MEDICAL X-RAY PROTECTION UP TO THREE MILLION VOLTS

Handbook 76

U.S. Department of Commerce
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U.S. Department of Commerce • Luther H. Hodges, Secretary
National Bureau of Standards • A. V. ASTIN, Director

Medical X-Ray Protection Up to Three Million Volts

Recommendations of the
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Foreword

X-ray protection is a cooperative venture requiring for its ultimate success the responsible actions of the manufacturers of apparatus, the designers and builders of the rooms housing it, the individuals in charge of installations, and the persons actually using the equipment. Guiding, advising, and checking on each of these are the qualified experts and the inspectors. Each must do his part conscientiously and sensibly to apply those rules which experience has shown to be necessary if the application of X-ray energy is to yield the greatest good and the least harm to the largest number of people. This Handbook, the latest in the series on this subject published by the National Bureau of Standards, contains recommendations and data of the National Committee on Radiation Protection and Measurements pertaining to all persons involved and is based on the best available authoritative information.

A. V. ASTIN, *Director*.

Preface

The multifaceted characteristic of these recommendations cannot be too strongly emphasized. For example, the maximum output or the tube housing leakage of an X-ray machine can be fairly readily determined using short exposure times. An exposure limitation based on such a determination might be a perfectly legitimate requirement to impose on the manufacturer of the equipment, but there would be no justification for extrapolating such a determination to continuous, 40-hour a week operation if it were known that the duty cycle of the tube was only 5 percent of this maximum value. The philosophy of dose limits based upon accumulated, RBE doses, enunciated by the International Commission on Radiological Protection and the National Committee on Radiation Protection and Measurements, other than the previously used short-term exposures, makes such distinctions imperative. At the operational level, too, it must be stressed that a collimating cone which is provided but left on the shelf does not meet the requirements of this Handbook.

It should be emphasized that this Handbook is not a legal document and that its provisions were not written to be used in their entirety as official regulations. Those recommendations phrased with the word "shall" represent requirements which are believed to be mandatory. Those using the word "should" cover a variety of less critical situations. It is desirable that these latter be applied whenever and wherever they are practicable. In some cases, equipment has not yet been developed to the point where the recommendations can be applied universally. In others, the recommendations have been met by the manufacturers of current equipment, but the Committee believes that the risk involved in the judicious use of older equipment is not sufficiently great to justify the condemnation of thousands of otherwise satisfactory units. Generally, the manner of use of X-ray equipment is of more importance than its mechanical design. There are other recommendations which may be quite practical or even considered mandatory in a large, very busy installation but which would be quite unnecessary in an installation with a single machine and a very low workload. Persons who are charged with the formulation of radiation protection regulations and who lack practical experience in the field should seek the advice of competent experts before establishing rigid rules based on the recommendations of this Handbook.

The basic requirements in the present Handbook are essentially the same as those of its immediate predecessor Handbook 60. The tables have been revised to conform with the present lower maximum permissible dose (MPD) and the differences in the maximum permissible doses allowed in controlled areas and in their environs. Recommendations have been altered, deleted, or added as necessary to cover situations created by recent technical advances in machine design and by the development of new radiological techniques. All tabular and graphic material has been placed in the appendixes. The format has been revised to avoid repetition. The philosophy, however, remains as it was originally expressed by the Advisory Committee on X-ray and Radium Protection 30 years ago, namely, that unnecessary radiation exposure should always be avoided and all exposure held to the minimum compatible with practical clinical requirements.

The other members of Subcommittee 3 are deeply indebted to Carl B. Braestrup and Harold O. Wyckoff who did the arduous work of recalculating the barrier thickness tables of Handbook 60 simultaneously for this Handbook and for their book, Radiation Protection.

It is with great sorrow that the committee realizes the passing of Dr. Eberhard, Chairman of this Subcommittee. His efforts in radiology in general, and for the NCRP in particular, have been of great value, and his friendly cooperation will be missed by all of us.

This report was prepared by Subcommittee 3, Medical X-rays up to Three Million Volts, which consists of the following members:

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Subcommittee 7. Monitoring Methods and Instruments, H. L. Andrews.
Subcommittee 8. Waste Disposal and Decontamination. (This subcommittee has been inactivated.)
Subcommittee 9. Protection Against Radiations from Ra, Co^{60}, and Cs^{137} Encapsulated Sources, C. B. Braestrup.
Subcommittee 10. Regulation of Radiation Exposure Dose Working Group, A. A. McAdams.
Subcommittee 11. Incineration of Radioactive Waste, G. W. Morgan.
Subcommittee 12. Electron Protection, L. S. Skaggs.
Subcommittee 13. Safe Handling of Bodies Containing Radioactive Isotopes, E. H. Quimby.
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Subcommittee M-2. Standards and Measurement of Radiological Exposure Dose, H. O. Wyckoff.
Subcommittee M-3. Standards and Measurement of Absorbed Radiation Dose, H. O. Wyckoff.
Subcommittee M-4. Relative Biological Effectiveness, V. P. Bond.

LAURISTON S. TAYLOR, *Chairman*
National Committee on Radiation Protection and Measurement
Washington, D.C., July 29, 1960.

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Medical X-ray Protection Up to 3 Million Volts

I. General

1. Definitions

Because the precise meaning given to one or more critical terms frequently determines the interpretation of a statement, 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 terminology. 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.

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".)

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

Added filter.—Filter added to the inherent filtration.

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

Barrier.—See Protective Barrier.

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

Constant potential.—(cp)-In radiological practice, this term is applied to a unidirectional potential (or voltage) which has little, or no, periodic variation. The periodic component is called the ripple potential (or ripple voltage).

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.)

Dead-man switch.—A switch so constructed that a circuit closing contact can only be maintained by continuous pressure by the operator.

Diagnostic-type protective tube housing.—X-ray tube housing so constructed that the leakage radiation at a distance of 1 m from the target cannot exceed 100 mr in 1 hr when the tube is operated at any of its specified ratings. See par. 4.1.f, 6.1.a, 7.1.a, 10.1.a.

Exposure.—See **Exposure dose.**

Exposure dose.—The exposure dose of X- or gamma radiation at a certain place is a measure of the radiation that is based upon its ability to produce ionization. The unit of exposure dose is the roentgen. (When the meaning is clear, this term may be shortened to "exposure").

Exposure dose rate (exposure rate).—Exposure dose per unit time.

Film badge.—A pack of appropriate photographic film and filters used to determine radiation exposure.

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

FSD.—Distance from focal spot to skin surface of patient.

Half-value layer (hvl).—Thickness of an absorber required to reduce a beam of radiation to one-half its incident exposure dose rate.

Inherent filtration.—Filtration in the useful beam due to the window of the X-ray tube and any permanent tube enclosure.

Installation.—A radiation source, with its associated equipment, and the space in which it is located.

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

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

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

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 (MPD).—The maximum RBE dose 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 RBE dose in rems may be considered numerically equal to the absorbed dose in rads and the exposure dose in roentgens numerically equal to the absorbed dose in rads. (See table 1, appendix A.)

Milliroentgen (mr).—One-thousandth of a roentgen.

Monitoring.—Periodic or continuous determination of the exposure rate in an area (area monitoring) or the exposure 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 2, appendix A.)

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

Pocket chamber.—A small condenser ionization chamber used for determining radiation exposure. An auxiliary charging and reading device is usually necessary.

Pocket dosimeter.—A small ionization instrument which indicates radiation exposure directly. An auxiliary charging device is usually necessary.

Primary protective barrier.—See protective barrier.

Protective apron.—Apron made of attenuating materials, used to reduce radiation exposure.

Protective barrier.—Barrier of attenuating materials used to reduce radiation exposure.

- **Primary protective barrier.**—Barrier sufficient to attenuate the useful beam to the required degree.
- **Secondary protective barrier.**—Barrier sufficient to attenuate stray radiation to the required degree.

Protective glove.—Glove made of attenuating materials used to reduce radiation exposure.

Qualified expert.—A person having the knowledge and training necessary to measure ionizing radiations and to advise regarding radiation protection.

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

Radiation.—Energy propagated through space. In this Handbook, radiation refers to X-rays.

- **Leakage radiation.**—All radiation coming from within the tube housing except the useful beam.
- **Scattered radiation.**—Radiation that, during passage through matter, has been deviated in direction. It may also have been modified by a decrease in energy.
- **Secondary radiation.**—Radiation emitted by any irradiated material.
- **Stray radiation.**—Radiation not serving any useful purpose. It includes leakage and secondary radiation.
- **Useful beam.**—That part of the radiation which passes through the window, aperture, cone, or other collimating device of the tube housing.

Radiation hazard.—A condition under which persons might receive radiation in excess of the maximum permissible dose, or radiation damage might be caused to materials.

Radiation protection (safety) officer.—Person directly responsible for radiation protection. (See par. 5.5.b.)

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.

RBE dose.—RBE (relative biological effectiveness) dose is numerically equal to the product of the dose in rads and an agreed conventional value of the RBE with respect to a particular form of radiation effect.

Rem.—The unit of RBE dose.

Roentgen (*r*).—The unit of exposure dose of X- or gamma radiation. One roentgen is an exposure dose of X- or gamma radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign.

Scattered radiation.—See **Radiation.**

Secondary protective barrier.—See **Protective barrier.**

Secondary radiation.—See **Radiation.**

Shutter.—A device, generally of lead, fixed to an X-ray tube housing to intercept the useful beam.

Stray radiation.—See **Radiation.**

Survey.—See **Radiation protection survey.**

Therapeutic-type protective tube housing.—X-ray tube housing so constructed that the leakage radiation at a distance of 1 m from the target cannot exceed 1 r in 1 hr and at a distance of 5 cm from any point on the surface of the housing accessible to the patient cannot exceed 30 r in 1 hr when the tube is operated at any of its specified ratings. (See par. 11.1.a., 4.1.f.)

Total filter.—The sum of the inherent and added filters.

Use factor (U).—The fraction of the workload during which the useful beam is pointed in the direction under consideration. (See table 3, Appendix A.)

Useful beam.—See **Radiation.**

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

Workload (W).—The use of an X-ray machine expressed in milliampere minutes per week.

X-ray apparatus.—Any device for the production of X-rays.

2. Plans for an X-ray installation

2.1. Qualified expert.

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

2.1.b. The expert should be provided with available data concerning the type, the kilovoltage, the contemplated use of the machine to be installed in each room, the expected workload, the expected use factors, the structural details of the building, and the type of occupancy of all areas that might be affected by the installation. Some structural details are included in section 3. Data for the determination of protective barrier thicknesses may be found in the appendixes of this Handbook.

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

2.2. Special attention must be given to the protection requirements of areas outside of controlled areas (environs).

2.3 The determination of primary barrier requirements may include consideration of the attenuation of the useful beam provided by the patient and objects normally in the path of the useful beam.

2.4. At times, shielding requirements may be reduced by locating the installation at a distance from occupied areas. The minimum safe distances shown in tables 4 and 5, appendix A, shall be considered when the omission of protective barriers is contemplated.

2.5. 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 no objection to directing the useful beam at occupied areas provided there is adequate shielding.)

2.6. Devices which permanently restrict the direction and size of the useful beam may reduce the area requiring primary barriers.

2.5. Openings in protective barriers should be held to a minimum. (See 3.8.)

2.6. The possibility should be considered that an occupied area may receive radiation from several sources or by several paths from a single source.

2.7. Protection for each occupied area should be computed on the basis of the expected maximum kilovoltages, workloads, use factors, and occupancy factors 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.

2.8. Special attention should be given to the protection of areas used for the storage of undeveloped films and of rooms for measuring low-activity radioactive materials. (Undeveloped X-ray films may be damaged by exposures totaling as little as 1 mr.) (See table 6, appendix A.)

3. Structural Details of Protective Barriers

(See Chapter II and Appendix B for minimum barrier requirements for specific applications.)

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

3.2. Surfaces of lead sheets at joints in the barrier should be in contact with a lap of at least one-half inch or twice the thickness of the sheets, whichever is the greater.

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

3.4. Joints between different kinds of protective materials shall be so designed that the overall protection of the barrier is not impaired. (See Figs. 1 and 2.)

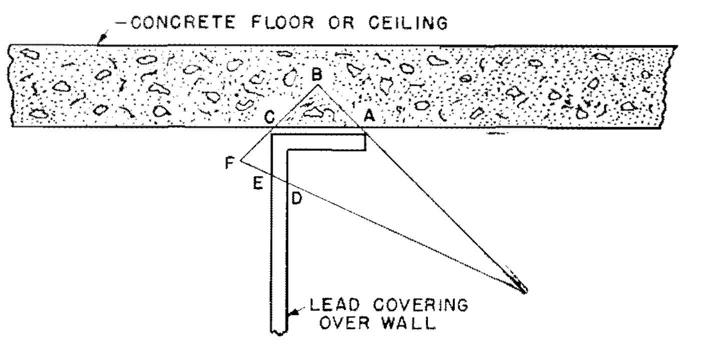

FIGURE 1. *Example of a wall joint.*

The sum of radiations through all paths ABCF and DEF to the point F shall 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.

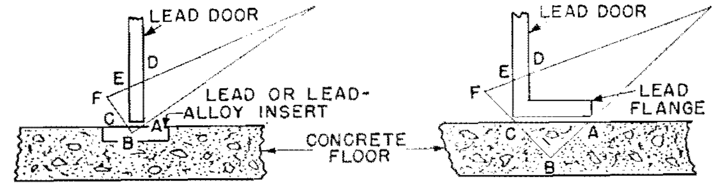

FIGURE 2. *Example of door baffle.*

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

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

3.6. Windows, window frames, doors, and door frames shall have the same lead equivalent as that requried of the adjacent wall. Where thick concrete walls are tapered in to openings, as is frequently done with observation windows, it may be necessary to add lead protective flanges around the window frame to compensate for the reduced thickness of concrete. 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 fig. 2 for example that fulfills the baffle requirement.) Special attention should be given to providing overlap of the shielding of the door frame and the shielding of the door.

3.7. Holes in protective barriers shall be covered so that overall attenuation is not impaired.

3.8. Louvers and holes in barriers for pipes, conduits, service boxes, and air ducts may require baffles to insure that the overall protection afforded by the barrier is not impaired. It is advisable to locate such holes outside of the range of directions of the useful beam.

4. Protection Surveys and Inspections

4.1. Protection survey.

4.1.a. All new installations, and existing installations not previously surveyed, shall have a protection survey made by, or under the direction of, a qualified expert. This shall also be done after any change in the installation which might produce a radiation hazard. In evaluating the results of the survey, account should be taken of actual operating conditions, including workload, use factor, occupancy, and attenuation of the useful beam provided by patients and objects normally in the path of the useful beam.

4.1.b. If the safe use of the installation depends upon mechanical or electrical restrictions of the orientation of the useful beam, an inspection shall be made to confirm that these restrictions are actually imposed.

4.1.c. All interlocks shall be tested to make certain that they are operating properly. An inspection shall be made to determine that any warning signals are properly located and functioning.

4.1.d. If there is any reasonable probability of an occupant of a given area receiving more than the maximum permissible dose, the exposure rate for that area shall be determined. (See par. 5.6.a.)

4.1.e. If personnel monitoring is used, an evaluation of the techniques shall be made.

4.1.f. A recommended method of testing for leakage radiation from a tube housing is to operate the tube, with the window of the housing blocked with at least 10 hvl of absorbing material (e.g., lead), at its maximum voltage and at its maximum current for continuous operation at that voltage. When this is not practical, the test may be made at a higher current, provided that careful consideration is given to the limitation of operating time in any 1 hr imposed by the duty cycle of the tube as determined from the manufacturer's tube rating and cooling charts.

4.2. Report of protection survey.

4.2.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.

4.2.b. Exposure rates determined in occupied areas should be indicated in milliroentgens per hour for therapeutic and flouroscopic installations and in milliroentgens per 100 ma-sec (or minutes) for diagnostic installations. If, at any of the indicated positions, any person is likely to be exposed to more than the maximum permissible dose, then recommendations of changes to eliminate the radiation hazard shall be made, with due regard to actual operating conditions, including workload, use factor, and occupancy.

4.2.c. Recommendations for corrective measures may include changes in operating techniques, equipment, mechanical restrictions of the beam direction, barriers, etc.

4.2.d. Recommendations shall include any necessary changes in the personnel monitoring technique.

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

4.2.f. Copies of each report shall be dated and kept on file by the expert and by the person in charge of the installation. Copies of pertinent sections dealing with limitations of occupancy, operating techniques, and/or workloads should be posted near the control panel.

4.3. Periodic inspections.

4.3.a. All interlocks, movable barriers, and protective garments and devices should be inspected periodically to see that they are not defective. Operating methods, work habits of employees, occupancy factors, and workloads should also be reviewed periodically.

4.3.b. Whenever hazardous conditions are discovered, they shall be corrected promptly.

5. Working Conditions

5.1. It is the responsibility of the user to assure that all X-ray equipment under his jurisdiction is operated only by persons competent in its safe use.

5.2. The user shall be ultimately responsible for the instruction of personnel in safe operating procedures and in the nature of injuries resulting from overexposure to X-rays. He should promulgate rules for working safety, including any restrictions of the operating technique known to be necessary.

5.3. Every operator should be familiar with the safety rules and with the sections of this Handbook applicable to his work and should be guided by the recommendations.

5.4. All persons entering a controlled area shall comply with all radiation safety instructions which concern or affect their conduct and shall use such safety devices as are furnished for their protection.

5.5. Radiation protection officer.

5.5.a. There should be a radiation protection officer attached to each installation who should be responsible to the user for advising on the establishment of safe working conditions according to current standards, including those recommended in this Handbook, and for compliance with all pertinent Federal, State, and local regulations.

5.5.b. The specific duties of the radiation protection officer should include:

(1) Establishing and maintaining operational procedures so that the radiation exposure of each worker is kept as far below the maximum permissible exposure as is practicable.

(2) Instructing personnel in safe working practices and in the nature of injuries resulting from overexposure to radiation.

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(3) Assuring that personnel monitoring devices are used where indicated and that records are kept of the results of such monitoring.

(4) Conducting periodic radiation surveys where indicated and keeping records of such surveys, including descriptions of corrective measures.

(5) Investigating each case of excessive or abnormal exposure to determine the cause and taking steps to prevent its recurrence.

5.6. Personnel monitoring.

5.6.a. Personnel monitoring shall be required in controlled areas for each individual, except patients, for whom there is any reasonable probability of receiving a dose exceeding one-fourth of the maximum permissible dose, taking into consideration the use of protective gloves, aprons, or other radiation limiting devices. (See table 1, Appendix A, and Addendum to HB–59, April 15, 1958, for details of the maximum permissible dose under various conditions.)

5.6.b. A qualified expert should be consulted about the establishment and operation of the monitoring system. At any time that operating conditions are changed, a qualified expert should be asked to re-evaluate the monitoring requirements of the installation.

5.6.c. Records shall be kept of all personnel monitoring results.

5.6.d. Monitoring may be done with film badges, pocket chambers, or pocket dosimeters. Weekly readings of film badges may be useful in detecting inadequacies of operating conditions, but monthly readings are recommended for the recording of accumulated doses. (With any monitoring device, the greatest uncertainty in determining exposure arises from the fact that the body may not be uniformly exposed. Ordinarily, the best place to wear a monitoring device is on the chest or abdomen. If a protective apron is worn, the monitoring device should be worn under the apron, provided preliminary monitoring of other parts of body areas not covered up by the apron indicate that there is no reason to expect exposures in excess of the limits prescribed for those parts of the body. Radiation monitoring devices should, of course, not be worn by the individual when he receives radiation exposure for medical or dental reasons.)

5.6.e. Blood counts are of no value for monitoring.

5.6.f. Radiation exposure of persons as part of medical and dental procedures is not to be included in the determination of the radiation exposure status of those persons.

5.7. Health.

5.7.a. Pre-employment medical history (including previous radiation exposure) and physical examination (including complete blood count and urinalysis) are advisable to determine pre-existing conditions and to establish baseline values for the individual.

5.7.b. Whenever it is known or suspected that a person has received exposure in excess of the maximum permissible dose, a blood count should be done immediately so as to be prepared to detect any later resultant changes. (It is doubtful that any significant change in the blood count can be detected if the single exposure to the whole body is less than 25 r.)

5.7.c. Records should be kept of reports of physical examinations and blood counts.

5.7.d. Vacations should not be considered a substitute for adequate protection against exposure to radiation.

II. Additional Rules for Specific Applications

6. Medical Fluoroscopic Installations

6.1. Equipment.

6.1.a. The tube housing shall be of *diagnostic type*. (See par. 4.1.f. for recommended method of testing leakage radiation.)

6.1.b. The target-to-panel or target-to-table top distance should not be less than 18 in. and shall not be less than 12 in. (See table 10, appendix A.)

6.1.c. A cone should extend from the tube housing as near to the panel or table top as is practical. Its walls shall provide the same degree of protection as is required of the housing, taking into consideration the incident angle of the useful beam.

6.1.d. The total filtration permanently in the useful beam shall be not less than 2.5-mm aluminum equivalent. This requirement may be assumed to have been met if the hvl is not less than 2.5-mm aluminum at normal operating voltages.

6.1.e. The equipment shall be so constructed that the entire cross section of the useful beam is attenuated by a primary barrier. This barrier is usually the viewing device, either a conventional fluoroscopic screen or some sort of image intensification mechanism.

(1) The required lead equivalent of the barrier should be at least 2.0 mm and shall be not less than 1.5 mm for 100 kvp, should be at least 2.4 mm and shall be not less than 1.8 mm for 125 kvp, and should be at least 2.7 mm and shall be

not less than 2.0 mm for 150 kvp. This may be constituted by the lead glass of conventional fluoroscopic screens. Special attention must be paid to the shielding of image intensifiers so that neither the useful beam nor scattered radiation from the intensifier itself can produce a radiation hazard to the operator or other personnel.

(2) Collimators shall be provided to restrict the size of the useful beam to less than the area of the barrier. For conventional fluoroscopes, this requirement may be assumed to have been met if, when the adjustable diaphragm is opened to its fullest extent, an unilluminated margin is left on the fluorescent screen, regardless of the position of the screen during use.

(3) The tube mounting and the barrier (viewing device) should be so linked together that, under conditions of normal use, the barrier (viewing device) always intercepts the useful beam. It is advisable that the exposure automatically terminate when the barrier (viewing device) is moved out of the useful beam.

(4) Collimators and adjustable diaphragms or shutters to restrict the size of the useful beam shall provide a minimum of 2.0 mm lead equivalent protection for 100 kvp, 2.4 mm for 125 kvp, and 2.7 mm for 150 kvp.

6.1.f. The exposure switch shall be of the dead-man type.

6.1.g. A manually reset, cumulative timing device shall be used which will either indicate elapsed time by an audible signal or turn off the apparatus when the total exposure exceeds a predetermined limit in one or a series of exposures. The device should have a maximum range of 5 min.

6.1.h. For routine fluoroscopy, the exposure rate measured at the panel or table top should be as low as possible and shall not exceed 10 r/min.

6.1.i. A shield of 0.25-mm lead equivalent between the patient and the fluoroscopist is recommended but shall not substitute for the wearing of a protective apron.

6.1.j. A device for covering the Bucky slot during fluoroscopy should be provided. The thickness of material used should provide protection equivalent to at least 0.25-mm lead.

6.1.k. Attention should be given to reducing the light intensity in the room.

6.1.l. Mobile fluoroscopic equipment shall meet the requirements of the previous paragraphs of this Section, except that:—

(1) In the absence of a panel or table top, a cone or spacer frame shall limit the target-to-skin distance to not less than 12 in.

(2) Image intensification shall always be provided. Conventional fluoroscopic screens shall not be used.

(3) It shall be impossible to operate the machine when the collimating cone or diaphragm is not in place.

(4) The maximum permissible dose rate of 10 r/min shall be measured at the minimum target-to-skin distance.

(5) Paragraph 6.1.j. does not apply.

6.2. Structural shielding.

Table 1 in Appendix B shows the barrier requirements for busy fluoroscopic installations. Ordinarily, only secondary barriers are necessary. Combined fluoroscopic-radiographic installations are governed by the requirements for radiographic units. (See Sec. 7.)

6.3. Operating procedures.

6.3.a. Fluoroscopic equipment shall be operated only by properly trained persons authorized by the individual in charge of the installation.

6.3.b. The eyes of the fluoroscopist should be adequately dark-adapted before he uses the fluoroscope. The use of an image intensifier may reduce the degree of adaptation necessary but should not be considered to eliminate the need for it.

6.3.c. The exposure of the patient should be kept to the minimum consistent with clinical requirements.

(1) To this end, the fluoroscopist should take advantage of the dose reducing possibilities presented by high kilovoltage, low milliamperage, field reducing shutters, and rapid observation. (See tables 9 and 10, Appendix A.)

(2) When properly used, image intensifiers may significantly reduce both observation time and exposure rate, but they do not inherently accomplish this. Special precautions are necessary when cineradiographic techniques are used, since tube currents and voltages are usually higher than those normally used for fluoroscopy, and exposures to both patients and personnel can become quite large.

(3) When fluoroscoping persons who have not passed the reproductive age, special attention should be paid to avoiding exposure of the gonads to the useful beam.

6.3.d. Unless measurements indicate otherwise protective aprons of at least a quarter millimeter lead equivalent should be worn by all persons in the fluoroscopic room, except the patient.

6.3.e. Protective gloves of at least a quarter millimeter lead equivalent should be worn by the fluoroscopist during every examination.

6.3.f. The hand of the fluoroscopist should not be placed in the useful beam unless the beam is attenuated by the patient and a protective glove.

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

7. Medical Radiographic Installations

(For special requirements see section 8, Mobile Units; Section 9, Chest Photofluorography. Photofluorographic installations other than those for chests shall be governed by radiographic requirements.)

7.1. Equipment.

7.1.a. The tube housing shall be of *diagnostic type*. (*See* Sec. 4.1.f.)

7.1.b. Diaphragms or cones shall be provided for collimating the useful beam and shall provide the same degree of protection as is required of the housing.

7.1.c. The total filtration permanently in the useful beam shall be not less than 2.5 mm of aluminum equivalent. This requirement may be assumed to have been met if the hvl is not less than 2.5-mm aluminum at normal operating voltages.

7.1.d. A device shall be provided to terminate the exposure after a preset time or exposure.

7.1.e. A dead-man type of exposure switch shall be provided and so arranged that it cannot be conveniently operated outside a shielded area. Exposure switches for "spot-film" devices used in conjunction with fluoroscopic tables are excepted from this shielding requirement.

7.2. Structural shielding.

Table 2 in Appendix B gives the barrier thickness requirements for busy radiographic installations.

7.2.a. All wall, floor, and ceiling areas exposed to the useful beam shall have primary barriers. Primary barriers in walls shall extend to a minimum height of 7 ft above the floor.

7.2.b. Secondary barriers shall be provided in all wall, floor, and ceiling areas not having primary barriers or where the primary barrier requirements are lower than the secondary barrier requirements.

7.2.c. Special attention must be paid to the protection of the operator.

(1) The operator's station at the control shall be behind a protective barrier, either in a separate room, in a protected booth, or behind a fixed shield which will intercept the useful beam and any radiation which has been scattered only once. In the case of control booths within radiographic rooms, a protective door and ceiling may be needed but usually are not required if the radiation entering the booth has been scattered more than once.

(2) A window of lead-equivalent glass equal to that required by the adjacent barrier shall be provided, large enough and so placed that the operator can see the patient without having to leave the protected area during the exposure.

(3) Provision should be made so that the operator may communicate with the patient audibly and clearly during exposures without leaving the protected area.

7.3. Operating procedures.

7.3.a. No person occupationally exposed to radiation shall be permitted to hold patients during exposures, nor shall any person be regularly used for this service.

7.3.b. Only persons required for the radiographic procedure shall be in the radiographic room during exposure. All such persons, except the patient, should wear protective aprons and gloves unless measurements indicate that these are not required. No parts of the bodies of these persons shall be in the useful beam.

7.3.c. The exposure of the patient should be kept to the minimum consistent with clinical requirements. (See table 7 and 9, Appendix A.)

(1) The radiographic field should not be larger than is clinically necessary. The radiologist should enforce proper collimation, providing either an adequate assortment of cones or an adjustable collimator with beam-defining light.

(2) The gonads of children and persons who have not passed the reproductive age should be protected from the useful beam by the use of careful field collimation or special gonad shields when this will not impair the value of the examination.

8. Special Requirements for Mobile Diagnostic Equipment

(See section 6 for special requirements for mobile fluoroscopic equipment.)

8.1. Equipment.

All recommendations of section 7.1 apply except 7.1.e.

8.1.a. All mobile equipment shall be provided with collimating cones or collimating diaphragms and spacer frames to limit the target-to-skin distance to not less than 12 in.[1] and the cross section of the useful beam to the necessary diagnostic size.

8.1.b. The exposure control switch shall be of the dead-man type and shall be so arranged that the operator can

[1] For mobile dental equipment provisions of section 10.1.c apply.

stand at least 6 ft from the patient and well away from the useful beam.

8.2. Structural shielding.

If a mobile unit is used routinely in one location, it should be considered a fixed installation, and consideration should be given to shielding requirements. (See section 7.2.)

8.3. Operating procedures.

All provisions of section 6.3 and 7.3 apply.

8.3.a. The operator should stand as far as possible from the tube and patient and well away from the useful beam during all exposures.

8.3.b. Personnel monitoring shall be required for all persons operating mobile X-ray equipment.

9. Special Requirements for Chest Photofluorographic Installations

9.1. Equipment.

All provisions of 7.1. apply.

9.1.a. A collimator shall restrict the useful beam to the area of the fluorographic screen.

9.2. Structural shielding.

All provisions of 7.2 apply.

9.2.a. A primary protective barrier shall be provided wherever the useful beam can strike. (If the apparatus is so designed that the useful beam can strike only the fluorographic screen, this barrier may be placed around the hood and camera or immediately behind the camera, thus obviating the need for primary protective barriers elsewhere.)

9.2.b. Secondary barriers shall be provided in those walls not having primary barriers.

9.3. Operating procedures.

All provisions of 7.3. apply.

9.3.a. All personnel shall be in shielded positions during exposures.

9.3.b. Personnel monitoring shall be required.

9.3.c. Special shielding devices or collimators to prevent exposure of the gonads to the useful beam may be required when young persons are examined with photofluorographic equipment.

10. Dental Radiographic Installations

10.1. Equipment.

10.1.a. The tube housing shall be of *diagnostic type*. (See section 4.1.f.)

10.1.b. Diaphragms or cones shall be used for collimating

the useful beam and shall provide the same degree of protection as the housing, consideration being given to the obliquity of the rays. The diameter of the useful beam at the cone tip shall be not more than 3 in.

10.1.c. A cone or spacer frame shall provide a target-to-skin distance of not less than 7 in. with apparatus operating above 50 kvp or 4 in. with apparatus operating at 50 kvp or below.

10.1.d. For equipment operating up to 70 kvp, the total filtration permanently in the useful beam shall be equivalent to at least 1.5 mm of aluminum. This requirement may be assumed to have been met if the hvl is not less than 1.5-mm aluminum at normal operating voltages. Equipment operating above 70 kvp shall meet the requirements of 7.1.c.

10.1.e. A device shall be provided to terminate the exposure after a preset time or exposure.

10.1.f. The exposure control switch shall be of the "deadman" type.

10.1.g. Where the workload is low enough that shielding is not required for the operator, the installation shall be so arranged that the operator can stand at least 6 ft from the patient and well away from the useful beam.

10.2. Structural shielding.

Table 3 in Appendix B gives barrier thickness requirements for busy dental installations.

10.2.a. Dental rooms containing X-ray machines shall be provided with primary barriers at all areas struck by the useful beam. Consideration shall be given to the attenuation provided by the patient.

10.2.b. Attention to the proper arrangement of the apparatus within the dental room may appreciably reduce the protective barrier requirements.

10.2.c. When dental X-ray units are installed in adjacent rooms or areas, protective barriers as specified in 10.2.a shall be provided between the rooms or areas. Consideration should be given to the possibility of exposure from multiple sources.

10.3. Operating procedures.

10.3.a. In no case shall the film be held by the dentist or his assistant during exposures.

10.3.b. During each exposure, the operator shall stand at least 6 ft from the patient or behind a protective barrier.

10.3.c. Only the patient shall be in the useful beam.

10.3.d. Neither the tube housing nor the pointer cone shall be hand held during exposures.

10.3.e. Fluoroscopy shall not be used in dental examinations.

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10.3.f. The exposure of the patient should be kept to the minimum consistent with clinical requirements. Table 8 in appendix A gives the average output of dental diagnostic equipment under various conditions.

11. Therapeutic X-ray Installations Operated at Potentials Up to 3 Million Volts

(See section 12 for special requirements for equipment operating below 60 kv)

11.1. Equipment.

11.1.a. The tube housing shall be of a therapeutic type.

11.1.b. Permanent diaphragms or cones used for collimating the useful beam shall afford the same degree of protection as the housing. Adjustable or removable beam-defining diaphragms or cones shall transmit not more than 5 percent of the useful beam obtained at the maximum kilovoltage and with maximum treatment filter. (See table 11 in Appendix A.) Special attention should be given in the case of cones which may be in contact with the patient's body during irradiation, to assure that the radiation transmitted through the cone wall at the point of contact is not greater than 5 percent of the useful beam as measured at the end of the cone farthest from the target.

11.1.c. The filter system shall be so arranged as to minimize the possibility of error in filter selection and alignment. 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, or, if the radiation from the slot is accessible to the patient, 30 r/hr at 5 cm from the external opening.

11.1.d. The X-ray tube shall be so mounted that it cannot turn or slide with respect to the aperture. A mark on the housing should show the location of the focal spot.

11.1.e. Means shall be provided to immobilize the tube housing during stationary portal treatment.

11.1.f. Valve tubes may require shielding.

11.1.g. A timer shall be provided to terminate the exposure after a pre-set time regardless of what other exposure limiting devices are present.

11.1.h. A beam monitoring device fixed in the useful beam is recommended to indicate any error due to incorrect filter, milliamperage, or kilovoltage, unless it introduces more filtration than is clinically acceptable.

11.1.i. Equipment utilizing shutters to control the useful beam shall have a shutter position indicator on the control.

11.1.j. Lead rubber, lead foil, etc., used for limiting the field, should transmit not more than 5 percent of the useful beam. (See table 12 in Appendix A.)

11.2. Structural shielding.

11.2.a. All wall, floor, and ceiling areas that can be struck by the useful beam, plus a border of 1 ft, shall be provided with primary protective barriers. All wall, floor, and ceiling areas that, because of restrictions in the orientation of the useful beam, cannot be struck by the useful beam shall be provided with secondary barriers. In all shielding design and survey evaluations, consideration should be given to present and future workloads, use factors, and occupancy factors. Estimated exposure should be integrated over a period of a year. Special consideration must be given to the protection of persons in the rooms above and below the treatment rooms. See tables 4 through 11 in Appendix B for barrier thickness requirements for busy therapeutic installations.

11.2.b. Shielding requirements may be reduced in some cases by locating treatment rooms as far as practicable from occupied areas. Corner rooms may be especially suitable, but outside walls and particularly windows may still require protection unless they are sufficiently distant from other occupied areas and buildings. (See tables 4 and 5 in Appendix A.)

11.2.c. The required barriers should be an integral part of the building. Movable lead screens are not recommended and with equipment operating above 125 kv, shall not be depended upon.

11.2.d. With equipment operating above 150 kv, the control station shall be within a protective booth or in an adjacent room.

11.2.e. Interlocks shall be provided so that when any door to the treatment room is opened either the machine will be shut off automatically or the radiation level within the room will be reduced to an average of not more than 2 mr/hr and a maximum of 10 mr/hr at a distance of 1 m in any direction from the target. After such a shutoff, or reduction in output, it shall be possible to restore the machine to full operation only from the control panel. (The 2 mr/hr average shall be obtained from measurements taken in not less than 5 directions from the target.)

11.2.f. In the design of barriers for installations operating above 1,000 kv, a maze, with the entrance door where it can be struck only by multiple-scattered radiation, may so reduce the barrier requirement for the door as to provide an overall economy.

11.2.g. Windows, mirror systems, or closed-circuit television viewing screens used for observing the patient shall be so located that the operator may see the patient and the control panel from the same position.

11.2.h. Provision for oral communication with the patient from the control room is desirable.

11.3. Operating procedures.

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

11.3.b. No person who works with ionizing radiation, unless he is the patient, 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 be in the treatment room with the patient during exposure, he shall be protected as much as possible from scattered radiation and shall not be in the useful beam.

11.3.c. Both the control panel and the patient should be kept under observation during exposure.

12. Special Requirements for X-ray Therapy Equipment Operated at Potentials of 60 kv and Below

12.1. Installations shall comply with the general requirements of sections 11.1, 11.2, and 11.3, except that the operator and other persons may be permitted in the treatment room during exposure. Because of the low penetration of X-rays generated at potentials of less than 60 kv, the hazard to personnel can be minimized by the wearing of quarter millimeter lead-equivalent aprons. The operator should take care to avoid exposure of persons other than the patient to the useful beam. Structural shielding, leaded doors, and interlocks may not be required. A movable shield or one attached to the control stand may be helpful in reducing radiation hazards.

12.2 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-to-skin distance of less than 3 m. It should be emphasized that grenz rays are X-rays, and that they may cause the same types of injury as harder X-rays, although these effects may be limited to the superficial layers of tissue.

12.3. The term "contact therapy" is used to describe short target-to-skin distance irradiation of accessible lesions. The potential employed is usually 40 to 50 kv. Because the dose rate at the surface of the window may be more than

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 hand held during irradiation, the operator shall wear protective gloves and apron. When the apparatus is not being used, a cap of 0.5-mm lead equivalent shall cover the aperture window of the tube housing.

12.4 Automatic timers shall be provided which will permit accurate presetting and determination of exposures as short as 1 sec.

12.5 Special precautions are required in the therapeutic application of apparatus constructed with beryllium or other low-filtration windows. As a dose rate of more than 1 million r/min is possible at the aperture, adequate shielding shall be required against the useful beam, and special safeguards are essential to avoid accidental exposures to the useful beam. There shall be on the control panel some easily discernible device which will give positive information as to whether or not the tube is energized.

12.6 Machines having an output of more than 1,000 r/min at any accessible place shall not be left unattended without the power being shutoff at the primary disconnecting means. The switch at the control should always be turned off first, then the primary main switch (or wall plug disconnected). This sequence should never be reversed.

III. Appendix A. Tables of general information

Tables:

1. Maximum permissible doses.
2. Occupancy factors.
3. Use factors.
4. Distance protection for controlled areas.
5. Distance protection for areas outside of controlled areas (environs).
6. Shielding requirements for radiographic films.
7. Average output of diagnostic equipment.
8. Average output of dental equipment.
9. Effect of tube potential on patient dose.
10. Effect of voltage, distance, and filtration on air exposure rate at panel of fluoroscopes.
11. Thickness of lead and brass required to reduce useful beam to 5 percent of its incident value.
12. Half-value layers of lead and concrete for various kilovoltages.
13. Secondary barrier requirements for leakage radiation from diagnostic-type protective tube housings.
14. Secondary barrier requirements for leakage radiation from therapeutic-type protective tube housings.
15. Densities of commercial building materials.
16. Commercial lead sheet thicknesses and weights.

Table 1. *Maximum permissible RBE doses* [d]

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

	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 in rems may be assumed to be equal to the exposure dose in roentgens.

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

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

Table 2. *Occupancy factors*

For use as a guide in planning shielding when complete occupancy data are not available. The maximum permissible dose levels stated in Addendum to H 59, April 15, 1958, summarized in table 1, are computed on the basis of the integration of doses received over a period of a year. Therefore, the degree of occupancy of an area should be considered in terms of the time which may be spent in that area by any one person over a period of a year.

Full occupancy (T=1)
Control space, offices, nurses stations, corridors, and waiting space large enough to hold desks, darkrooms, workrooms, shops, restrooms, and lounge rooms routinely used by occupationally exposed personnel, living quarters, children's play areas, occupied space in adjoining buildings.
Partial occupancy (T=¼)
Corridors too narrow for desks, utility rooms, rest, and lounge rooms not used routinely by occupationally exposed personnel, wards and patient's rooms, elevators using operators, unattended parking lots, patient's dressing rooms.
Occasional occupancy (T=1/16)
Closets too small for future occupancy, toilets not used routinely by occupationally exposed personnel, stairways, automatic elevators, sidewalks, streets.

Table 3. *Use factors for primary barriers*

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

	Radiographic	Dental	Therapeutic [a]
Floor	1	1/16	1
Walls	¼	¼	¼
Ceiling	1/16	1/16	1/16

[a] Use factors for the walls and ceiling may be much greater, or the use factor for the floor smaller, when rotation therapy is used.

Table 4. *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 5. *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	115	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 6. *Shielding for radiographic films*

[Indicated thicknesses required to reduce radiation to 1 mr 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.

Table 7. *Average output of diagnostic equipment*

Target distance		Tube potential						
		50 kvp	60 kvp	70 kvp	80 kvp	90 kvp	100 kvp	125 kvp
		r/100 ma-sec						
in.	*cm*							
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

Measured in air with total filtration equivalent to 2.5 mm Al.

Table 8. *Dental unit output*

Kvp	FSD	Total filter	r/ma-min
	in.	*mm Al*	
50	4	1.5	12
70	8	1.5	8.3
70	16	1.5	2.1
90	8	2.5	8.4
90	16	2.5	2.1

Table 9. *Effect of tube potential on patient's dose*

[Filter—2 mm Al]

Thickness of part	Ratio of entrance to exit dose				
	50 kvp	75 kvp	100 kvp	125 kvp	150 kvp
10 cm	85	30	18	11	8
20 cm	1,250	400	140	60	30

Based on chart by F. Wachsman. Fortschr Rö.-Str., LXXV, 728 (1951); Brit. J. Radiol., Supp. No. 6, 87 (1955).

Table 10. *Effect of voltage, distance and filtration on air exposure rate at panel of fluoroscopes*

Potential	Current	Target-to-skin distance	Equivalent aluminum filtration [a]			
			1 mm	2 mm	3 mm	4 mm
kvp	*ma*	*in.*	*r/min*	*r/min*	*r/min*	*r/min*
80	3	12	27.5	14.6	9.0	6.1
		15	17.6	9.3	5.8	3.9
		18	12.4	6.5	4.0	2.7
100	3	12	38.5	22.8	15.5	11.2
		15	24.6	14.6	9.9	7.2
		18	17.1	10.1	6.9	5.0
120	3	12	55.0	33.1	22.7	16.8
		15	35.2	21.2	14.5	10.7
		18	24.5	14.7	10.1	7.5

[a] Filtration includes that of the table top and the tube with its inherent and added filter.

Table 11. *Thicknesses of lead and brass required to reduce useful beam to 5 percent*

Tube potential	hvl	lead	Brass
kvp	*mm*	*mm*	*mm*
60	1.2 Al	0.10	0.3
100	1.0 Al	.15	.8
100	2.0 Al	.25	1.0
100	3.0 Al	.35	1.2
140	0.5 Cu	.7	4.0
200	1.0 Cu	1.0	9.0
250	3.0 Cu	1.7	18.0
300	4.0 Cu	2.7	22.3

Composition of brass used, 65 percent copper, 35 percent zinc (yellow brass).

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

TABLE 13. *Secondary barrier requirements for leakage radiation from diagnostic-type 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	1.3	2.6	3.6	4.2	4.9	5.6
4	0.5	1.8	2.8	3.4	4.1	4.8
5	-----	1.2	2.1	2.7	3.5	4.1
6	-----	0.6	1.6	2.2	2.9	3.6
7	-----	.2	1.2	1.8	2.5	3.2
8	-----	-----	0.8	1.3	2.1	2.8
9	-----	-----	.4	1.0	1.7	2.4
10	-----	-----	.2	0.7	1.4	2.1
12	-----	-----	-----	.3	0.9	1.6

TABLE 14. *Secondary barrier requirements for leakage radiation from therapeutic-type 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 15. *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.

TABLE 16. *Commercial lead sheets*

Thickness		Weight
mm	*in*	*lb/sq ft*
0.79	1/32	2
1.00	5/128	2 1/2
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

IV. Appendix B. Shielding requirements for busy installations

Tables:

1. Secondary barrier requirements for fluoroscopic installations.
2. Shielding requirements for radiographic installations.
3. Shielding requirements for dental installations.
4. Shielding requirements for 100 kvp therapeutic installations.
5. Shielding requirements for 150 kvp therapeutic installations.
6. Shielding requirements for 200 kvp therapeutic installations.
7. Shielding requirements for 250 kvp therapeutic installations.
8. Shielding requirements for 300 kvp therapeutic installations.
9. Shielding requirements for 1,000 kvcp therapeutic installations.
10. Shielding requirements for 2,000 kvcp therapeutic installations.
11. Shielding requirements for 3,000 kvcp therapeutic installations.

13. General Considerations in Use of Tables

Kilovoltages, workloads, and distances shown are those commonly encountered in *busy* installations. Graphs and formulas for the calculation of barrier requirements for situations not covered by these tables may be found in appendix C.

W=workload in milliampere-minute per week; U=use factor; T=occupancy factor.

In these tables, no account has been taken of the attenuation provided by the patient or objects normally in the path of the useful beam.

In all tables, the maximum permissible exposure, *for design purposes only*, is considered to be 100 mr/week for controlled areas and 10 mr/week for environs (occupied space outside of controlled areas).

It should be remembered that lead sheet less than 0.5-mm thick is frequently more expensive than heavier sheet both in cost of material and cost of installation.

Concrete thicknesses are computed on the basis of a concrete density of 147 lb/ft³ (2.35 g/cm³).

TABLE 1. *Secondary barrier requirements for busy fluoroscopic installations*

[W=2,000 ma-min/week at 100 kvp, 800 ma-min/week at 125 kvp, or 400 ma-min/week at 150 kvp.]

For type of area	UT	Distance from tube to occupied area																			
		5 ft (1.52 m)					7 ft (2.13 m)					10 ft (3.05 m)					14 ft (4.26 m)				
		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete	
		mm	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*pfs* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]
Controlled	1	0.7	1/32	1.6	2.2	27	0.6	1/32	1.4	2.0	25	0.4	...	0.9	1.4	17	0.2	...	0.5	0.8	10
Environs	1	1.4	1/16	3.3	4.6	56	1.2	1/16	2.8	3.8	47	1.0	1/32	2.3	3.2	39	0.8	1/32	1.9	2.8	34
	1/4	1.0	1/32	2.3	3.2	39	0.8	1/32	1.9	2.8	34	0.7	1/32	1.6	2.2	27	.5	...	1.2	1.7	21
	1/16	0.7	1/32	1.6	2.2	27	.5	...	1.2	1.7	21	.3	...	0.7	1.1	13	.1	...	0.2	0.4	5

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 g/cm³ (147 lb/ft³).

Table 2. *Shielding requirements for busy radiographic installations*

[W=1,000 ma-min/week at 100 kvp, 400 ma-min/week at 125 kvp, or 200 ma-min/week at 150 kvp.]

Type of barrier	UT	Distance from tube to occupied area																			
		5 ft (1.52 m)					7 ft (2.13 m)					10 ft (3.05 m)					14 ft (4.26 m)				
		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete	
For controlled areas:		*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*pfs* [a]	*in.*	*psf* [a]	*mm*	*in.G*	*psf* [a]	*in.*	*psf* [a]
Primary	1	1.9	1/16	4.4	6.1	75	1.7	1/16	4.0	5.3	65	1.4	1/16	3.3	4.6	56	1.2	1/16	2.8	3.8	47
	1/4	1.4	1/16	3.3	4.6	56	1.2	1/16	2.8	3.8	47	1.0	1/32	2.3	3.2	39	0.8	1/32	1.9	2.8	34
	1/16	1.0	1/32	2.3	3.2	39	0.8	1/32	1.9	2.8	34	0.7	1/32	1.6	2.2	27	.5	------	1.2	1.7	21
Secondary	1	0.5	------	1.2	1.7	21	.4	------	0.9	1.4	17	.2	------	0.5	0.8	10	0	------	------	0	------
For environs:																					
Primary	1	2.7	3/32	6.3	8.1	99	2.4	3/32	6.6	7.2	88	2.2	3/32	5.1	6.6	81	2.0	3/32	4.7	6.2	76
	1/4	2.2	3/32	5.1	6.6	75	1.9	1/16	4.4	6.1	75	1.7	1/16	4.0	5.3	65	1.5	1/16	3.5	5.0	61
	1/16	1.7	1/16	4.0	5.3	65	1.5	1/16	3.5	5.0	61	1.3	1/16	3.0	4.0	53	1.1	1/32	3.5	2.6	43
	1/64	1.2	1/16	2.8	4.1	50	1.0	1/32	2.3	3.9	39	0.8	1/32	1.9	2.8	34	0.6	1/32	1.4	2.1	26
	1/256	0.8	1/32	1.9	2.8	34	0.6	1/32	1.4	2.8	25	.4	------	0.9	1.4	17	.2	------	0.5	0.8	10
Secondary	1	1.2	1/16	2.8	3.8	47	1.0	1/32	2.3	3.2	39	.8	1/32	1.9	2.8	34	.6	1/32	1.4	2.1	26
	1/4	0.8	1/32	1.9	2.8	34	0.6	1/32	1.4	2.0	25	.4	------	0.9	1.4	17	.2	------	0.5	0.8	10
	1/16	.5	------	1.2	1.7	28	.3	------	0.7	1.1	13	.1	------	.2	0.4	5	0	------	------	0	------

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 gm/cm³ (147 lbs./ft³).

Table 3. *Shielding requirements for busy dental installations*

[W=800 ma-min/week at 70 kvp.]

Type of Barrier	UT	Distance from tube to occupied area											
		5 ft (1.52 m)			7 ft (2.13 m)			10 ft (3.05 m)			14 ft (4.26 m)		
		Lead		Concrete [a]	Lead		Concrete [a]	Lead		Concrete [a]	Lead		Concrete [a]
For controlled areas:		*mm*	*in.*	*in.*	*mm*	*in.*	*in.*	*mm*	*in.*	*in.*	*mm*	*in.*	*in.*
Primary	1	0.8	1/32	2.8	0.7	1/32	2.4	0.6	1/32	2.1	0.5	1/32	1.8
	1/4	.6	1/32	2.1	.5	1/32	1.8	0.4	------	1.5	.3	------	1.1
	1/16	.4	------	1.5	.3	------	1.1	0.2	------	0.8	.1	------	0.4
Secondary	1	.3	------	1.1	.2	------	0.8	0	0	0	0	0	0
For Environs:													
Primary	1	1.2	1/16	4.0	1.1	1/32	3.8	1.0	1/32	3.4	0.9	1/32	3.1
	1/4	1.0	1/32	3.4	0.9	1/32	3.1	0.8	1/32	2.8	.7	1/32	2.4
	1/16	0.8	1/32	2.8	.7	1/32	2.4	.6	1/32	2.1	.5	1/32	1.8
	1/64	.6	1/32	2.1	.5	1/32	1.8	.4	------	1.5	.3	------	1.1
	1/256	.4	------	1.5	.3		1.1	.2	------	0.8	.1	------	0.4
Secondary	1	.6	1/32	2.1	.5	1/32	1.8	.4	------	1.5	.3	------	1.1
	1/4	.4	------	1.5	.3	------	1.1	.2	------	0.8	.1	------	0.4
	1/16	.2	------	0.8	.1	------	0.4	.1	------	.4	------	0	0

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 gm/cm³ (147 lb/ft³).

TABLE 4. *Shielding requirements for busy 100 kvp therapeutic installations*

[W=4,000 ma-min/week]

Type of barrier	UT	5 ft (1.52 m) Lead			5 ft Concrete		7 ft (2.13 m) Lead			7 ft Concrete		10 ft (3.05 m) Lead			10 ft Concrete		14 ft (4.26 m) Lead			14 ft Concrete		20 ft (6.10 m) Lead			20 ft Concrete	
		mm	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]
For controlled areas:																										
Primary	1	2.3	3/32	5.4	7.1	87	2.0	3/32	4.7	6.3	77	1.8	1/16	4.2	5.7	70	1.6	1/16	3.7	5.2	64	1.4	1/16	3.3	4.6	56
	1/4	1.8	1/16	4.2	5.7	70	1.6	1/16	3.7	5.2	64	1.4	1/16	3.3	4.6	56	1.2	1/16	2.8	4.0	49	1.0	1/32	2.3	3.4	42
	1/16	1.4	1/16	3.3	4.6	56	1.2	1/16	2.8	4.0	49	1.0	1/32	2.3	3.4	42	0.8	1/32	1.9	2.8	34	0.6	1/32	1.4	2.1	26
Secondary	1	1.3	1/16	3.0	4.3	53	1.1	1/32	2.6	3.7	45	0.9	1/32	2.1	3.1	38	.7	1/32	1.6	2.4	29	.5	1/32	1.2	1.8	22
For environs:																										
Primary	1	3.2	1/8	7.5	9.2	113	2.9	1/8	6.8	8.5	104	2.7	1/8	6.3	8.0	98	2.4	3/32	5.6	7.3	89	2.2	3/32	5.1	6.8	83
	1/4	2.7	1/8	6.3	8.0	98	2.4	3/32	5.6	7.3	89	2.2	3/32	5.1	6.8	83	1.9	1/16	4.4	6.0	74	1.7	1/16	4.0	5.5	67
	1/16	2.2	3/32	5.1	6.8	83	1.9	1/16	4.4	6.0	74	1.7	1/16	4.0	5.5	67	1.4	1/16	3.3	4.6	56	1.2	1/16	2.8	4.0	49
	1/64	1.7	1/16	4.0	5.5	67	1.4	1/16	3.3	4.6	56	1.2	1/16	2.8	4.0	49	1.0	1/32	2.3	3.4	42	0.8	1/32	1.9	2.8	34
	1/256	1.2	1/16	2.8	4.0	49	1.0	1/32	2.3	3.4	42	0.8	1/32	1.9	2.8	34	0.6	1/32	1.4	2.1	26	.5	1/32	1.2	1.8	23
Secondary	1	2.1	3/32	4.9	6.6	81	1.8	1/16	4.2	5.7	70	1.6	1/16	3.7	5.2	64	1.4	1/16	3.3	4.6	56	1.2	1/16	2.8	4.0	49
	1/4	1.6	1/16	3.7	5.2	64	1.4	1/16	3.3	4.6	56	1.2	1/16	2.8	4.0	49	1.0	1/32	2.3	3.4	42	0.8	1/32	1.9	2.8	34
	1/16	1.2	1/16	2.8	4.0	49	1.0	1/32	2.3	3.4	42	0.8	1/32	1.9	2.8	34	0.6	1/32	1.4	2.1	26	.5	1/32	1.2	1.8	22

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 g/cm³ (147 lb/ft³).

TABLE 5. *Shielding requirements for busy 150 kvp therapeutic installations*

[W=4,000 ma-min/week]

Type of barrier	UT	5 ft (1.52 m) Lead			5 ft Concrete		7 ft (2.13 m) Lead			7 ft Concrete		10 ft (3.05 m) Lead			10 ft Concrete		14 ft (4.26 m) Lead			14 ft Concrete		20 ft (6.10 m) Lead			20 ft Concrete	
		mm	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]
For controlled areas:																										
Primary	1	3.1	1/8	7.2	10.4	127	2.9	1/8	6.8	10.0	123	2.5	3/32	5.8	8.8	108	2.3	3/32	5.4	8.2	100	2.0	3/32	4.7	7.2	88
	1/4	2.5	3/32	5.8	8.8	108	2.3	3/32	5.4	8.2	100	2.3	3/32	4.7	7.2	88	1.8	1/16	4.2	6.5	80	1.5	1/16	3.5	5.4	66
	1/16	2.0	3/32	4.7	7.2	88	1.8	1/16	4.2	6.5	80	1.5	1/16	3.5	5.4	66	1.3	1/16	3.0	4.7	58	1.1	1/32	2.6	3.9	48
Secondary	1	1.7	1/16	4.0	6.1	75	1.5	1/16	3.5	5.4	66	1.2	1/16	2.8	4.3	53	1.0	1/32	2.3	4.3	53	0.8	1/32	1.9	2.9	36
For environs:																										
Primary	1	4.1	5/32	9.6	13.3	163	3.9	5/32	9.1	12.8	157	3.5	5/32	8.2	11.6	142	3.3	1/8	7.7	11.1	136	3.0	1/8	7.0	10.2	125
	1/4	3.5	5/32	8.2	11.6	142	3.3	1/8	7.7	11.1	136	3.0	1/8	7.0	10.2	125	2.8	1/8	6.5	9.7	119	2.4	3/32	5.6	8.5	104
	1/16	3.0	1/8	7.0	10.2	125	2.8	1/8	6.5	9.7	119	2.4	3/32	5.6	8.5	104	2.2	3/32	5.1	7.8	96	1.8	1/16	4.2	6.5	80
	1/64	2.1	3/32	5.6	8.5	104	2.2	3/32	5.1	7.8	96	1.8	1/16	4.2	6.5	80	1.6	1/16	3.7	5.8	71	1.3	1/16	3.0	4.7	58
	1/256	1.8	1/16	4.2	6.5	80	1.6	1/16	3.7	5.8	71	1.3	1/16	3.0	4.7	58	1.1	1/32	2.6	3.9	48	0.8	1/32	1.9	2.9	36
Secondary	1	2.6	3/32	6.1	9.1	111	2.4	3/32	5.6	8.5	104	2.0	3/32	4.7	7.2	88	1.8	1/16	4.2	6.5	80	1.4	1/16	3.3	5.8	62
	1/4	2.0	3/32	4.7	7.2	88	1.8	1/16	4.2	6.5	80	1.4	1/16	3.3	5.1	62	1.2	1/16	2.8	4.3	53	0.9	1/32	2.1	4.1	39
	1/16	1.4	1/16	3.3	5.1	62	1.2	1/16	2.8	4.3	53	0.9	1/32	2.1	3.2	39	0.7	1/32	1.6	2.5	31	.5	1/32	1.2	2.3	22

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 g/cm³ (147 lb/ft³).

TABLE 6. *Shielding requirements for busy 200 kvp therapeutic installations*

[W=40,000 ma-min/week]

Type of barrier	UT	Distance from tube to occupied area																								
		5 ft (1.52 m)					7 ft (2.13 m)					10 ft (3.05 m)					14 ft (4.26 m)					20 ft (6.10 m)				
		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete	
For controlled areas:		*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]
Primary	1	6.4	1/4	14.9	16.7	205	5.9	1/4	13.7	15.8	194	5.4	7/32	12.6	14.8	181	4.9	3/16	11.4	13.7	168	4.4	3/16	10.3	12.7	156
	1/4	5.4	7/32	12.6	14.8	181	4.9	3/16	11.4	13.7	168	4.4	3/16	10.3	12.7	156	3.9	5/32	9.1	11.6	142	3.4	1/8	7.9	10.5	129
	1/16	4.4	3/16	10.3	12.7	156	3.9	5/32	9.1	11.6	142	3.4	1/8	7.9	10.5	129	3.0	1/8	7.0	9.6	118	2.6	3/32	6.1	8.5	104
Secondary	1	4.1	5/32	9.6	12.1	148	3.6	5/32	8.4	11.0	135	3.1	1/8	7.2	9.8	120	2.6	3/32	6.1	8.5	104	2.2	3/32	5.1	7.4	91
For environs:																										
Primary	1	8.1	11/32	18.9	19.9	244	7.6	5/16	17.7	19.0	233	7.1	9/32	16.5	18.0	221	6.6	9/32	15.4	17.1	209	6.1	1/4	14.2	16.2	198
	1/4	7.1	9/32	16.5	18.0	221	6.6	9/32	15.4	17.1	209	6.1	1/4	14.2	16.2	198	5.6	7/32	13.0	15.2	186	5.1	7/32	11.9	14.2	174
	1/16	6.1	1/4	14.2	16.2	198	5.6	7/32	13.0	15.2	186	5.1	7/32	11.9	14.2	174	4.6	3/16	10.7	13.1	160	4.1	5/32	9.6	12.1	148
	1/64	5.1	7/32	11.9	14.2	174	4.6	3/16	10.7	13.1	160	4.1	5/32	9.6	12.1	148	3.6	5/32	8.4	11.0	135	3.2	1/8	7.5	10.0	123
	1/256	4.1	5/32	9.6	12.1	148	3.6	5/32	8.4	11.0	135	3.2	1/8	7.5	10.0	123	2.7	1/8	6.3	8.8	108	2.3	3/32	5.4	7.9	94
Secondary	1	5.6	7/32	13.0	15.2	186	5.1	7/32	11.9	14.2	174	4.6	3/16	10.7	13.1	160	4.1	5/32	9.6	12.1	148	3.6	5/32	8.4	11.0	135
	1/4	4.6	3/16	10.7	13.1	160	4.1	5/32	9.6	12.1	148	3.6	5/32	8.4	11.0	135	3.2	1/8	7.5	10.0	123	2.7	1/8	6.3	8.8	108
	1/16	3.6	5/32	8.4	11.0	135	3.2	1/8	7.5	10.0	123	2.7	1/8	6.3	8.8	108	2.3	3/32	5.4	7.7	94	1.7	1/16	4.0	6.7	74

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 g/cm³ (147 lb/ft³).

TABLE 7. *Shielding requirements for busy 250 kvp therapeutic installations*

[W=40,000 ma-min/week]

Type of barrier	UT	Distance from tube to occupied area																								
		5 ft (1.52 m)					7 ft (2.13 m)					10 ft (3.05 m)					14 ft (4.26 m)					20 ft (6.10 m)				
		Lead [b]			Concrete [b]		Lead [b]			Concrete [b]		Lead [b]			Concrete [b]		Lead [b]			Concrete [b]		Lead [b]			Concrete [b]	
For controlled areas:		*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]
Primary	1	11.3	15/32	26.4	19.3	236	10.4	7/16	24.3	18.0	221	9.5	3/8	22.2	16.8	206	8.6	11/32	20.1	15.6	191	7.7	5/16	18.0	14.4	176
	1/4	9.5	3/8	22.2	16.8	206	8.6	11/32	20.1	15.6	191	7.7	5/16	18.0	14.4	176	6.8	9/32	15.9	13.2	162	6.0	1/4	14.0	12.0	147
	1/16	7.7	5/16	18.0	14.4	176	6.8	9/32	15.9	13.2	162	6.0	1/4	14.0	12.0	147	5.2	7/32	12.1	10.8	132	4.4	3/16	10.3	9.6	118
Secondary	1	6.4	1/4	14.9	12.6	154	5.7	7/32	13.3	11.5	141	5.0	7/32	11.7	10.5	129	4.2	5/32	9.8	9.4	115	3.5	5/32	8.2	8.3	102
For environs:																										
Primary	1	13.9	9/16	32.4	22.9	281	13.0	17/32	30.3	21.6	265	12.1	1/2	28.2	20.4	250	11.2	15/32	26.1	19.2	235	10.3	13/32	24.0	18.0	221
	1/4	12.1	1/2	28.2	20.4	250	11.2	15/32	26.1	19.2	235	10.3	13/32	24.0	18.0	221	9.4	3/8	21.9	16.7	205	8.5	11/32	19.8	15.5	190
	1/16	10.3	13/32	24.0	18.0	221	9.4	3/8	21.9	16.7	205	8.5	11/32	19.8	15.5	190	7.6	5/16	17.7	14.3	175	6.7	9/32	15.6	13.0	159
	1/64	8.5	11/32	19.8	15.5	190	7.6	5/16	17.7	14.3	175	6.7	9/32	15.6	13.0	159	5.9	1/4	13.8	11.8	145	5.1	7/32	11.9	10.7	131
	1/256	6.7	9/32	15.6	13.0	159	5.9	1/4	13.8	11.8	145	5.1	7/32	11.9	10.7	131	4.4	3/16	10.3	9.6	118	3.7	5/32	8.6	8.5	104
Secondary	1	8.8	11/32	20.5	16.0	196	8.0	5/16	18.7	14.8	181	7.3	9/32	17.0	13.8	169	6.5	1/4	15.2	12.7	156	5.8	1/4	13.5	11.7	143
	1/4	7.3	9/32	17.0	13.8	169	6.5	1/4	15.2	12.7	156	5.8	1/4	13.5	11.7	143	5.0	7/32	11.7	10.5	129	4.4	3/16	10.3	9.6	118
	1/16	5.8	1/4	13.5	11.7	143	5.0	7/32	11.7	10.5	129	4.4	3/16	10.3	9.6	118	3.8	5/32	8.9	8.8	107	3.2	1/8	7.5	7.7	94

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 g/cm³ (147 lb/ft³).

[b] 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.

TABLE 8. *Shielding requirements for busy 300 kvp therapeutic installations*

[W=40,000 ma-min/week]

Type of barrier	UT	Distance from tube to occupied area																								
		5 ft (1.52 m)					7 ft (213 m)					10 ft (3.05 m)					14 ft (4.26 m)					20 ft (6.10 m)				
		Lead [a]			Concrete[a]		Lead [a]			Concrete[a]		Lead [a]			Concrete[a]		Lead [a]			Concrete[a]		Lead [a]			Concrete[a]	
		mm	*in.*	*psf* [b]	*in.*	*psf* [b]	*mm*	*in.*	*psf* [b]	*in.*	*psf* [b]	*mm*	*in.*	*psf* [b]	*in.*	*psf* [b]	*mm*	*in.*	*psf* [b]	*in.*	*psf* [b]	*mm*	*in.*	*psf* [b]	*in.*	*psf* [b]
For controlled areas:																										
Primary	1	17.8	11/16	41.3	21.6	265	16.3	21/32	37.8	20.5	251	14.9	19/32	34.6	19.3	237	13.5	17/32	31.3	18.0	221	12.1	15/32	28.1	16.8	206
	1/4	14.9	19/32	34.4	19.3	237	13.5	17/32	31.1	18.0	221	12.1	15/32	28.1	16.8	206	10.7	7/16	25.1	15.7	192	9.4	3/8	22.1	14.4	176
	1/16	12.1	15/32	27.9	16.8	206	10.7	13/32	24.9	15.7	192	9.4	3/8	22.0	14.4	172	8.3	5/16	19.3	13.2	162	7.0	9/32	16.3	12.0	147
Secondary	1	10.6	13/32	24.6	13.2	162	9.4	3/8	21.9	12.0	147	8.1	5/16	19.1	10.8	132	6.8	9/32	15.8	9.6	118	5.4	7/32	12.6	8.4	103
For environs:																										
Primary	1	22.1	7/8	51.3	25.6	314	20.6	13/16	47.9	24.5	300	19.2	3/4	44.6	23.3	285	17.8	23/32	41.3	22.0	270	16.4	21/32	38.1	20.8	255
	1/4	19.2	3/4	44.4	23.3	286	17.8	11/16	41.1	22.0	270	16.4	21/32	38.1	20.8	255	15.1	5/8	35.1	19.7	241	13.8	17/32	32.0	18.4	225
	1/16	16.4	21/32	37.8	20.8	255	15.1	19/32	34.9	19.7	241	13.8	17/32	32.0	18.4	221	12.6	1/2	29.2	17.3	211	11.2	7/16	26.2	16.0	196
	1/64	13.8	17/32	31.7	18.4	226	12.6	1/2	28.8	17.3	212	11.2	7/16	26.0	16.0	191	10.0	13/32	23.2	14.9	181	8.6	11/32	20.2	13.6	167
	1/256	11.2	7/16	25.8	16.0	196	10.0	3/8	22.6	14.9	183	8.6	11/32	20.0	13.6	162	7.4	5/16	17.2	12.4	152	6.1	1/4	14.2	11.2	137
Secondary	1	14.9	19/32	34.6	17.2	211	13.7	17/32	31.8	16.0	196	12.3	1/2	28.8	14.8	181	11.1	7/16	25.8	13.6	167	9.7	3/8	22.5	12.4	152
	1/4	12.3	1/2	28.5	14.8	181	11.1	7/16	25.8	13.6	167	9.7	3/8	22.7	12.4	152	8.5	11/32	19.8	11.2	137	7.1	9/32	16.5	10.0	123
	1/16	9.7	3/8	22.5	12.4	152	8.5	11/32	19.8	11.2	137	7.1	9/32	16.7	10.0	123	5.9	1/4	13.7	8.8	108	4.5	3/16	10.5	7.6	93

[a] Constant potentials may require 15 to 25 percent larger thickuesses of lead and 5 to 15 percent larger thicknesses of concrete than those given here for pulsating potentials.

[b] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 g/cm³ (147 lb/ft³).

TABLE 9. *Shielding requirements for busy 1,000 kvp therapeutic installations*

[W=4,000 ma-min/week]

Type of barrier	UT	Distance from tube to occupied area																								
		7 ft (2.13 m)					10 ft (3.05 m)					14 ft (4.26 m)					20 ft (6.10 m)					30 ft (9.15 m)				
		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete	
		mm	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]	*mm*	*in.*	*psf* [a]	*in.*	*psf* [a]
For controlled area:																										
Primary	1	130	5.1	300	32	390	120	4.7	280	30	370	115	4.5	270	28.5	350	105	4.1	240	26.5	330	100	3.9	230	25	310
	1/4	115	4.5	270	28.5	350	105	4.1	240	26.5	330	100	3.9	230	25	310	90	3.5	200	23	280	85	3.3	200	21.5	260
	1/16	100	3.9	230	25	310	90	3.5	210	23	280	85	3.3	200	21.5	260	75	3.0	180	19.5	240	70	2.8	170	18	220
Secondary	1	45	1.8	104	14.7	180	36.5	1.4	85	13.3	163	28.5	1.1	66	12.0	147	21	0.8	49	10.5	129	14.5	0.6	34	7.0	86
	1/4	28.5	1.1	66	11.9	146	21	0.8	49	10.5	129	14.5	0.6	34	7.5	92	11	0.4	25	6.0	74	5	0.2	12	4.5	55
	1/16	16	0.6	37	7.5	92	11	0.4	25	6.0	74	5.0	0.2	12	4.5	55	4	0.2	9	3.1	38	0	0	..	0	.
For environs:																										
Primary	1	160	6.3	370	38	470	145	5.7	330	36	440	140	5.5	320	34.5	420	130	5.1	300	32.5	400	125	4.9	290	31	380
	1/4	140	5.5	320	34.5	420	130	5.1	300	32.5	400	125	4.9	290	31	380	115	4.5	270	29	360	110	4.3	250	27.5	340
	1/16	125	4.9	290	31	380	115	4.5	270	29	360	110	4.3	250	27.5	340	100	3.9	230	25.5	310	95	3.5	210	24	290
Secondary	1	71.5	2.8	166	19.5	239	63	2.5	146	18.0	221	55	2.2	128	16.6	203	47	1.9	109	13.5	165	37.5	1.5	87	13.5	165
	1/4	55	2.2	128	16.1	197	47	1.9	109	13.5	165	39	1.5	91	13.8	169	31	1.2	72	12.4	152	22	0.9	51	9.0	110
	1/16	39.5	1.6	92	13.8	169	31	1.2	72	12.4	152	23	0.9	54	11.0	135	18.5	0.7	43	9.5	116	11.5	0.5	27	6.0	74

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 g/cm³ (147 lb/ft³).

TABLE 10. *Shielding requirements for busy 2,000 kvcp therapeutic installations*

[W = 2,000 ma-min/week]

Type of barrier	*UT*	Distance from tube to occupied area																								
		7 ft (2.13 m)					10 ft (3.05 m)					14 ft (4.23 m)					20 ft (6.10 m)					30 ft (9.15 m)				
		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete	
For controlled area:		*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]	*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]	*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]	*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]	*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]
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	410	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
Secondary	1	67	2.6	156	15	300	54	2.2	128	14	181	43	1.7	100	12	164	31	1.2	72	10	147	19	0.6	36	8.2	126
	1/4	43	1.7	100	12	163	31	1.2	72	10	147	22	0.8	47	8.5	129	13	0.5	30	7	113	8	0.3	15	5.0	93
	1/16	22	0.9	54	9	131	13	0.5	30	7	110	8	0.3	17	5.4	83	5	0.2	10	4	48	2	0.1	4	2.1	27
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
Secondary	1	107	4.2	302	22	298	94	3.7	221	20	267	83	3.3	193	18	238	71	2.8	165	16	208	57	2.4	142	14	172
	1/4	83	3.3	193	18	224	71	2.8	165	16	195	59	2.3	137	14	187	47	1.9	109	12	169	32	1.3	76	10	149
	1/16	59	2.2	128	14	187	47	1.9	109	12	169	36	1.4	81	11	153	24	1.0	60	9	136	14	0.5	31	7	114

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 g/cm^3 (147 lb/ft^3).

TABLE 11. *Shielding requirements for busy 3,000 kvcp therapeutic installations*

[W = 2,000 ma-min/week]

Type of barrier	*UT*	Distance from tube to occupied area																								
		7 ft (2.13 m)					10 ft (3.05 m)					14 ft (4.23 m)					20 ft (6.10 m)					30 ft (9.15 m)				
		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete		Lead			Concrete	
For controlled area:		*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]	*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]	*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]	*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]	*mm*	*in.*	*psf*[a]	*in.*	*psf*[a]
Primary	1	310	12.2	725	64	780	295	11.6	690	61	745	280	11.0	655	58	710	265	10.4	620	55	670	249	9.8	580	52	635
	1/4	280	11.0	655	58	710	265	10.4	620	55	670	250	9.8	585	52	635	235	9.3	550	50	610	219	9.6	510	46	560
	1/16	250	9.8	585	52	635	235	9.3	550	50	610	220	8.7	515	47	575	205	8.1	480	44	540	188	7.4	440	41	500
Secondary	1	93	----	----	19.3	----	78	----	----	16.9	----	63	----	----	14.5	----	48	----	----	12.5	----	31	----	----	10.4	----
	1/4	63	----	----	14.5	----	48	----	----	12.5	----	34	----	----	10.7	----	22	----	----	9.0	----	13	----	----	7.1	----
	1/16	34	----	----	10.7	----	22	----	----	9.0	----	14	----	----	7.1	----	9	----	----	5.8	----	6	----	----	4.0	----
For environs:																										
Primary	1	358	14.1	840	73	890	343	13.5	800	70	855	329	13.0	770	68	830	314	12.4	735	65	795	298	11.7	700	61	745
	1/4	328	12.9	710	68	830	314	12.4	735	65	795	299	11.8	700	62	755	285	11.2	665	59	720	268	10.6	625	56	685
	1/16	299	11.8	700	62	755	285	11.2	665	59	720	270	10.6	630	56	685	255	10.0	595	53	650	238	9.4	560	50	610
	1/64	270	10.6	630	56	685	255	10.0	595	53	650	240	9.5	560	50	610	225	8.9	525	48	585	210	8.3	490	44	540
	1/256	240	9.5	560	50	610	225	8.9	525	48	585	210	8.3	490	44	540	195	7.7	455	42	510	180	7.1	420	29	475
Secondary	1	143	----	----	28.8	----	128	----	----	25.9	----	113	----	----	22.9	----	98	----	----	20.3	----	80	----	----	17.1	----
	1/4	113	----	----	22.9	----	98	----	----	20.3	----	83	----	----	17.6	----	68	----	----	15.2	----	50	----	----	12.8	----
	1/16	83	----	----	17.6	----	68	----	----	15.2	----	53	----	----	13.2	----	38	----	----	11.3	----	23	----	----	9.3	----

[a] Pounds per square foot computed from millimeters of lead or inches of concrete and a concrete density of 2.35 g/cm^3 (147 lb/ft^3).

V. Appendix C. Determination of Protective Barrier Thicknesses

The thickness of protective barrier necessary to reduce the dose 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 1 through 11, Appendix B 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 3 to 7, Appendix C.

14. 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 dose 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 3 through 7 show the dose 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 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.

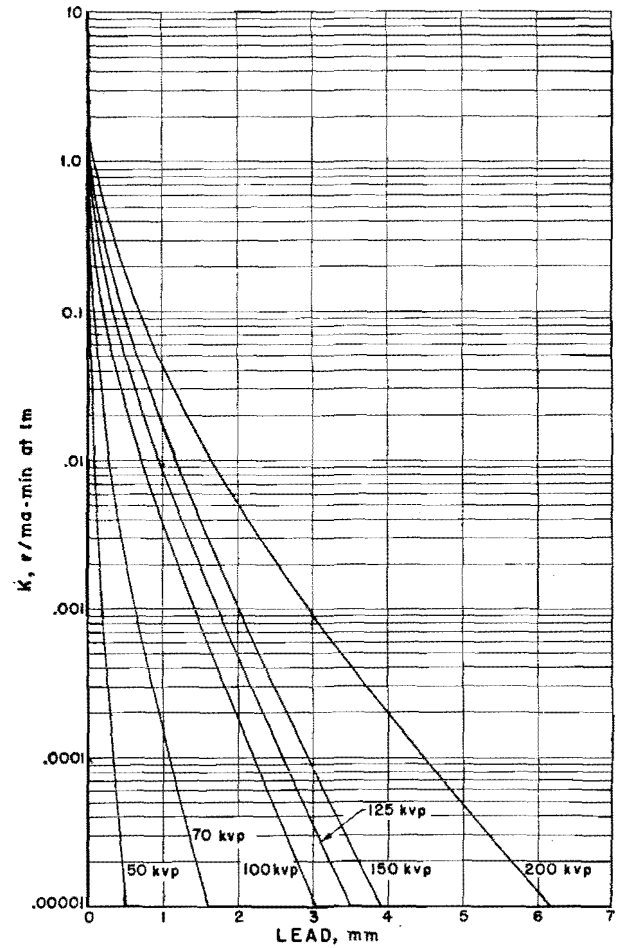

FIGURE 3. *Attenuation in lead of X-rays produced by potentials of 50- to 200-kv peak.*

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). 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.

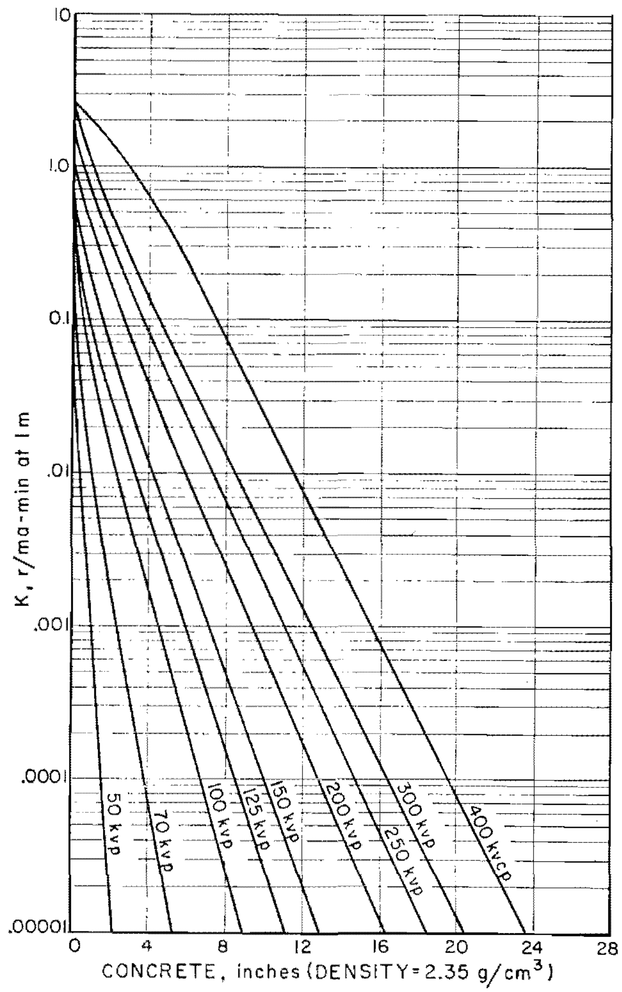

FIGURE 4. *Attenuation in concrete of X-rays produced by potentials of 50 to 400 kv.*

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 1959). 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).

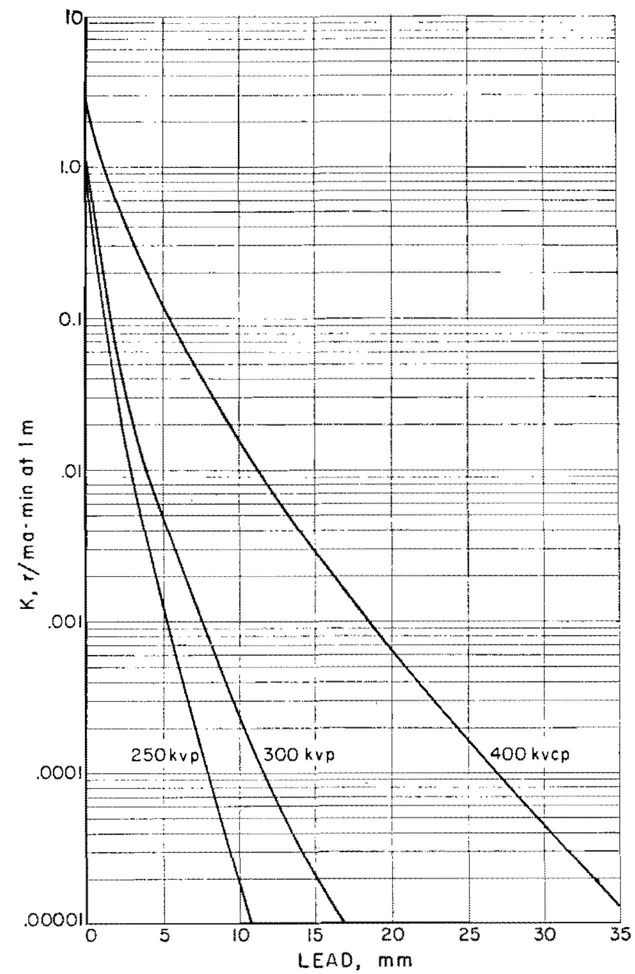

FIGURE 5. *Attenuation in lead of X-rays produced by potentials of 250 to 400 kv.*

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). The 400-kvcp curve was obtained with a constant potential generator and inherent filtration of approximately 3 mm of copper (Miller and Kennedy, 1955). The 300-kvp curve is for pulsed waveform and 3 mm of aluminum (Trout et al., 1959).

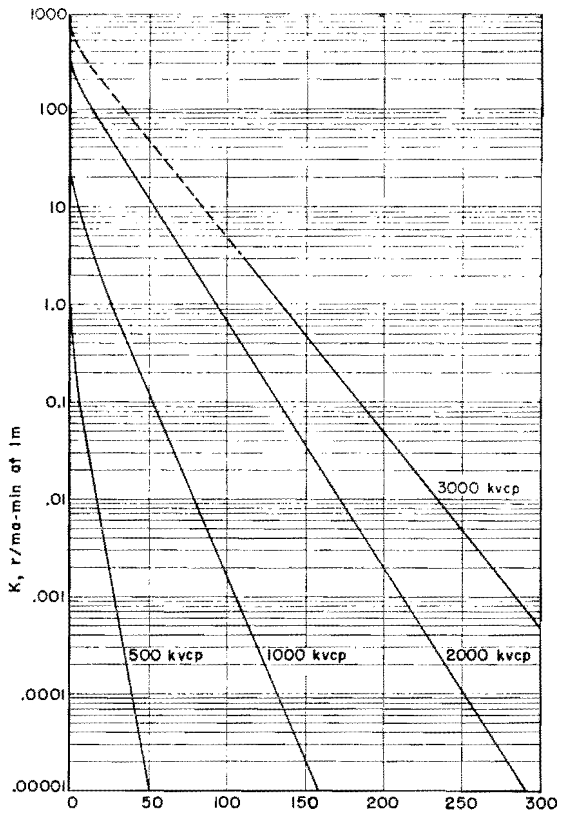

FIGURE 6. *Attenuation in lead of X-rays produced by potentials of 500- to 3,000-kv constant potential.*

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 curves 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). 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. 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.

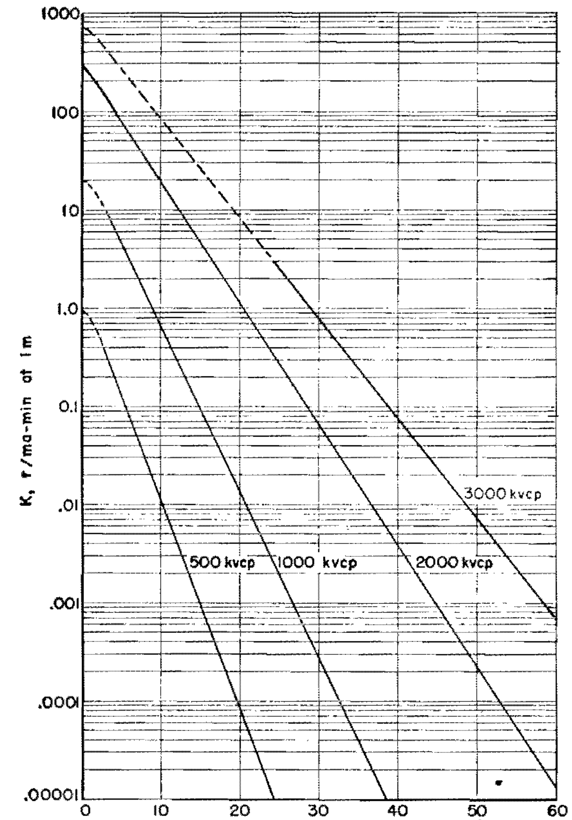

FIGURE 7. *Attenuation in concrete of X-rays produced by potentials of 500- to 3,000-kv constant potential.*

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). 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. 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.

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.

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

where

- P=Maximum permissible dose
  - 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. (See table 3 of Appendix A for typical values.)
- T=occupancy factor. (See table 2 of Appendix A 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.

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

Therefore,

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

Reference to figures 3 and 4 show 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 no detailed attenuation data for these materials, 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 15 in Appendix A 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 15 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 A, to be just slightly more than 1 hvl for 100 kvp highly filtered radiation. Thus, the addition of 0.3mm of lead would amply take care of the situation.

15. 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 type of tube housing (diagnostic or therapeutic); (2) the operating potential of the tube; (3) the weekly operating time of the tube;

(4) the distance from the tube to the occupied area; (5) the nature and degree of occupancy; and (6) whether the area in question is a controlled area. The maximum amount of leakage radiation allowed through a diagnostic type tube housing is set at 0.1 r at 1 m in any 1 hr and that through a therapeutic type housing at 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 A gives representative hvl thicknesses for lead and concrete for various kilovoltages. Tables 13 and 14 give the number of hvl's necessary to reduce the dose 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 dose 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 thickeness 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 kvp or below,

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

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

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

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

$$K=\frac{1{,}000\times P\times d^2}{120\ WT} \quad \text{(Use 500 kvcp curve).} \quad (4)^3$$

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

$$K=\frac{1{,}000\times P\times d^2}{300\ WT} \quad \text{(Use 500 kvcp curve).} \quad (5)^3$$

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.

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

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