details are included in section 4 and planning suggestions in section 5.

b. Final plans, detailed drawings, and all pertinent specifications should be approved by the expert before construction begins.

2.2. The possibilities of multiple exposure from several different radiation sources shall be considered.

\*2.3. Included in section 2.1.b.

2.4. Protection survey.

a. A protection survey should be made by or under the direction of a qualified expert of all new installations requiring structural shielding, existing installations not previously surveyed, and after every change that might increase the radiation hazard.

b. The completed installation should be compared with the plans and specifications previously approved.

c. If safe use of the installation depends upon mechanical restrictions of the orientation of the X-ray beam and limitations (voltage, current, time, permanent filter, and maximum aperture) in the output of the tube, then an inspection shall be made to see that these restrictions are actually imposed.

d. All interlocks shall be tested to make certain that they are operating properly. A check shall be made to determine that there are a sufficient number of warning signs, properly placed.

<sup>1</sup> An asterisk before a section number indicates that the content is appreciably different from the corresponding section of Handbook 41. However, this Handbook is complete in itself and reference by the reader to H41 is unnecessary.

e. A preliminary survey shall be made with a suitably sensitive radiation-detecting instrument, which may be a Geiger counter, an ionization chamber, or a scintillation counter. Every location shall be tested that is habitually occupied or can be occupied while X-rays are being produced.

f. Every location that shows more than one-fifth the maximum permissible dose shall be investigated further with a radiation-measuring device that is suitably independent of direction and quality, or corrected therefor. X-ray-sensitive films and Geiger or scintillation counters may not be suitable for such measurements. The X-ray machine should be operating at its maximum rated voltage during these measurements.<sup>2</sup>

g. The methods of operation of the equipment should be investigated to determine whether or not proper precautions are being taken against radiation hazard.

h. If personnel monitoring is used, an evaluation of the technique shall be made. (See section 3.5.)

#### 2.5. Report of protection survey.

a. The expert shall report his findings in writing to the person or agency requesting the survey and to the person in charge of the installation.

\*b. Dose rates at critical positions shall be indicated in milliroentgens per hour or milliroentgens per hundred milli-ampere-seconds. If, at any of the indicated positions, the permissible dose is likely to be exceeded in a 40-hr week,<sup>3</sup> the time that personnel can safely remain at this position or the maximum permissible workload shall also be specified.

\*c. Deleted.

d. The report shall include recommended corrections in the operating technique, barrier thickness, or mechanical restriction of the beam that will eliminate radiation hazards in occupied positions.

e. The report should indicate whether or not a further survey is necessary after corrections have been made.

f. Recommendations shall include changes in the personnel-monitoring technique if required.

g. Copies of each report shall be kept on file by the expert and by the person in charge of the installation.

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<sup>2</sup> In evaluating the measurements, the workload shall be based on past or expected working conditions of the installation and on reasonable use factors and occupancy factor.

<sup>3</sup> The 40-hr workweek is now more common than the 48-hr workweek used in Handbook 41.

## 2.6. Periodic inspections.

\*a. All interlocks, movable barriers, and protective garments and devices should be inspected every 6 mo to see that they are not defective. Operating methods and habits of employees should be reviewed for changes in workload or occupancy.

\*b. Included in section 2.6.a.

c. Records of dates, findings, and changes shall be kept on file.

2.7. Whenever hazardous conditions are discovered they shall be corrected promptly.

## 3. Working Conditions

3.1. The person in charge shall be responsible for the working conditions in the X-ray department.

3.2. He shall be responsible for the instruction of personnel in safe working practices and in the nature of injuries resulting from overexposure to X-rays. He should promulgate special safety rules for his department, including any restrictions of the operating technique shown to be necessary.

\*3.3. Every employee should read the special safety rules and the sections of this Handbook applicable to his work.

\*3.4. Every employee and authorized visitor shall be responsible for carrying out all radiation-safety rules that concern or affect his conduct and shall use such safety devices as are furnished for his protection.

### \*3.5. Personnel monitoring.

a. Personnel monitoring shall be required for each individual for whom there is any reasonable possibility of receiving a weekly dose of X-rays exceeding one-fourth the maximum permissible dose, taking into consideration the use of protective gloves, aprons, or other radiation-limiting devices; except that, if monitoring over a period of 8 consecutive weeks shows that the dose does not exceed one-half the maximum permissible dose, then the routine monitoring of that individual may be eliminated. If the operating conditions are changed, a new monitoring test over an 8-week period shall be made.

b. It is recommended that a qualified expert be consulted on the establishment of the monitoring system. Permanent records shall be kept of all personnel-monitoring results.

c. Monitoring may be done with film badges,<sup>4</sup> pocket chambers, or pocket dosimeters. *Periodic blood counts should not be regarded as a means of radiation monitoring.*

**\*3.6. Health.**

a. The person in charge shall be responsible for the protection of employees, patients, and authorized visitors against radiation injuries and for the execution of health regulations for all employees.

b. A preemployment physical examination is generally advisable. This should include a complete occupational history; a description of any unusual exposure to radiation resulting from previous occupation, accident, or diagnostic or therapeutic exposure; a family history with special emphasis upon heritable defects; and a careful and complete physical examination. This last should include urinalysis, chest film, and a complete blood count, the latter repeated after a month. No further blood counts are necessary except when the maximum permissible dose is exceeded.

c. In the case of an exposure in excess of the maximum permissible dose, an immediate blood count should be taken. This is valuable for comparison with later blood counts.

d. Reports of physical examination and blood counts should become a permanent record.

e. Vacations should not be considered protection against overexposure to radiation.

<sup>4</sup> See table 1 for partial list of films and their useful dose ranges. Suitable calibration and controls are required, of course, for their use. See National Bureau of Standards Handbook 57 for details of film-badge monitoring.

TABLE 1. *Approximate useful exposure ranges of some films used for radiation monitoring*<sup>a</sup>

Film type	Approximate useful range in roentgens	
	100 to 200 kv region <sup>b</sup>	Million-volt region
Dupont types:		
Medical X-ray film, Xtra Fast, 508.....	0.002 to 1.8.....	0.05 to 6.
Medical X-ray film, Par Speed, 502.....	0.0025 to 2.2.....	0.1 to 10.
Industrial X-ray film, very fine grain, 510.....	0.03 to 5.....	1 to 50.
Microfilm, positive, 606.....	0.5 to 140.....	15 to 700.
Eastman Kodak types:		
Industrial X-ray film, type K.....	0.0015 to 1.1.....	0.05 to 8.
Fine Grain Release Positive, 5302.....	0.45 to 22.....	15 to 700.
Dental X-ray film, Periapical, Ultra-Speed.....	0.002 to 6.....	0.05 to 25.
Spectroscopic film, 548-0, double-coated.....	100 to 2,400.....	1,000 to 15,000.

<sup>a</sup> When developed in Kodak liquid X-ray developer for 5 min at a temperature of 20° C.

<sup>b</sup> Film sensitivities vary with photon energy by the order of a factor of 10 in this region.

#### 4. Structural Details of Protective Barriers

4.1. See chapter II for minimum barrier requirements for specific applications.

4.2. Lead barriers shall be mounted in such a manner that they will not cold-flow because of their own weight. They shall be protected against mechanical damage. It is recommended that lead barriers less than 1 mm thick be bonded to panels of some rigid supporting material.

4.3. Movable barriers should not be depended upon for protection above 100 kv.

4.4. Surfaces of 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.

4.5. Welded or burned lead seams are permissible, provided the lead equivalent of the seams is not less than the minimum requirement. (See chapter II.)

\*4.6. Joints between different kinds of protective materials shall be so designed that the over-all protection of the barrier is not impaired. (See figs. 1 and 2.)

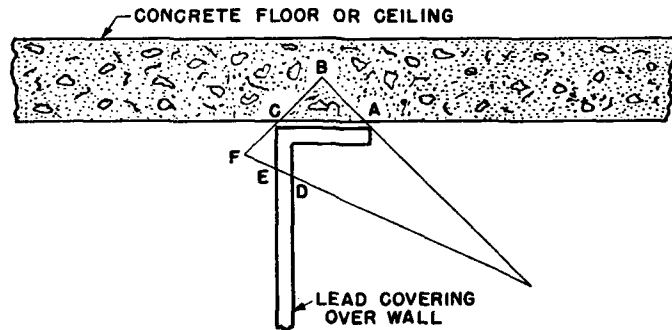


FIGURE 1. Example of a wall joint.

The sum of radiations through all paths ABCF and DEF to the point F shall not be more than the maximum permissible dose if F is in an occupied area. The framework supporting the lead wall is here considered to be of relatively X-ray-transparent material.

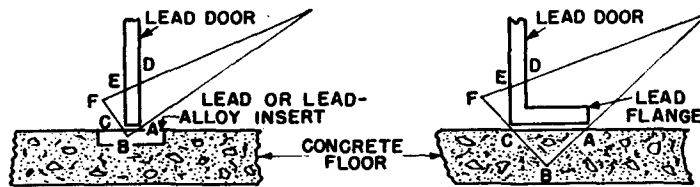


FIGURE 2. Example of door baffle.

The sum of radiations through all paths ABCF and DEF to the point F shall not be more than the maximum permissible dose if F is in an occupied area. The supporting structure for the lead door is here considered to be a framework of relatively X-ray-transparent material.

4.7. Joints at the floor and ceiling shall be so designed that the over-all protection is not impaired. (See fig. 1 for example that fulfills this requirement.)

4.8. Nails, bolts, or other fasteners through a lead sheet shall not impair the over-all protection.

4.9. Windows and doors shall have the same lead equivalent as that required of the surrounding wall. A door baffle or threshold may be required above 125 kv, if the discontinuity can be struck by the primary beam. (See fig. 2 for example that fulfills the baffle requirement.) Special attention shall be given to providing adequate overlap of the shielding of the door frame and the shielding of the door.

4.10. Holes in the barrier for pipes, conduits, air ducts, and louvers shall be provided with baffles so that the transmitted radiation is not more than that permissible for the surrounding barrier. Such holes preferably should not be struck by the primary beam.

## 5. Plans for an X-ray Installation

5.1. The cost of X-ray shielding can be materially reduced by locating the installation at a distance from occupied areas. The minimum safe distances shown in the pertinent tables of chapter II shall be considered when omission of protection on outside walls and windows is contemplated.

\*5.2. Deleted.

→ 5.3. Devices for restricting the angulation of the tube may reduce the amount of protection required.

5.4. Openings in radiation barriers should be held to a minimum.

5.5. The possibilities of radiation coming from several radiation sources at the same time or by several paths from a single source into an occupied area should be considered.

5.6. Protection against the useful beam shall be computed without a patient in the beam.

\*5.7. Deleted.

\*5.8. Protection for each occupied area shall be computed for the maximum kilovoltage, workload, and occupancy factor. *If the workload and occupancy factor are not known, average values may be used from the pertinent tables of chapter II. Special consideration should be given to the protection of film-storage areas and rooms used for measuring low-activity radioactive materials.*

## II. Additional Rules for Specific Applications

### 6. Medical Fluoroscopic X-ray Installations

See section 9 for special requirements for mobile units

#### 6.1. Equipment.

a. The tube housing shall be a diagnostic type.

b. The useful beam shall be limited by a cone and an adjustable diaphragm that, when open to its fullest extent, leaves a margin<sup>5</sup> of at least one-quarter inch of unilluminated fluorescent screen regardless of screen position during use.

c. The cone shall extend from the tube housing to a position as near the panel as possible. Its walls shall provide the same degree of protection as the tube housing, but may not require so great a thickness because of the obliquity of the rays.

\*d. Included in section 6.1.b.

e. The total filter—permanently in the useful beam—shall be equal to at least 2½ mm of aluminum. With this filtration the aluminum HVL is approximately 2.4 mm at 100 kv.

\*f. Included in section 6.1.c.

\*g. The target-to-table-panel distance *should* not be less than 18 in. and *shall* not be less than 12 in.

h. A "high-low" milliamperage change-over switch may be provided for the purpose indicated in section 6.3.c.

i. A manually reset cumulative timing-device should be used which will either indicate elapsed time or turn off the apparatus when the total exposure exceeds a certain previously determined limit given in one or in a series of exposures. If the device indicates elapsed time, it should have a maximum range of 5 min.

j. The fluoroscopic screen shall be covered with transparent protective material having a lead equivalent of at least 1.5 mm for 100 kv, or 1.8 mm for 130 kv.

\*k. For routine fluoroscopy the dose rate measured at the panel or table top shall be less than 10 r/min.

\*l. An apron of ¼ mm lead-equivalent hanging between the patient and the fluoroscopist in horizontal fluoroscopy is recommended but shall not substitute for the wearing of a protective apron.

<sup>5</sup> The margin requirement does not apply to installations where image amplifiers are used but a protective shield shall be provided in these installations so that the useful beam does not produce a radiation hazard.

**\*6.2. Structural shielding.**

Table 2 shows the barrier requirements for a workload of 4,000 ma-min/week (milliamperere-minutes per week) and occupancy factors of one, one-quarter, and one-sixteenth.

**6.3. Operation of apparatus.**

a. The fluoroscopic equipment shall be operated only by a properly trained person authorized by the radiologist in charge to conduct fluoroscopic examinations.

b. The eyes of the fluoroscopist should be well dark-adapted before he uses the fluoroscope.

c. Fluoroscopic work shall be performed in the minimum time possible using the lowest dose rate and smallest aperture consistent with clinical requirements. If a high-low switch is available, as suggested in section 6.1.h., then the low dose rate shall be used to locate the area of interest and the high dose rate only momentarily to explore the area of interest.

\*d. Unless measurements indicate that they are not needed, protective aprons shall be worn by the physician, nurse, technician, and all other persons within the fluoroscopic room who are frequently or habitually exposed to radiation hazard. The necessary lead equivalent of the apron should be determined from personnel monitoring results; but *if no measurements have been made*, the lead equivalent of the apron shall be at least  $\frac{1}{4}$  mm.

\*e. Unless measurements indicate that they are not needed, protective gloves shall be worn by the fluoroscopist during every examination. The necessary lead equivalent of the gloves should be determined from personnel monitoring results; but *if no measurements have been made*, the gloves shall have a lead equivalent of at least  $\frac{1}{4}$  mm and shall cover the whole hand—outer surface, palm, fingers, and wrist.

\*f. The hand of the fluoroscopist, either with or without gloves, shall never be placed in the useful beam unless the beam is attenuated by the patient.

g. Only persons needed in the fluoroscopic room should be there during the X-ray exposure.

## **7. Medical Radiographic X-ray Installations**

For special requirements, see section 8, dental units; section 9, mobile units; section 10, fluorography; and sections 11 and 12, units operating above 150 kv.

### **7.1. Equipment.**

a. The tube housing shall be a diagnostic type.

b. Diaphragms or cones shall be used for collimating the useful beam and shall provide the same degree of protection

TABLE 2. Protection requirements <sup>a</sup> for fluoroscopic installations

Tube potential <sup>b</sup>	Workload × occupancy factor (WT) <sup>c</sup>	Lead thickness <sup>d</sup> required for secondary barrier <sup>e</sup> at a target-to-occupied-area distance of—						Concrete thickness <sup>d</sup> <sup>f</sup> required for secondary barrier <sup>e</sup> at a target-to-occupied-area distance of—																		
		3 ft		5 ft		8 ft		10 ft		15 ft		20 ft		3 ft		5 ft		8 ft		10 ft		15 ft		20 ft		
		mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	
100	4,000	0.8	0.5	0.3	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1,000	0.5	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
125	4,000	1.1	0.8	0.5	0.3	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1,000	0.7	0.4	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
150	4,000	1.3	1.0	0.7	0.5	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1,000	0.9	0.5	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	250	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

<sup>a</sup> As the useful beam is always intercepted by the protective fluoroscopic screen cover, only secondary barriers are required.

<sup>b</sup> Constant potentials may require 15 to 25 percent larger thicknesses of lead and 5 to 15 percent larger thicknesses of concrete than those given here for pulsating potentials. These differences were estimated from the data of Miller and Kennedy at 275 to 525 kVp and from the data of Trout at 50 to 250 kVp. As these experimenters used very different filtrations, the differences indicated here may be high, especially for concrete.

<sup>c</sup> For living quarters the product of workload and occupancy factor shall be multiplied by 4 for computing the protective barriers.

<sup>d</sup> These values are slightly different from those obtained by using the method in section 19.2.c. This is because the rules outlined in the appendix are approximate, whereas these values were obtained only after rigorous use of available data.

<sup>e</sup> Note that a target-to-skin distance of 50 cm is assumed (see section 19.2.b.).

<sup>f</sup> Section 19.3. indicates an approximate method of determining the shielding requirement for other building materials. The concrete requirements for this Handbook are based on a concrete density of 2.35 g/cm<sup>3</sup>.

as the tube housing, but may not require so thick a wall because of the obliquity of the rays.

\*c. The total filter—permanently in the useful beam—shall be equal to at least  $2\frac{1}{2}$  mm of aluminum. With this filtration the aluminum HVL is approximately 2.4 mm at 100 kv.

\*d. The aluminum equivalent of the table top shall not be more than 1 mm at 100 kv when a Bucky diaphragm is used under the table top.

e. It is recommended that a timer or radiation exposure meter be provided to terminate the exposure after a preset time or exposure.

f. A "dead-man" type of exposure switch shall be used and so arranged that it cannot be operated outside a shielded area.

#### \*7.2. Structural shielding.

a. Radiographic-room floor and wall areas exposed to the useful beam shall have a primary protective barrier. The primary barrier in the walls shall extend to a height of 7 ft. (Generally the useful beam will not strike the wall above this height.) *Unless there is reason to assume otherwise,* the workload (W) used should be 1,000 ma-min/week at 100 kv, 400 at 125 kv, and 200 at 150 kv; and the use factor (U) should be one for the floor and one-quarter for all walls. Table 3 gives the primary barrier requirements for these conditions and also lower values of WUT for smaller occupancy factors (T).

b. Secondary protective barriers shall be provided in the ceiling and in those walls not having primary barriers. (See table 3.)

c. Control apparatus for the radiographic equipment shall be located in an adjacent room or in a booth within the same room. The control booth either shall be so arranged that the radiation has to be scattered at least twice before entering the booth, or shall be provided with a protective door.

d. The operator shall be able to see the patient through a window of lead equivalent sufficient for the required protection and so placed that the operator is always in a shielded position.

e. Special attention should be given to protection of undeveloped X-ray films, for these may be damaged by exposures totalling less than 1 mr. It is suggested that a small supply be stored in a lead-lined box in or near the X-ray rooms and the main supply stored elsewhere.



### 7.3. Operation of apparatus.

a. The installation should be so arranged that the useful beam is directed away from occupied areas as much as possible.

\*b. Deleted.

c. No person shall be regularly employed to hold patients during exposure nor shall anyone from the department of radiology ever be permitted to perform such service. The person holding the patient should wear protective gloves and a protective apron. No part of this person's body should be in the unattenuated useful beam.

d. Only persons required for the radiographic procedure shall be in the radiographic room during exposure.

e. The radiographic field shall not be larger than clinically necessary.

f. The patient shall not be exposed needlessly and the diagnostic objective should be attained without harmful overexposure. Table 4 is included as a guide to the dose rates to be expected in the radiographic voltage range.

TABLE 4. Typical patients' dose rates measured in air, 2½-mm Al total filter

Target-to-skin distance		Tube potential												
		50 kvp		60 kvp		70 kvp		80 kvp		90 kvp		100 kvp		125 kvp
in.	cm	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec	r/100 ma-sec
8	20	4.0	6.4	9.5	13.0	18.0	22.0	34.2						
12	30	1.8	2.8	4.2	5.8	8.0	9.8	15.2						
18	46	0.8	1.3	1.8	2.5	3.4	4.2	6.7						
24	61	.4	0.7	1.1	1.4	1.9	2.3	3.8						
36	91	.2	.3	0.5	0.6	0.9	1.1	1.7						
54	137	.1	.1	.2	.3	.4	0.5	0.7						
72	183	.1	.1	.1	.2	.2	.3	.4						

## 8. Dental Radiographic Installations

### 8.1. Equipment.

a. The tube housing shall be a diagnostic type.

b. Diaphragms or cones shall be used for collimating the useful beam and shall provide the same degree of protection as the tube housing, but may not require so thick a wall because of the obliquity of the rays.

- \*c. Included in section 8.3.f.
- d. A timer shall be provided to terminate the exposure after a preset time.
- \*e. The exposure control switch shall be of the "dead-man" type and shall be provided with a cord sufficiently long that the operator can stand at least 5 ft from the patient for all exposures and well away from the useful beam. See table 5 for barrier requirements.
- \*f. The total filter—permanently in the useful beam—shall be equal to at least  $1\frac{1}{2}$  mm of aluminum. With this filtration the aluminum HVL is approximately 1.2 mm at 65 kv.

\*8.2. Structural shielding.

a. Dental rooms containing X-ray machines shall be provided with a primary protective barrier at the sides and behind the chair, and in the floor and ceiling. *Unless there is reason to assume otherwise*, a workload of 200 ma-min/week should be used for a small general dental office and a workload of 800 ma-min/week for a busy dental radiographic room. A use factor of one-quarter should be assumed for all walls, and one-sixteenth for the floor and ceiling. Table 5 shows primary protective barrier requirements for these conditions and several occupancy factors. Primary protective barrier requirements for other conditions may be computed according to the method outlined in section 19.1.

b. Included in section 8.2.a.

c. In case dental X-ray equipment is installed in adjacent rooms, protective barriers as specified in section 8.2.a. shall be provided between the rooms.

d. Table 5 may be used to compute the shielding requirements for cephalometric techniques where intensifying screens are used as the exposures are of the same order as those in ordinary techniques.

8.3. Operation of apparatus.

a. The film should be held by the patient when an X-ray is taken or, if this is impossible, by some other person not habitually exposed to X-rays.

b. Only the patient shall be in the unattenuated useful beam.

c. Neither the tube housing nor the pointer cone shall be hand-held during exposure.



\*d. The position of the operator and/or assistant shall comply with the conditions presented in table 5 for WUT values corresponding to  $U=1$  and  $T=1$  (i.e., 100-percent occupancy of the area).

\*e. Hand-held fluoroscopic screens shall not be used.

\*f. The radiographic field should not be larger than clinically necessary.

\*g. A cone should be used for all routine exposures. In some cases the cone must be removed for special techniques, as for example temporomandibular-joint exposures where a skin dose of 25 r or more may be obtained during a single exposure with 65 kvp, 1.5 mm aluminum total filter, and 60 ma-sec. The regular cone should be reinstalled immediately after completion of such exposures.

## 9. Special Requirements for Mobile Medical Diagnostic Equipment

### 9.1. Equipment.

a. The tube housing shall be a diagnostic type.

b. All mobile equipment shall be provided with cones or metal frames so that the minimum target-to-skin distance is at least 12 in.

c. The total filter—permanently in the useful beam—shall be equal to at least  $1\frac{1}{2}$  mm of aluminum. With this filtration the aluminum HVL is approximately 1.2 mm at 65 kv.

\*d. The exposure control switch shall be of the "dead-man" type and shall be provided with a cord sufficiently long that the operator can stand at least 6 ft from the patient for all exposures.

### 9.2. Operation of apparatus.

a. The operator should stand as far as possible from the tube and patient during exposure, and should wear a protective apron.

b. The operator shall not stand in the useful beam.

c. An operator, standing at least 6 ft from the tube and patient, should not make more than 250 ma-min of exposure during any 1 week. This corresponds approximately to the weekly permissible dose. Rotation of operators is recommended for greater workloads.

\*d. A cone or metal frame shall be used to assure a minimum target-to-skin distance of 12 in.

## 10. Fluorographic Equipment

### 10.1. Equipment.

a. The tube housing shall be a diagnostic type.

\*b. A collimator shall restrict the useful beam to the area of the fluorographic screen.

\*c. Deleted. Not necessary with change in section 10.1.b.

\*d. A primary protective barrier (see table 6) shall be provided wherever the useful beam can strike. Placing this barrier around the hood and camera, or behind the camera, eliminates the need for primary protective barriers elsewhere.

\*e. The controls shall be operable only from behind a protective barrier. The observation window should be so placed that the useful beam is not usually directed at the window.

### \*10.2. Structural shielding.

a. Incorporated in section 10.1.d.

b. Table 6 shows the thickness of secondary protective barriers required under specified conditions.

### \*10.3. Operation of apparatus.

a. Incorporated in section 10.1.e.

b. Personnel monitoring is recommended for mobile installations.

c. All personnel shall be in shielded positions during exposure.

## 11. Therapeutic X-ray Installations Operated at Potentials of 400 kv and Below

See section 11.4 for special requirements

### 11.1. Equipment.

a. The tube housing shall be a therapeutic type.

b. Permanent diaphragms or cones shall be used for collimating the useful beam and shall afford the same degree of protection as the tube housing. Adjustable or removable beam-defining diaphragms shall not transmit more than 5 percent of the useful beam obtained with the maximum treatment filter. (See table 7.)

TABLE 6. Protection requirements for fluorographic installations

Tube potential <sup>a</sup>	WUT <sup>b</sup>	Useful beam protection														Lead thickness required for secondary barrier <sup>c</sup> at a target-to-occupied-area distance of—				Concrete thickness <sup>e, f</sup> required for secondary barrier <sup>c</sup> at a target-to-occupied-area distance of—							
		Lead thickness required for primary barrier at a target-to-occupied-area distance of—														Distance without barrier <sup>d</sup>				Lead thickness required for secondary barrier <sup>c</sup> at a target-to-occupied-area distance of—				Concrete thickness <sup>e, f</sup> required for secondary barrier <sup>c</sup> at a target-to-occupied-area distance of—			
		3 ft	5 ft	8 ft	10 ft	15 ft	20 ft	3 ft	5 ft	8 ft	10 ft	15 ft	20 ft	3 ft	5 ft	8 ft	10 ft	3 ft	5 ft	8 ft	10 ft	3 ft	5 ft	8 ft	10 ft		
kvp 100	ma-min per week 2,000	2.1	1.7	1.4	1.3	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9			
	500	1.6	1.3	1.0	0.9	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5			
	125	1.2	0.9	0.6	0.5	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3			
	30	0.8	0.5	0.3	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
150	7	0.4	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
	1,000	2.5	2.1	1.8	1.6	1.3	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1			
	250	2.0	1.6	1.3	1.1	0.9	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7			
	60	1.4	1.1	0.8	0.7	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3			
	15	1.0	0.7	0.5	0.3	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
	4	0.6	0.3	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			

<sup>a</sup> Constant potentials may require 15 to 25 percent larger thicknesses of lead and 5 to 15 percent larger thicknesses of concrete than those given here for pulsating potentials. These differences were estimated from the data of Miller and Kennedy at 275 to 525 kvp and from the data of Trout at 50 to 250 kvp. As these experimenters used very different filtrations, the differences indicated here may be high, especially for concrete.

<sup>b</sup> W = workload, U = use factor, T = occupancy factor. Use factor for secondary barrier is always 1. For living quarters the product of workload and occupancy factor shall be multiplied by 4 for computing the protective barriers.

<sup>c</sup> Section 19.3 indicates an approximate method of determining the shielding requirement for other building materials. The concrete requirements for this Handbook are based on a concrete density of 2.35 g/cm<sup>3</sup>.

<sup>d</sup> Distance from target at which the weekly useful beam dose will not exceed 0.3 r. These distances were computed from the outputs at zero barrier thickness given in figures 3 and 4 and the air absorption coefficient for double the minimum wavelength.

<sup>e</sup> These values are slightly different from those obtained by using the method in section 19.2.c. This is because the rules outlined in the appendix are approximate, whereas these values were obtained only after rigorous use of available data.

<sup>f</sup> Note that a target-to-skin distance of 50 cm is assumed (see section 19.2.b.).

<sup>g</sup> Equivalent to 3,000 40-ma-sec exposures per week.

c. The filter system shall be so arranged as to minimize the possibility of error. Filters shall be secured in place to prevent them from dropping out during treatment. The filter slot shall be so constructed that the radiation escaping through it does not exceed 1 r/hr at 1 m.

d. The X-ray tube shall be centered and mounted so that it cannot turn or slide with respect to the aperture. A mark on the housing should show the location of the focal spot. Special precautions are necessary if the inherent filtration of the useful beam is very low. (See section 11.4.d.)

e. Devices shall be provided to immobilize the tube housing during treatment.

f. Open valve-tubes may require shielding.

g. A timer shall be provided to terminate the exposure after a preset time.

\*h. A beam-monitoring device fixed in the useful beam is recommended to indicate any error due to incorrect filter, milliamperage, or kilovoltage.

i. Lead rubber, lead foil, etc., used for limiting the field should transmit less than 5 percent of the useful beam. (See table 7.)

TABLE 7. Guide to thickness of adjustable beam-defining diaphragms

Attenuating material	Approximate thickness of attenuating material necessary for the reduction of the useful-beam dose rate to 5 percent at a potential of—					
	60 kvp HVL=1.2 Al <sup>a</sup> Filter= 1½ Al <sup>b</sup>	100 kvp HVL=3.0 Al <sup>a</sup> Filter= 3 Al <sup>b</sup>	140 kvp HVL=0.5 Cu <sup>a</sup> Filter= ¼ Cu <sup>b</sup>	200 kvp HVL=1.0 Cu <sup>a</sup> Filter= 0.5 Cu <sup>b</sup>	250 kvp HVL=3.0 Cu <sup>a</sup> Filter= 3 Cu <sup>b</sup>	400 kvp HVL=5.0 Cu <sup>a</sup> Filter= 5 Cu <sup>b</sup>
Lead.....	mm 0.1	mm 0.3	mm 0.7	mm 1.0	mm 1.7	mm 3.5
Brass.....	.3	1.2	4	9	18	-----

<sup>a</sup> Half-value layer in millimeters.

<sup>b</sup> Approximate total filtration in millimeters.

### 11.2. Structural shielding.

a. The required barriers should be a permanent part of the building or equipment. Movable lead screens are not recommended and shall not be depended upon above 100 kv.

b. The cost of structural shielding can be reduced considerably by locating the treatment rooms as remotely as possible from occupied areas, thus taking advantage of the reduction due to distance (inverse-square law). This is

particularly true for the higher voltages where thicker barriers are required. Corner rooms are especially suited; the outside walls and windows do not require any protection if they are sufficiently distant from other occupied buildings and areas. Consideration should be given to future occupancy of nearby areas. See table 8 for the minimum distance required. Where most treatments are given with the beam pointed toward the floor, special consideration shall be given to the protection of persons habitually in the rooms directly below the treatment room.

c. The control shall be located outside the treatment room for voltages above 100 kv.

\*d. All wall, ceiling, and floor areas that can be struck by the useful beam, plus a border of at least 1 ft, shall be provided with primary protective barriers. *Unless there is reason to assume otherwise*; the work load should be taken at the largest value in the second column of table 8; and this should be multiplied by a use factor of one for the floor, one-quarter for the walls, and one-sixteenth for the ceiling; and then further multiplied by the occupancy factor for the area that the barrier protects (see table 10). Table 8 gives the barrier requirements for these conditions. All wall, ceiling, and floor areas that, because of restrictions in the beam orientation, cannot be struck by the useful beam shall be provided with secondary protective barriers.

\*e. Incorporated in section 11.2.d.

### 11.3. Operating methods.

a. The installation shall be operated in compliance with any limitations indicated by the protection survey.

b. No person who works with ionizing radiation shall be in the treatment room during exposure. No other person shall be there except when it is clinically necessary. If a person is required to hold the patient, he shall not be in the useful beam and shall be protected as much as practicable from scattered radiation.

c. Both the patient and the control panel shall be under observation during exposure. Provision for oral communication with the patient from the control room is desirable.

d. The useful beam should be directed toward unoccupied areas whenever consistent with therapeutic requirements.

\*e. The machine shall shut off automatically when the door to the treatment room is opened. After such a shut-off, it shall be possible to turn on the machine only from the control panel. Entrances to other areas of radiation hazard should be similarly protected by interlocks.

TABLE 8. Protection requirements for therapeutic installations

Tube potential kVp	WUT * ma-min per week	Useful beam protection															Lead thickness <sup>d</sup> required for secondary barrier at a target-to-occupied-area distance of—					Concrete thickness <sup>b, c</sup> required for secondary barrier at a target-to-occupied-area distance of—										
		Lead thickness required for primary barrier at a target-to-occupied-area distance of—										Concrete thickness <sup>b</sup> required for primary barrier at a distance of—					Distance with-out barrier <sup>e</sup>					Lead thickness <sup>d</sup> required for secondary barrier at a target-to-occupied-area distance of—					Concrete thickness <sup>b, c</sup> required for secondary barrier at a target-to-occupied-area distance of—					
		3 ft	5 ft	8 ft	10 ft	15 ft	20 ft	3 ft	5 ft	8 ft	10 ft	15 ft	20 ft	3 ft	5 ft	8 ft	10 ft	15 ft	20 ft	ft	3 ft	5 ft	8 ft	10 ft	15 ft	3 ft	5 ft	8 ft	10 ft	15 ft		
50	1,000	0.3	0.2	0.2	0.1	0.1	1.2	1.0	0.7	0.5	0.3	4.0	3.4	2.7	2.2	1.5	1.1	0.8	0.6	0.4	0.3	40	1.3	1.0	0.7	0.5	0.3	4.0	3.3	2.7	2.2	1.5
	250	0.2	0.2	0.1	0.1	0.1	0.8	0.6	0.4	0.3	0.2	3.0	2.6	2.1	1.5	1.1	0.8	0.6	0.4	0.3	0	25	0.9	0.5	0.3	0	0	3.0	2.2	1.3	0.8	0
	60	0.2	0.1	0.1	0	0	0.6	0.3	0.2	0.1	0	2.0	1.4	1.1	0.8	0.3	0	0	0	0	0	13	0.4	0.3	0	0	0	1.9	0.8	0	0	0
	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	---	---	---	---	---	---	---	---	---	---
100	4,000	2.3	2.0	1.7	1.5	1.3	1.1	1.0	0.8	0.7	0.5	7.0	6.0	5.2	4.7	4.0	3.4	2.7	2.2	1.5	1.1	150	1.7	1.3	0.9	0.7	0.5	5.0	3.8	2.7	2.2	1.5
	1,000	1.8	1.5	1.2	1.1	0.8	0.7	0.5	0.4	0.4	0.3	4.7	4.7	3.9	3.4	2.7	2.2	1.5	1.1	0.8	0.3	90	1.1	0.7	0.4	0.3	0	3.3	2.0	1.2	0.9	0
	250	1.4	1.1	0.8	0.7	0.4	0.2	0.3	0.2	0.2	0.1	3.0	2.1	1.4	1.1	0.8	0.3	0	0	0	0	25	0.5	0.3	0	0	0	1.7	0.9	0	0	0
	60	1.0	0.7	0.5	0.4	0.2	0	0	0	0	0	1.8	1.1	0.6	0.3	0	0	0	0	0	0	15	---	---	---	---	---	---	---	---	---	---
150	4,000	3.1	2.7	2.3	2.1	1.8	1.6	1.4	1.2	1.0	0.8	10.4	9.2	8.0	7.4	6.4	5.7	4.0	3.4	2.7	2.2	180	1.7	1.3	0.9	0.7	0.5	5.0	3.8	2.6	2.0	1.3
	1,000	2.5	2.1	1.8	1.6	1.3	1.1	0.9	0.7	0.5	0.4	7.7	6.2	5.7	4.7	4.0	3.4	2.7	2.2	1.5	1.1	110	1.1	0.7	0.4	0.3	0	3.3	2.0	1.2	0.9	0
	250	2.0	1.6	1.3	1.1	0.9	0.7	0.5	0.4	0.3	0.2	5.7	4.5	4.0	3.0	2.3	1.5	1.1	0.8	0.3	0	65	0.5	0.3	0	0	0	1.7	0.9	0	0	0
	60	1.4	1.1	0.8	0.7	0.4	0.2	0	0	0	0	3.4	2.3	1.3	0.9	0.3	0	0	0	0	0	35	---	---	---	---	---	---	---	---	---	---
200	4,000	6.4	5.7	5.0	4.7	4.1	3.7	3.2	2.9	2.4	2.0	16.9	15.3	14.0	13.2	12.0	11.2	8.0	7.4	6.4	5.7	440	4.1	3.4	2.7	2.4	1.8	9.7	8.1	6.6	6.0	4.9
	1,000	5.4	4.7	4.0	3.7	3.2	2.9	2.4	2.1	1.6	1.3	10.6	9.0	7.6	6.9	5.7	4.8	4.1	3.4	2.7	2.2	300	3.1	2.4	1.7	1.4	1.1	7.5	6.0	4.7	4.1	3.0
	2,500	4.4	3.7	3.1	2.9	2.4	2.1	1.6	1.3	1.0	0.8	8.4	7.0	6.0	5.5	4.8	3.7	2.9	2.4	1.7	1.4	200	2.1	1.4	1.0	0.7	0.5	5.5	4.1	2.9	2.4	1.6
	60	3.5	2.8	2.3	2.0	1.6	1.3	1.0	0.8	0.4	0.3	5.5	4.8	3.7	2.9	2.4	1.6	1.1	0.8	0.3	0	70	---	---	---	---	---	---	---	---	---	---
250	4,000	11.3	10.0	8.7	8.2	7.2	6.5	5.6	5.0	4.2	3.6	19.0	17.4	15.9	15.2	13.8	12.9	10.4	9.1	8.4	7.4	600	6.4	5.3	4.4	3.8	3.1	11.3	9.6	8.0	7.4	6.1
	1,000	9.5	8.2	7.0	6.5	5.6	5.0	4.2	3.6	3.0	2.4	14.6	12.9	11.4	10.6	9.3	8.4	7.0	6.0	5.5	4.8	350	5.0	3.8	2.9	2.4	1.8	9.1	7.4	5.9	5.3	4.1
	2,500	7.7	6.5	5.5	5.0	4.2	3.6	2.9	2.4	2.0	1.4	10.5	9.1	8.4	7.1	6.1	5.3	4.4	3.4	2.7	2.2	220	3.5	2.4	1.7	1.3	0.9	6.9	5.3	3.9	3.3	2.3
	60	6.1	5.0	4.0	3.6	2.9	2.4	1.8	1.4	1.1	0.8	8.4	7.0	6.0	5.5	4.8	3.7	2.9	2.4	1.7	1.4	130	---	---	---	---	---	---	---	---	---	---
150	4.6	2.7	2.4	2.4	1.8	1.4	1.0	0.8	0.4	0.3	4.0	3.4	2.7	2.2	1.5	1.1	0.8	0.3	0	0	80	---	---	---	---	---	---	---	---	---	---	---



11.4. Special requirements for X-ray therapy equipment operating at potentials of 50 kv and below.

a. Installations shall comply with the general requirements of sections 11.1, 11.2, and 11.3 except that the operator is allowed to be in the treatment room during irradiation. He shall take special care to avoid exposure to the useful beam. Structural shielding generally is not required. Because of the short target-window distance and low inherent filter, the dose rate at the tube aperture may be extremely high.

b. The term "grenz ray" is used to describe very soft X-rays produced at potentials below 20 kv. Because of the low penetration of these rays, it is not necessary to shield the operator or other persons in the treatment room unless they are exposed to the useful beam at a target distance of less than 3 m. However, it should be emphasized that grenz rays are X-rays and that they may cause the same type of injurious effects as harder X-rays, although limited to superficial layers of tissue.

\*c. The term "contact therapy" is used to describe short-distance irradiation of accessible lesions. The potential is usually 40 to 50 kv. Because the dose rate at the surface of the window of the tube housing is sometimes as high as 10,000 r/min, rigid precautions are necessary to prevent accidental exposure to the useful beam. The leakage radiation at the surface of the tube housing shall not exceed 0.1 r/hr. If the tube is to be hand-held during irradiation, the operator shall wear protective gloves and apron. When the apparatus is not being used for treatment, a cap (0.5-mm lead equivalent) shall cover the aperture window of the tube housing. The automatic timer shall be adjustable in graduations at least as fine as 1 sec.

d. Special precautions shall be required in the therapeutic application of apparatus constructed with beryllium or other low-filtration windows for both grenz-ray and higher kilovoltage therapy. As a dose rate of more than 1 million roentgens per minute is possible at the aperture, adequate shielding shall be required against the useful beam; and special safeguards are essential to avoid accidental exposures.

\*e. Machines having an output of more than 1,000 r/min at any accessible place shall not be left unattended without the power being shut off, first at the control and then at the primary disconnecting means (i. e., wall plug or main switch). These shall never be turned off in the reverse order.

## 12. Therapeutic X-ray Installations Operated at Potentials above 400 kv

### 12.1. Equipment.

- a. The tube housing shall be a therapeutic type.
- b. Permanent diaphragms or cones shall be used for collimating the useful beam and shall afford the same degree of protection as the tube housing. Adjustable or removable beam-defining diaphragms shall not transmit more than 5 percent of the useful beam. For 1 million-volt machines, this requires approximately 21 mm of lead; for 2 million-volt, approximately 43 mm of lead.
- c. Devices shall be provided to immobilize the tube housing during treatment.
- d. A beam-monitoring device fixed in the useful beam is recommended to indicate any error due to incorrect filter, milliamperage, or kilovoltage.
- e. A timer shall be provided to terminate the exposure after a preset time.
- \*f. Incorporated in section 12.3.c.

### 12.2. Structural shielding.

- a. The general rules of sections 4 and 5 shall be followed for structural shielding.
- \*b. The cost of structural shielding can be reduced considerably by locating the treatment rooms as remotely as possible from occupied areas, taking advantage of the reduction due to distance (inverse-square law). Corner rooms are especially suited; the outside walls and windows do not require any protection if they are sufficiently distant from other occupied buildings and areas. Consideration should be given to future occupancy of nearby areas. See table 9 for the minimum distance required. Where most treatments are given with the beam pointed toward the floor, special consideration shall be given to the protection of persons habitually in the rooms directly below the treatment room. All wall, ceiling, and floor areas that might be struck by the useful beam, plus a border of at least 1 ft, shall be provided with primary protective barriers. *Unless there is reason to assume otherwise*; the workload should be taken at the largest value in the second column of table 9; and this should be multiplied by a use factor of one for the floor, one-quarter for the walls, and one-sixteenth for the ceiling;

TABLE 9. Protection requirements for therapeutic installations

Tube potential <sup>a</sup>	WUT <sup>b</sup>	Useful beam protection																									
		Lead thickness required for primary barrier at a target-to-occupied-area distance of—						Concrete thickness required for primary barrier at a target-to-occupied-area distance of—						Dis- tance without bar- rier		Lead thickness required for secondary barrier at a target-to-occupied-area distance of—						Concrete thickness required for secondary barrier at a target-to-occupied-area distance of—					
		5 ft	8 ft	10 ft	15 ft	20 ft	30 ft	5 ft	8 ft	10 ft	15 ft	20 ft	30 ft	ft	in.	5 ft	8 ft	10 ft	15 ft	20 ft	30 ft	5 ft	8 ft	10 ft	15 ft	20 ft	30 ft
keep 1,000	ma-min per week	mm	mm	mm	mm	mm	mm	in.	in.	in.	in.	in.	in.	ft	in.	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
2,000	4,000	115	110	100	95	85	80	31.0	27.5	25.5	24.0	22.0	20.0	700	70	40	32	28	25	22	20	72	56	48	37	30	25
	1,000	110	100	95	85	80	70	27.5	25.5	24.0	22.0	20.5	18.5	450	45	28	20	15	11	9	5	50	37	30	23	19	15
	250	95	80	70	65	55	45	24.0	22.0	20.5	18.5	17.0	15.0	290	29	15	11	9	5	5	1	30	23	20	15	12	10
	60	80	70	65	55	45	35	20.5	18.5	17.0	15.0	13.5	11.5	170	17												
	15	55	50	45	35	30	20	17.0	14.5	13.5	11.5	10.0	8.0	90	9												
	4,000	240	225	215	205	190	180	51.0	47.0	46.0	43.0	41.0	38.0	1,540	154												
	1,000	215	200	190	180	165	155	46.0	42.0	41.0	38.0	36.0	33.0	1,100	110												
	250	190	175	165	155	140	130	41.0	37.0	36.0	33.0	31.0	28.0	800	80												
	60	165	150	140	130	115	105	36.0	32.0	31.0	28.0	26.0	23.0	500	50												
	15	140	125	115	105	90	80	31.0	27.0	26.0	23.0	21.0	18.0	300	30												
	500	205	190	180	170	155	145	44.0	40.0	39.0	36.0	34.0	31.0	900	90												
	125	180	165	155	145	130	120	39.0	35.0	34.0	31.0	29.0	26.0	620	62												
	30	155	140	130	120	105	95	34.0	30.0	29.0	26.0	24.0	21.0	400	40												
	8	135	120	110	100	85	75	29.0	25.0	24.0	21.0	19.0	16.0	220	22												
	2	110	95	85	75	60	50	24.0	20.0	19.0	16.0	14.0	11.0	120	12												

<sup>a</sup> Pulsating potentials require the order of 10 percent less thickness than those given here for constant potentials.

<sup>b</sup> W = workload, U = use factor, T = occupancy factor. Use factor for secondary barrier is always 1. For living quarters the product of workload and occupancy factor shall be multiplied by 4 for computing the protective barriers.

<sup>c</sup> Section 19.3 indicates an approximate method of determining the shielding requirement for other building materials. The concrete requirements for this Handbook are based on a concrete density of 2.35 g/cm<sup>3</sup>.

<sup>d</sup> Distance from target at which the weekly useful beam dose will not exceed 0.3 r. These distances were computed from the outputs at zero barrier thickness given in figure 6 and the air absorption coefficient for double the minimum wavelength.

<sup>e</sup> These values are slightly different from those obtained by using the method in section 19.2.c. This is because the rules outlined in the appendix are approximate, whereas these values were obtained only after rigorous use of available data.

<sup>f</sup> Note that a target-to-skin distance of 50 cm is assumed (see section 19.2.b.).

<sup>g</sup> A maximum value of WUT = 4,000 is assumed for a resonance-type generator.

<sup>h</sup> A maximum value of WUT = 500 is assumed for a Van de Graaff-type generator.

and then further multiplied by the occupancy factor for the area that the barrier protects (see table 10). Table 9 gives the barrier requirements for these conditions. All wall, ceiling, and floor areas that, because of restrictions in the beam orientation, cannot be struck by the useful beam shall be provided with secondary protective barriers.

\*c. Included in section 12.2.b.

\*d. Included in section 12.2.b.

\*e. Included in section 12.2.b.

f. A maze, with the access door at the entrance where it can be reached only by multiply-scattered X-rays, may so reduce the thickness requirement for the door as to be an over-all economy.

g. The control shall be located outside the treatment room.

h. The observation window shall have a lead equivalent at least as great as that required for the surrounding wall.

### 12.3. Operating methods.

a. The installation shall be operated in compliance with any limitations indicated by the protection survey.

b. Both the patient and the control panel shall be under observation during exposure. Provision for oral communication with the patient from the control room is desirable.

\*c. The machine shall shut off automatically when the door to the treatment room is opened. After such a shutoff, it shall be possible to turn on the machine only from the control panel. Entrances to other areas of radiation hazard should be similarly protected by interlocks.

## **\*III. Electrical Protection**

Chapter III, sections 13 through 18, has been deleted in this revision, as it has been decided that electrical shock and fire hazards are not within the scope of this Handbook. For material on this subject see, for example, the pertinent sections of the latest edition of the National Electrical Code.

## **IV. Appendix**

### **\*19. Determination of Protective Barriers**

Tables 2, 3, 5, 6, 8, and 9 give directly the required thickness of lead or concrete for average weekly workloads, usual range of distance, and common degrees of occupancy. For

other conditions, the curves in this section should be used, together with the pertinent equations given below.

#### 19.1. Primary protective barriers.

Formulas for computing the primary protective barrier can be derived with the aid of figure 8. The maximum weekly dose in roentgens permitted at a position, A, in occupied space is  $0.3/T$ , where  $T$  is the occupancy factor (see table 10). By the inverse-square law, the permitted dose at 1 m from the target is  $\frac{0.3}{T} \left(\frac{D}{3.28}\right)^2$  where the 3.28 factor changes the distance,  $D$ , from feet to meters. This dose is produced by the portion of the workload,  $WU$ , during which the beam is pointed at A. It is convenient to determine the ratio,

$$K = \left[ \frac{0.3}{T} \left( \frac{D}{3.28} \right)^2 \right] / WU,$$

which can be rounded off to

$$0.03 D^2/WUT. \quad (1)$$

This ratio<sup>6</sup> gives the roentgens per milliamper-minute permitted at 1 m from the target and is thus in the same unit as the ordinates of the curves in this section. The attenuation curve for a particular tube potential therefore indicates the barrier thickness required for different values of  $K$ . For illustrative purposes, the barrier is placed immediately in front of the tube in figure 8. Actually this same barrier may be placed anywhere between the tube and position A.

#### 19.2. Secondary protective barriers.

As the qualities of the scattered and leakage radiation are different, the barrier requirement for each is computed separately. The secondary protective barrier is then determined from these results.

a. The leakage radiation has already been hardened in its passage through the tube housings so that its HVL has attained a constant value that depends only on the tube potential. Table 11 lists such HVL thicknesses. The number of HVL's required in the secondary barrier for leakage radiation depends upon (1) the type of tube housing (which limits the permissible leakage), (2) the distance from the tube to occupied areas, and (3) the weekly operating time of the tube.

<sup>6</sup> Note that  $WT$  must be multiplied by 4 when computing protection for living quarters (See definition of **Maximum permissible dose**.)

Representative values are listed in table 12 for diagnostic-type tube housings and in table 13 for therapeutic-type tube housings. The barrier thickness can be obtained by multiplying the number of half-value layers by the HVL for the tube voltage.

b. Figure 9 assists in formulating the equations for computing the barrier requirements for 90-degree-scattered radiation. As in section 19.1 the permissible weekly dose at position A is  $0.3/T$ . By the inverse-square law the dose at 1 m from the scattering source is  $\frac{0.3}{T} \left(\frac{D}{3.28}\right)^2$  or approximately  $0.03 D^2/T$ , where the 3.28 factor changes the distance,  $D$ , from feet to meters. It has been determined experimentally that the incident dose rate for most practical cases is 1,000 times larger than  $0.03 D^2/T$  or  $30 D^2/T$ . If it is assumed that the scatterer is at 50 cm from the target, the permitted dose in the useful beam at 1 m from the target is  $\frac{30}{T} \left(\frac{1}{2}\right)^2 D^2$  or approximately  $7 D^2/T$ . Again it is convenient to obtain the ratio

$$K_{400} = \frac{7D^2}{WT} \text{ (for 400 kv and below).} \quad (2)$$

The barrier for shielding against scattered radiation is always placed between the scatterer and position A, but for *the derivation only* it can be considered to be as indicated in figure 9. Actually the quality of the scattered beam may be different from that of the useful beam, but to a sufficient approximation for barrier computation the two may be considered to be the same for 400 kv and below. The curves in this section show the barrier thickness required for different values of  $K_{400}$  and the tube potential. For 1,000- and 2,000-kv X-rays, the scattered radiation can be assumed to have the same quality as 500-kv X-rays. As the 1,000- and 2,000-kv outputs are respectively 20 and 300 times the output for a 500-kv tube, the values of  $K$  are

$$K_{1,000} = \frac{0.35D^2}{WT} \text{ (for 1,000 kv).} \quad (3)$$

$$K_{2,000} = \frac{0.023D^2}{WT} \text{ (for 2,000 kv).} \quad (4)$$

The 500-kv attenuation curves of figures 6 and 7 may be used to obtain the barrier requirements for different values of  $K$  computed from equations (3) and (4).

c. If the barrier requirements of sections 19.2.a. and 19.2.b. are approximately equal, the secondary barrier thickness is obtained by adding 1 HVL to the larger requirement. If one of the barrier requirements is at least 3 HVL greater than the other, then it alone will govern the thickness requirement of the secondary protective barrier.

19.3 Determination of barrier thickness for other building materials.

Many materials other than concrete are used for structural purposes. Often they also attenuate the radiation appreciably and therefore can fulfill at least part of the barrier requirements. Unfortunately there are no detailed attenuation data for many of these materials. However, to a first approximation, their concrete equivalents may be calculated on the basis of density alone. Concrete equivalent is equal to the density of the material multiplied by the thickness of the material and divided by 2.35. As 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 needed). Table 14 lists some common building materials and the range of densities.

TABLE 10. *Occupancy factors*

For use as a guide in planning shielding where complete occupancy data are not available.

Full occupancy (T=1)
Control space, wards, office workrooms, darkrooms, corridors and waiting space large enough to hold desks, restrooms used by the radiologic staff and others routinely exposed to radiation, play areas, occupied rooms in adjacent buildings.
Partial occupancy (T=1/4)
Corridors in X-ray departments too narrow for future desk space, restrooms not used by radiologic personnel, unattended parking lots, utility rooms.
Occasional occupancy (T=1/6)
Stairways, automatic elevators, streets, closets too small for future workrooms, toilets not used by radiologic personnel.

TABLE 11. *Half-value layer* <sup>a</sup>

Attenuating material	HVL for a tube potential of—										
	50 kvp	70 kvp	100 kvp	125 kvp	150 kvp	200 kvp	250 kvp	300 kvp	400 kvp	1,000 kvp	2,000 kvp
Lead (mm).....	0.05	0.18	0.24	0.27	0.3	0.5	0.8	1.1	1.5	2.2	8.0
Concrete (in.).....	.2	.5	.7	.8	.9	1.0	1.1	1.2	1.3	1.8	2.45

<sup>a</sup> Approximate values determined at high filtration.

TABLE 12. Structural shielding necessary to protect against leakage through a diagnostic-type tube enclosure

(0.1 r/hr at 1 m, by definition)

Distance from target	Operating time				
	5 hr/week	10 hr/week	15 hr/week	25 hr/week	40 hr/week
<i>ft</i>	<i>No. of HVL</i>	<i>No. of HVL</i>	<i>No. of HVL</i>	<i>No. of HVL</i>	<i>No. of HVL</i>
3	1.0	2.0	2.6	3.3	4.0
4	0.2	1.2	1.8	2.5	3.2
5	0	0.5	1.1	1.8	2.5
6	-----	0	0.6	1.3	2.0
7	-----	-----	.1	0.8	1.5
8	-----	-----	0	.5	1.2
9	-----	-----	-----	.1	0.8
10	-----	-----	-----	0	.5
12	-----	-----	-----	-----	0

TABLE 13. Structural shielding necessary to protect against leakage through a therapeutic-type tube enclosure

(1 r/hr at 1 m, by definition)

Distance from target	Operating time				
	5 hr/week	10 hr/week	15 hr/week	25 hr/week	40 hr/week
	<i>No. of HVL</i>	<i>No. of HVL</i>	<i>No. of HVL</i>	<i>No. of HVL</i>	<i>No. of HVL</i>
3	4.3	5.3	5.9	6.6	7.3
4	3.4	4.4	5.0	5.7	6.4
5	2.8	3.8	4.4	5.1	5.8
6	2.3	3.3	3.9	4.6	5.3
7	1.8	2.8	3.4	4.2	4.8
8	1.4	2.4	3.1	3.8	4.4
9	1.1	2.1	2.7	3.4	4.1
10	0.8	1.8	2.4	3.1	3.8
12	.4	1.3	1.9	2.7	3.3
15	0	0.7	1.3	2.0	2.7
20	0	0	0.4	1.2	1.8
30	0	0	0	0	0.7

TABLE 14. Densities of commercial building materials

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

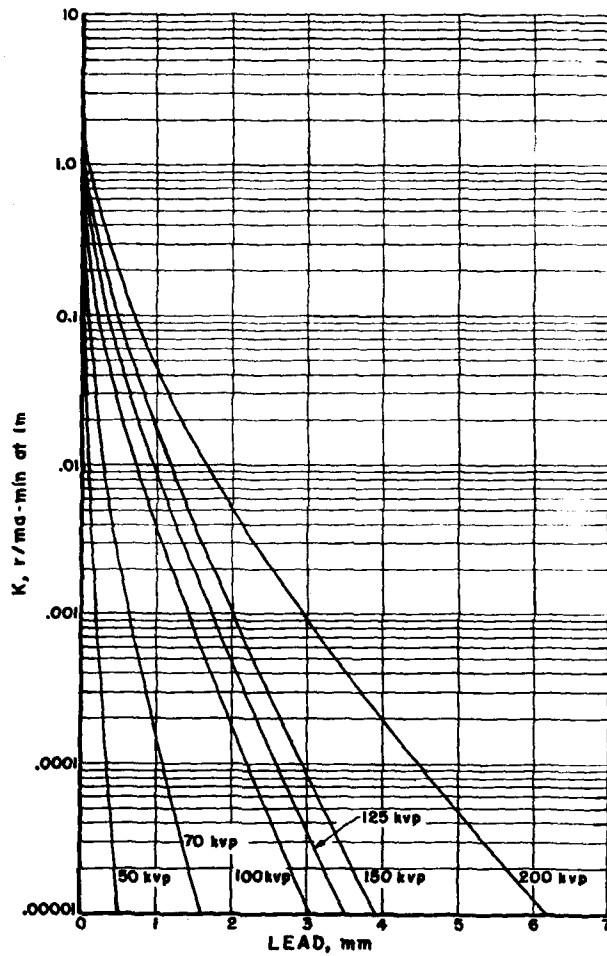


FIGURE 3. Attenuation in lead of X-rays produced by potentials of 50 to 200 kilovolts peak.

The measurements were made with a 90° angle between the electron beam and the axis of the X-ray beam and with a pulsed wave form. The curves at 50 and 70 kvp were obtained by interpolation and extrapolation of available data (Braestrup, 1944). 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.

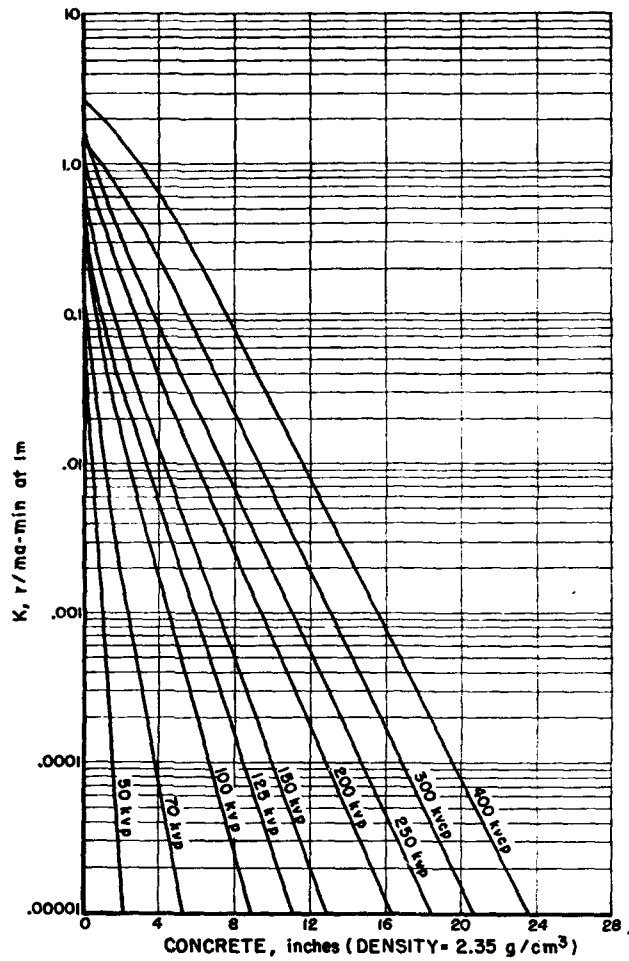
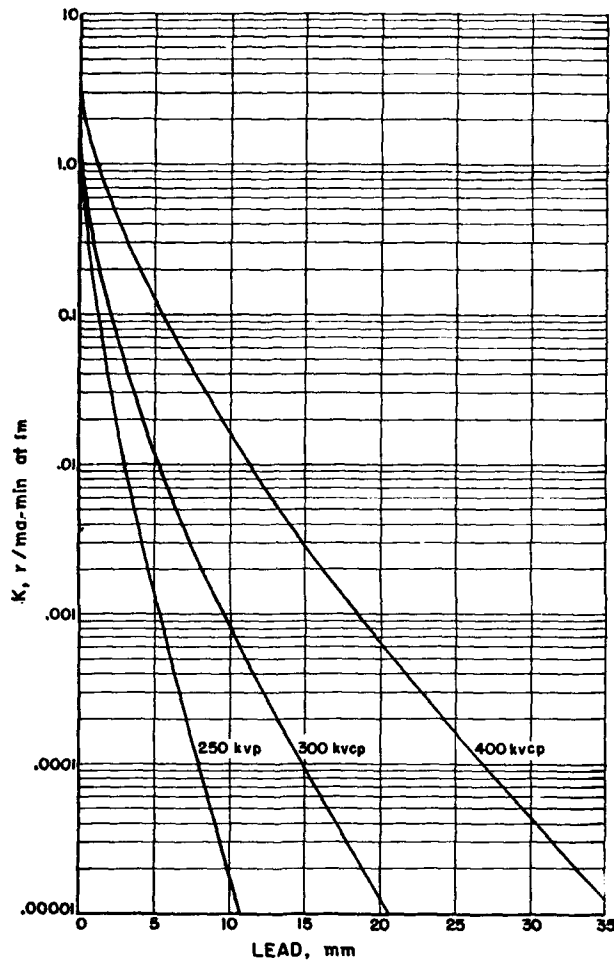


FIGURE 4. Attenuation in concrete of X-rays produced by potentials of 50 to 400 kilovolts

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 250 kVp are for a pulsed wave form. The filtrations were 1 mm of aluminum for 50 kVp, 1½ mm of aluminum for 70 kVp, 2 mm of aluminum for 100 kVp, and 3 mm of aluminum for 125 to 250 kVp (Trout et al. 1955). The 300- and 400-kVp curves were interpolated from data obtained with a constant potential generator and inherent filtration of approximately 3 mm of copper (Miller and Kennedy, 1955).



**FIGURE 5.** Attenuation in lead of X-rays produced by potentials of 250 to 400 kilovolts

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 wave form and a filtration of 3 mm of aluminum (Braestrup, 1944). The 300- and 400-kvcp curves were interpolated from data obtained with a constant potential generator and inherent filtration of approximately 3 mm of copper (Miller and Kennedy, 1956).

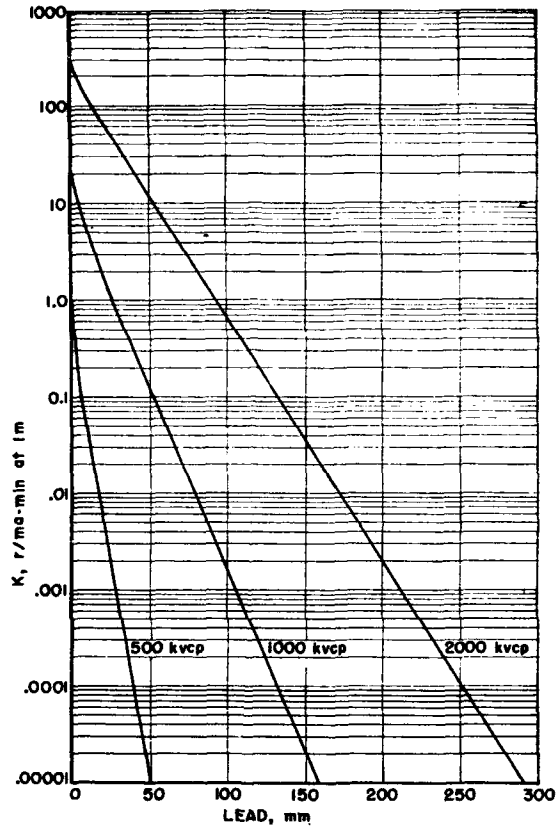
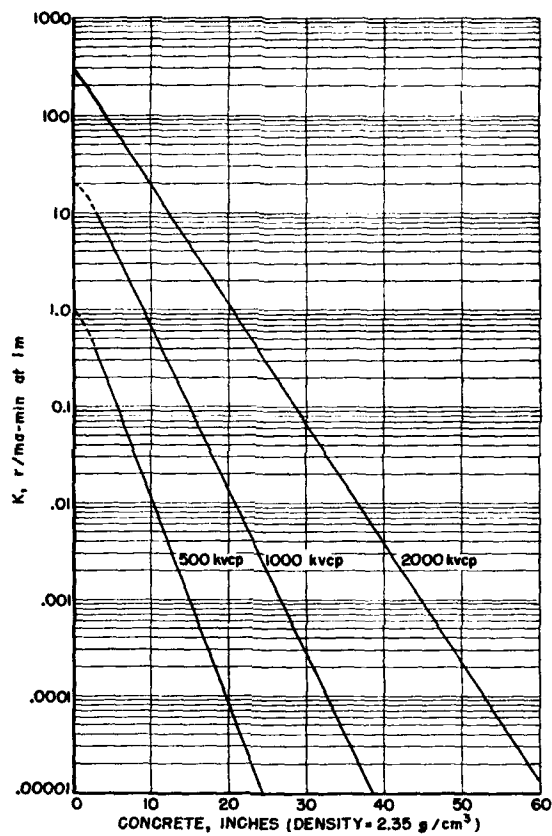


FIGURE 6. Attenuation in lead of X-rays produced by potentials of 500 to 2,000 kilovolts constant potential.

The measurements were made with a  $0^\circ$  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 tungsten, 2.8 mm of copper, 2.1 mm of brass, and 13.7 mm of water (Wyckoff et al. 1948). The 2,000-kvcp curve was obtained by extrapolating to broad-beam conditions (E. E. Smith) the data of Evans et al. 1952. The inherent filtration was equivalent to 6.8 mm of lead.



**FIGURE 7.** Attenuation in concrete of X-rays produced by potentials of to 2,000 kilovolts constant potential.

The measurements were made with a  $0^\circ$  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 tungsten, 2.8 mm of copper, 2.1 mm of brass, and 18.7 mm of water (Wyckoff, et al. 1948). The 2,000-kvcp curve was obtained by extrapolating to broad-beam conditions (E. E. Smith) the data of Evans, et al. 1952. The inherent filtration was equivalent to 6.8 mm of lead.

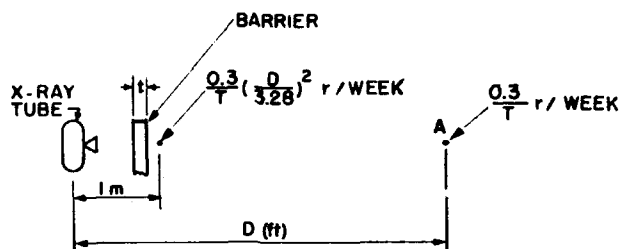


FIGURE 8. The steps in the computation of equation (1) for the useful beam.

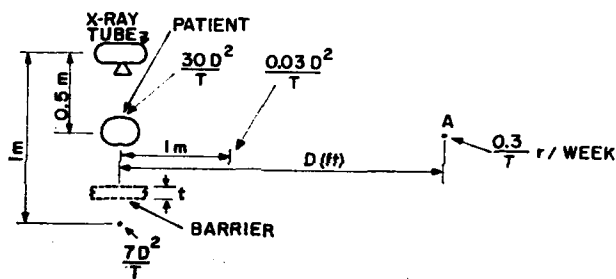


FIGURE 9. The steps in the computation of equation (2) for scattered radiation.

Note that the patient is irradiated at 0.5 m but that the value of K is evaluated at the 1 m distance. Note also that the barrier as pictured is placed in the useful beam but is actually in the beam of scattered radiation.

**\*20. Incorporated in appropriate sections.**

**\*21. Incorporated in appropriate sections.**

**\*22. Incorporated in appropriate sections.**

**\*23. Deleted.**

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