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STRUCTURAL SHIELDING DESIGN AND EVALUATION FOR MEDICAL USE OF X RAYS AND GAMMA THE RAYS OF ENERGIES UP TO 10 Me V

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Preface

This report of the National Council on Radiation Protection and Measurements, which supersedes NCRP Report No. 34, is concerned with structural shielding design and evaluation for medical installations utilizing x rays and gamma rays of energies up to 10 MeV. The report contains recommendations and technical information as well as a discussion of the various factors which must be considered in the selection of appropriate shielding materials and in the calculation of the barrier thickness.

Recent availability of new data used to calculate the shielding requirements has resulted in revision of some of the shielding requirement tables set out in Appendix C. Specific values of the parameters used in the formulation of the tables are explicitly given. The calculational procedures are presented in such a manner as to facilitate their use in deriving customized shielding requirements not to be found in the tables. An adjunct to the report presenting full sized reproductions of the curves for barrier requirements is also an innovation for the NCRP.

This report is mainly intended for radiological physicists, radiologists, and regulatory personnel who specialize in radiation protection. Sections of the report should be of interest also to architects, hospital administrators, and others who are concerned with the planning of new radiation facilities.

The present report was prepared by the Council's Scientific Committee 9 on Medical X- and Gamma-Ray Protection Up to 10 MeV (Structural Shielding Design). Serving on the Committee during the preparation of this report were:

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The Council wishes to express its appreciation to the members of

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1. Introduction

This report, which supersedes NCRP Report No. 34 [1][1], presents recommendations and technical information related to the design and installation of structural shielding. It includes a discussion of the various factors to be considered in the selection of appropriate shielding materials and in the calculation of barrier thicknesses. It is mainly intended for radiological physicists, radiologists, and regulatory personnel who specialize in radiation protection. Sections of the report should be of interest also to architects, hospital administrators, and others who are concerned with the planning of new radiation facilities.

The concept of Maximum Permissible Dose Equivalent (MPD) as expressed by the NCRP, i.e. the maximum dose equivalent that persons shall be allowed to receive in a stated period of time, has been used as the basis for the recommendations in this report. The numerical values of the maximum permissible dose equivalents (see Table 1, Appendix C) are such that the probability of adverse biological effects is extremely low and is considered to present an acceptable risk. The MPD values used in this report are those agreed upon by the NCRP at the time of publication of this report. They are considered reasonable in light of the present scientific knowledge concerning the biological effects of ionizing radiation, and constitute acceptable standards for the use of ionizing radiation with safety. They are not limits above which biological damage can be assumed. In addition to specifying values for the Maximum Permissible Dose Equivalent, the NCRP recommendations call for radiation exposure to be kept at a level "as low as practicable" (or at the lowest practicable level). This subject is dealt with in detail in NCRP Report No. 39 [2]. For the purposes of this report, maximum average weekly exposure values of 100 mR for radiation workers and 10 mR for other workers have been selected for shielding design. These numerical values should not be interpreted as an alternate definition of their MPD. In most instances shielding design for radiation workers can be based upon an average weekly exposure value less than the 100 mR maximum average weekly exposure (e.g., 10 mR average weekly exposure) without an objection-

[1] Figures in brackets indicate the literature references listed on page 109.

roentgens of exposure may be considered numerically equivalent to the number of rads of absorbed dose in tissue or the number of rems of dose equivalent.

Terms used in the report are defined in Appendix A. Since, however, recommendations throughout the report are expressed in terms of *shall* and *should*, the use of these terms is explained here:

(1) *Shall* indicates a recommendation that is necessary to meet the currently accepted standards of radiation protection[2].

(2) *Should* indicates an advisory recommendation that is to be applied when practicable[2].

[2] In the following sections of this report, the words "shall" and "should" are italicized to emphasize that they are being used in the special sense conveyed by the explanation given here.

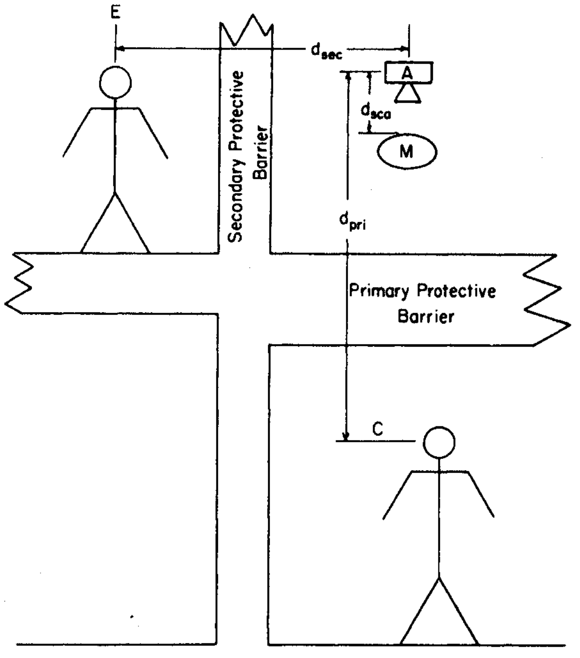

Fig. 2-1. Elevation view of radiation room and its surroundings with indication of distances of interest for radiation shielding calculations. A is the radiation source, M the patient, and C and E positions that may be occupied by persons.

required. Some of the physical factors used in determining the barrier requirements for beam sources are shown in Figure 2-1. The source at A, surrounded by its protective housing[5], emits a beam of x or gamma radiation directed at the patient, M. This beam is attenuated somewhat as it passes through the patient; it is usually attenuated much more by the primary protective barrier before irradiating a person at position C, at a distance d_{pri} from the radiation source.

The leakage radiation from the protective housing and the radiation scattered by the patient are attenuated by the secondary protective barrier before irradiating persons at position E, at a distance of d_{sec} from the source and the patient. Radiation scattered from the primary protective barrier may also reach position E. However, the

[5] The source is usually contained in a protective housing with the shielding material close to the source. The thickness of the shielding material required to obtain a given attenuation is essentially independent of its distance from the source. However, by placing the shielding close to the source, the surface area (and hence the volume and weight of the shield) is smaller than if the shielding were to be placed at a greater distance.

Tables 5 through 24 (Appendix C) give, directly, the minimum barrier requirements for typical radiation installations and can be used in most cases. The numerical value of the barrier thickness required has been rounded-off to the nearest 0.05 mm of lead and 0.5 cm of concrete for peak x-ray tube potentials up to 300 kV and to the nearest 0.5 cm of lead or concrete for peak x-ray tube potentials greater than 300 kV. In special cases, where the tables do not include the necessary values of the parameters, computation of the barrier requirements is necessary. Appendix B outlines the computations required and illustrates how the values given in the tables of Appendix C were obtained.

The equations used for computation of barrier requirements and the tabular values obtained from them assume that only one primary source is producing the radiation exposure at a given point. If more than one primary source can contribute to such an exposure, the pertinent tabular barrier requirements must be increased. For example, suppose that two sources could contribute to the exposure in a room. The barriers should be increased so that the exposure from both does not exceed the design exposure limit. If the sources are of similar energy, this is usually done by adding a half-value-layer to the barrier requirement calculated for each source independently. Under this condition each of the sources contributes one-half of the design exposure limit. However, if the radiation energy of one of the two sources is substantially less than the other, the required degree of protection may be achieved more economically by increasing the calculated barrier thickness for the lower energy source by several half-value-layers.

shielding material for barriers for x rays from machines operating at 300 kV or below. However, changing economic conditions and local price variations may negate this rule for specific cases. Careful economic comparisons *should* be made in cases where the economic choice is not obvious.

3.2.1 *Lead.* Lead can be installed in many ways and in different forms.

(a) *Sheet Lead.* Sheet lead is commercially available in thicknesses from less than a millimeter to about a centimeter (about $^1/_{32}$ inch to $^3/_8$ inches)[6]. Its flexibility permits it to be installed on curved or irregular surfaces. It can be nailed in place, although care must be taken to avoid sagging that would result if the spacing between nails were too great. Nail holes may result in significant radiation leaks. In such cases the holes *should* be covered with supplementary lead. Where the edges of two lead sheets meet, continuity of shielding *shall* be ensured at the joints by a sufficient overlap of the lead sheets or by the use of a cover strip over butt joints (see Section 4). The principal disadvantages of sheet lead are that it is not self-supporting and it is easily damaged. For these reasons, it is usually necessary to cover sheet lead with some form of wallboard, tile or plaster.

(b) *Lead-lined Wallboard.* Plywood, pressed wood or other vegetable fiber board sheets are commercially available with sheet lead firmly cemented to one side or laminated between sheets of the material. A variety of finishes is available and the sheets are readily installed with lead-lined strips of the same material covering the joints. Such wallboards may be removed and re-installed at a new location, a distinct advantage for temporary x-ray installations.

(c) *Lead-lined Lath.* Lead-lined lath is similar to lead-lined wallboards except that the lead is bonded to a perforated board to which plaster will adhere.

(d) *Lead-lined Blocks.* Lead-lined blocks, consisting of two cinder or concrete half-blocks with sheet lead sandwiched between them, are commercially available in the same size as standard blocks. In the use of lead-lined blocks, the lead sheets *shall* have sufficient overlap at the joints. (See Section 4.) The shielding afforded by the concrete or cinder block component supplements that of the lead and may be considered in shielding design. Lead-lined block partitions offer the advantages that they are relatively simple to construct, particularly in a new building; they provide considerable structural strength, and may be surfaced in the usual manner by the application of plaster or other conventional wall finishes.

[6] See Table 26 (Appendix C) for the relationship between thickness and weight per unit area of lead.

composition similar to that of concrete but may differ in density. Thus the concrete thickness values indicated in Appendix C must be adjusted for the difference in density to obtain the same required weight per unit area.

Hollow blocks of cinder, gypsum or similar materials may also be used for shielding if appropriate allowance is made for the voids. The concrete equivalence of the block may be estimated on the basis of the thickness and density of the thinnest solid part of the block. The actual equivalence will be somewhat greater depending upon the particular geometry.

Plaster containing barium provides higher attenuation than common plaster and has been used for low voltage x-ray installations. Its disadvantages are that considerable care is necessary to ensure uniform density, it is more apt to develop cracks with age than common plaster and the cost of installation is higher.

3.2.4 *Steel and Other Materials*. The use of steel for shielding is generally advantageous where space is limited or where structural strength is of major importance. Thick steel plates are sometimes used in megavoltage facilities. Conventional steel partitions and doors may, in some cases, serve as secondary protective barriers for low voltage installations where the shielding requirements are minimal [5].

Earth or sand fill may sometimes be used to advantage for shielding purposes. Provision *shall* be made, however, to ensure that the shielding material remains in place.

It is generally impractical to use wood products for shielding purposes due to the great thicknesses required.

3.2.5 *Transparent Materials*.

(a) *Plate Glass*. The use of ordinary plate glass (density 2.5–2.7 g cm^{-3}, refractive index 1.5–1.6) for shielding is generally advantageous only where the protection requirements are minimal. Since its composition is comparable to that of concrete, the thickness indicated for concrete in the tables may be used, with a density correction, for determining the shielding requirements [6]. Multiple thicknesses of plate glass have been employed in megavoltage installations. In such cases, an optically clear fluid having a suitable index of refraction, such as glycerin or mineral oil, *should* be used in the space between the glass plates to decrease the reflection from the interfaces and thereby increase light transmission. The light reflection losses may be reduced by more than a factor of ten by the use of such optical fluids.

4. Shielding Details

4.1 General

The shielding of the radiation room *shall* be so constructed that the protection is not impaired by joints, by openings for ducts, pipes, etc. passing through the barriers, or by conduits, service boxes, etc. embedded in the barriers. Doors (or other means of access to the room) and observation windows also require special consideration to ensure adequate protection without sacrifice of operational efficiency. These and related problems are considered in detail in this section.

It is important that the shielding be designed and installed properly; corrections made after the room is completed can be expensive. It is often impractical to make an overall experimental determination of the adequacy of the shielding prior to the completion of the building construction and the installation of the radiation equipment; however, shielding voids may be detected by the use of a suitable portable x-ray or gamma-ray source. Periodic visual inspection during the entire construction period is recommended in any case. Sometimes properly constructed shielding is later impaired by the removal of part of it for the installation of ducts and recessed boxes in walls, ceilings and floors or of hardware in lead-lined doors.

While specific recommendations are given, alternate methods of shielding may prove equally satisfactory. From the point of view of radiation protection, the particular method used is not important provided that the radiation survey of the completed installation establishes that the structural shielding is adequate.

4.2 Joints

The joints between lead sheets *should* be constructed so that their surfaces are in contact and with an overlap of not less than 1 cm ($^1/_2$ inch) or twice the thickness of the sheet, whichever is greater. Welded, or burned, lead seams are satisfactory if the lead equivalence of the seams is not less than that required of the barrier.

Protective barriers of solid block (or brick) construction *should*

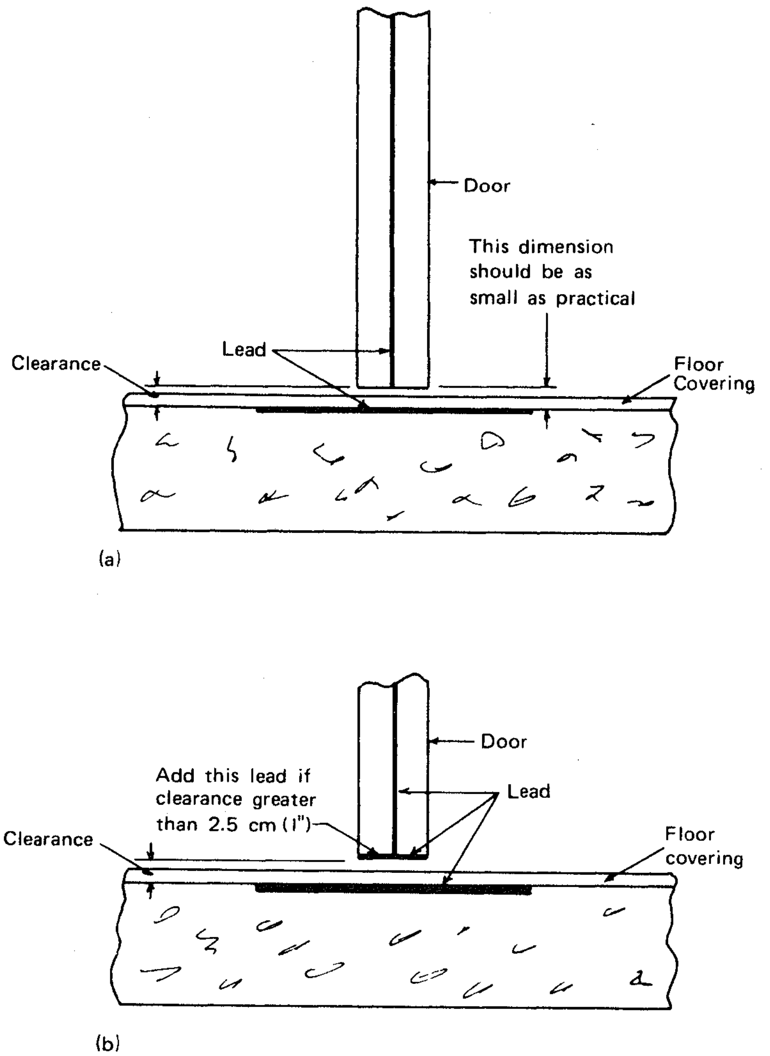

Fig. 4-2. Typical lead baffles under doors exposed to the useful beams generally not required for diagnostic installations.

(1) energy of radiation
(2) orientation and field size of useful beam
(3) size and location of opening in the protective barrier
(4) geometrical relationship between radiation source and opening
(5) geometrical relationship between opening and persons, materials or instruments to be protected.

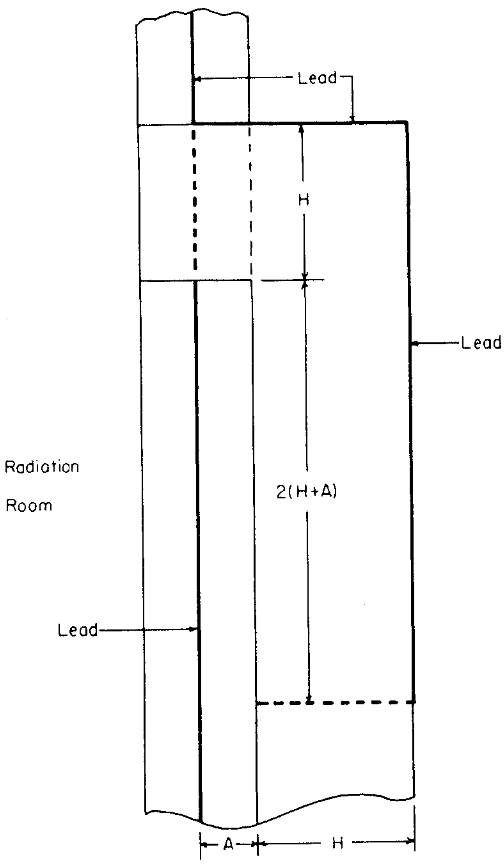

Fig. 4-4. Typical baffle design for openings in secondary protective barrier.

from the finished floor[9], openings in the walls above this height generally do not require radiation baffles. For orthovoltage (150 kV to 500 kV) and megavoltage installations, the wall shielding *should* extend to the ceiling barrier or to the roof, necessitating baffles for ducts, conduits, etc. passing through the walls. Where ducts terminate at a grille in the wall surface of a primary protective barrier, a lead-lined baffle may be required in front of the grille; the baffle must be at a sufficient distance to permit adequate flow of air and must extend far enough beyond the perimeter of the opening in order to provide the required degree of protection. This is illustrated in Figures 4-6 and 4-7.

[9] This height has been chosen because the height of the x-ray source and of most individuals is less than 2.1 m (7 feet).

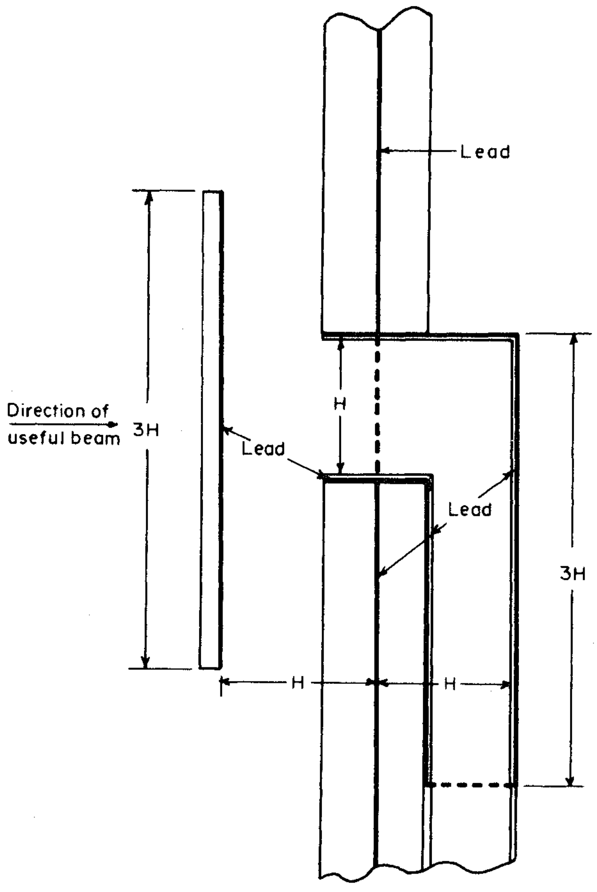

Fig. 4-7. Typical baffle design for openings in primary protective barrier for orthovoltage installations.

Service boxes, conduits, etc. imbedded in concrete barriers may require lead shielding to compensate for the displaced concrete. For example, if the outside diameter of a steel conduit is large[10], if the conduit passes through the barrier in line with the useful beam, or if the concrete does not fit tightly around the conduit, compensatory shielding is required.

Where supplementary lead shielding is required, its thickness[11]

[10] The conduit size not requiring compensatory shielding depends on radiation energy and type of barrier. Usually conduits 5 cm (2 inches) O.D. or less, do not require lead or other additional shielding.

[11] For such conduits it is usually practical to wrap the conduit with lead of half the total thickness required.

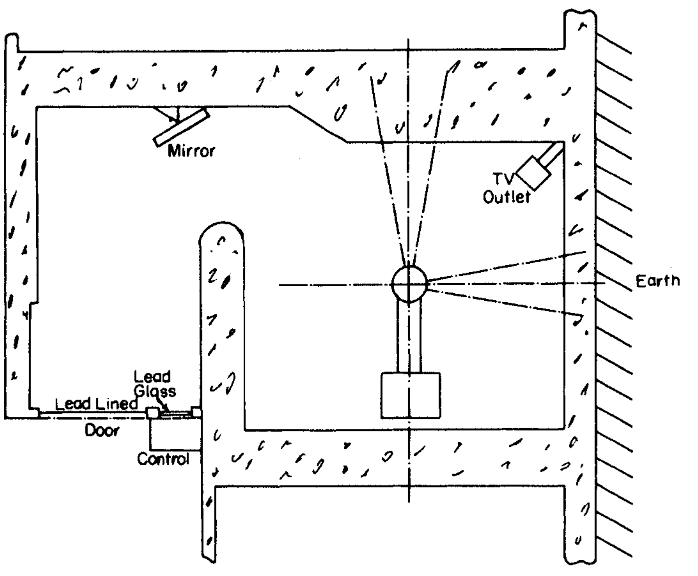

Fig. 4-9. Typical maze design for megavoltage therapy installation. The door and window are exposed only to radiation which has been scattered at least twice.

should be at least equal to the lead equivalence of the displaced concrete. The lead equivalence of the concrete will depend upon the energy of the radiation and may be obtained from the ratio of the *TVL*'s shown in Table 27 (Appendix C). The shielding *should* cover not only the back of the service boxes, but also the sides, or extend sufficiently to offer equivalent protection. This is shown in Figure 4-8. As illustrated in Figure 4-8, conduits passing through the barrier *should* have sufficient bends to reduce the radiation to the required level.

4.4 Access to Radiation Room[12]

Various methods are used for providing access to the radiation room. The most convenient is achieved by means of a door leading directly into the room. In the case of megavoltage installations, however, such a door requires heavy shielding, even when located in a wall exposed only to leakage and scattered radiation; it may weigh several tons and require an expensive motor drive; it will also require means for emergency manual operation. A maze arrangement gener-

[12] See Section 5.3.2 for design of control booths located within the diagnostic room.

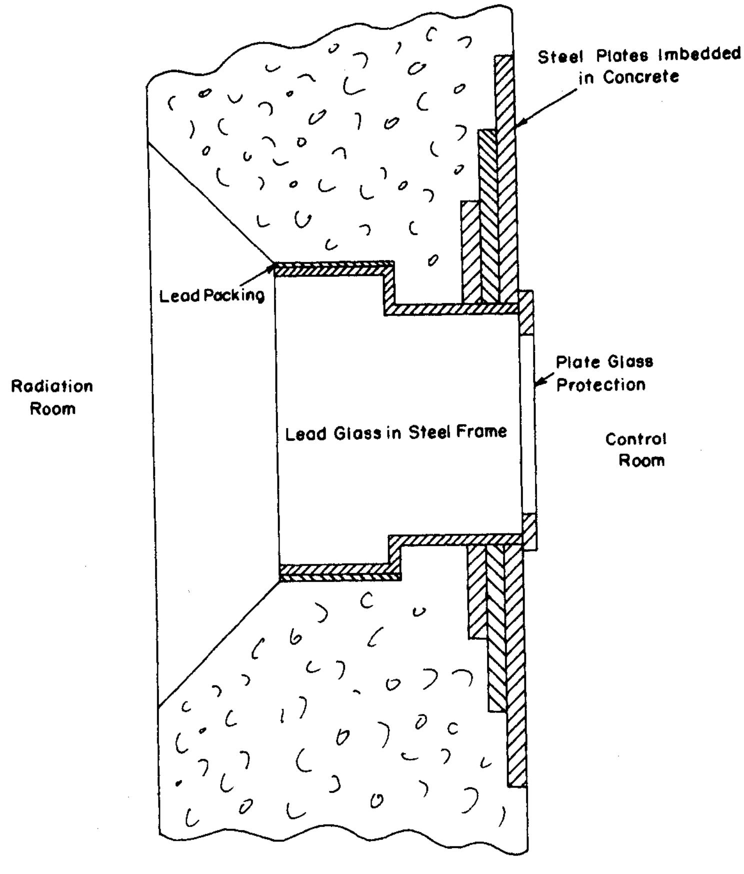

Fig. 4-11. Alternate lead glass observation window design for megavoltage installations.

special problems. Such windows are generally located in concrete protective barriers. To obtain a maximum field of vision for a given size window, the wall around the window is usually bevelled off on the radiation room side. The lead glass, therefore, must be mounted in a shielded frame which compensates for the reduced concrete thickness. Two typical designs are shown in Figures 4-10 and 4-11.

min) the maximum milliampere rating of diagnostic equipment does not affect the shielding requirements. Studies of the use of radiographic and fluoroscopic x-ray equipment indicate that the weekly workload seldom exceeds 1000 mA min and 1500 mA min, respectively [4]. Table 2 (Appendix C) shows typical workloads for various types of installations. These values *should* be used when specific information is not available.

The increased use of x rays for diagnostic purposes during the recent decades has not resulted in proportionally higher workloads. This is due to the employment of more sensitive x-ray films, intensifying screens and other image recording devices. In addition, the newer and more involved diagnostic procedures require more preparation time, thus reducing the number of examinations that can be carried out in a room in a week.

The majority of radiographs are taken with tube potentials considerably less than 100 kV. To simplify shielding design, however, an operating potential of 100 kV is usually assumed; this, in general, is a safe assumption and yet does not increase significantly the cost of shielding. When potentials greater than 100 kV are used, the increased barrier transmission is normally offset by a reduction in the workload. At higher kilovoltage, fewer milliampere-seconds are required for a given radiographic procedure. The barrier thickness specified in Table 5 (Appendix C) for a weekly workload of 1000 mA min at 100 kV will provide essentially the same degree of shielding for a weekly workload of 400 mA min at 125 kV or 200 mA min at 150 kV.

5.1.3 *Unprocessed Film Storage*. Protection of unprocessed x-ray films during storage requires special consideration since an exposure of less than 1 mR over a portion of the film may produce undesirable shadows. The exposure limit will depend upon the film type and the energy of the radiation. When films are stored in areas adjacent to an x-ray room it is usually necessary to provide more shielding than that required for personnel. This is particularly important when unprocessed films are stored for extended periods of time or when stored above the height of the shielding. Table 6 (Appendix C) gives the barrier thicknesses required to reduce the exposure to 0.2 mR for various workloads, distances, and storage periods.

5.1.4 *Room Lighting*. In fluoroscopic rooms utilizing image intensifiers, the general room illumination *should* be controlled from within the room by means of a dimmer. Such devices *should* also be provided in radiographic rooms that utilize a beam defining light. When direct fluoroscopic viewing is used, low intensity red lights are required to

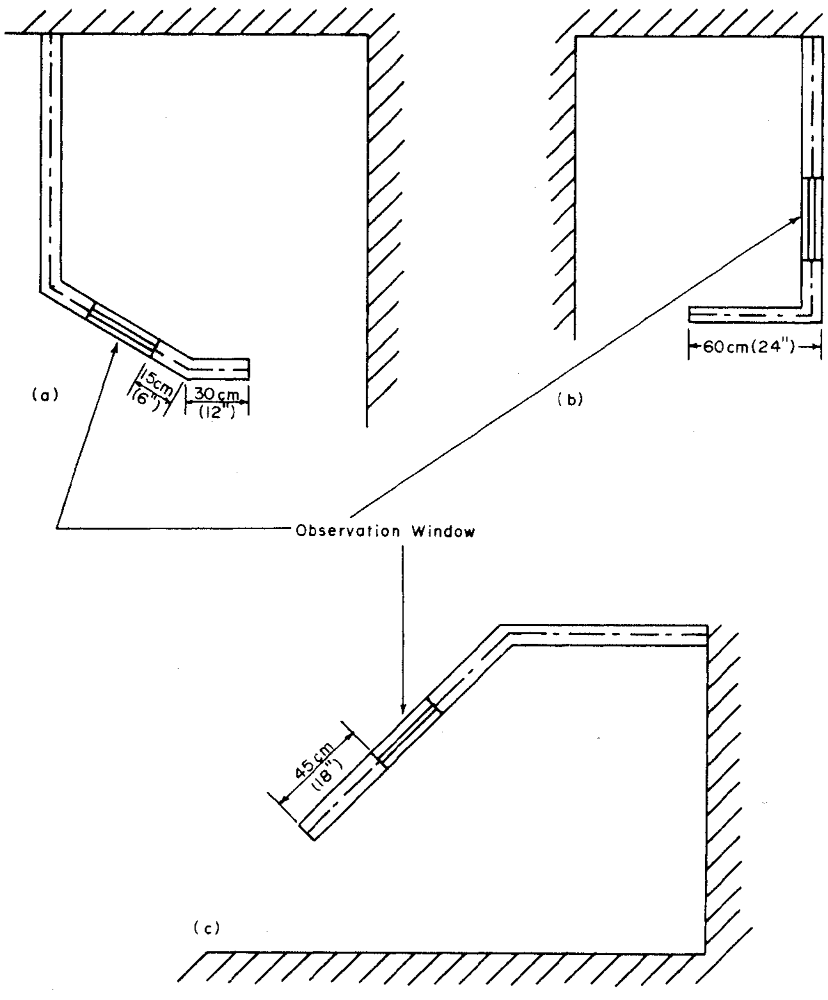

Fig. 5-1. Typical designs of control stations.

exposure to the useful beam or scattered radiation, electrical interlocks *shall* be provided to ensure that exposures cannot be made when the door is open.

Provision *shall* be made for the operator to observe and communicate with the patient from a shielded position at the control panel. When an observation window is provided, it *shall* have a lead equivalence at least equal to that required of the partition (or the door) in which it is located. The exposure switch *shall* be so arranged that it cannot be conveniently operated outside the shielded area [9].

An efficient traffic pattern for the operator and easy communicasecondary barriers. However, in most new construction, the saving obtained by limiting the primary protective barrier to only a section of the wall is insignificant compared with the need for special care during construction and future restrictions on use of the room. See Section 5.3.2 for protection requirements for operator's control positions.

5.5 Cystoscopic Installations

In cystoscopic procedures, the direction of the useful beam is generally at the floor or at one wall. Therefore, a primary protective barrier[15] is required for the floor and for the one wall. Only secondary protective barriers are required for the ceiling and other wall areas not exposed to the useful beam. See Section 5.3.2 for operator's control station protection requirements.

5.6 Surgical Suites

Structural shielding *shall* be provided when radiographic procedures are routinely performed in the operating rooms. If the workload is low, masonry building construction may provide sufficient shielding. It is often advisable to provide a primary protective barrier which will allow personnel to remain in the room during radiographic exposures. Furthermore, special electrical safety requirements are necessary for x-ray equipment used in the presence of explosive gases[16].

5.7 "Special Procedure" Installations

Special procedure rooms are used for cardiovascular radiology, neuroradiology and tomography and differ from conventional diagnostic rooms only in terms of the auxiliary equipment required. In general, the workload is limited by the time consumed in associated

[15] The primary protective barrier does not necessarily have to extend over the entire floor or wall; it may be limited to the area exposed to the useful beam plus a suitable margin of at least 30 cm (12 inches).

[16] Detailed information may be obtained from Underwriters' Laboratories, Inc., 207 East Ohio Street, Chicago, Illinois 60611.

6. Therapy Installations[17]

6.1 General

There is considerable variation in the shielding requirements for therapy installations due to the wide range of energies and different types of equipment used. Careful planning may result in appreciable savings, particularly in the megavoltage range where the shielding is very costly. Provision for future requirements may prevent subsequent serious inconvenience and expensive alterations. This consideration is important because of the trend toward higher energies and greater workloads.

6.1.1 *Location*. Operational efficiency and initial cost, as well as feasibility of future expansion, should be considered when locating a therapy installation. Proximity to adjunct facilities, ready access for in-patients and out-patients, and consolidation of all therapeutic radiological services, however, may be more important than construction cost. For bottom floor rooms below grade, the reduction in shielding costs for floors and outside walls should be weighed against the expense of excavation, watertight sealing and of providing access. For rooms on or above grade, the outside walls and especially windows usually require shielding if nearby areas are occupiable; additional structural support may be required for heavy equipment and for shielding floors, walls, and ceilings.

6.1.2 *Provision for Future Needs*. Cost and inconvenience of future alterations may be reduced by providing extra rooms initially or by allowing for future enlargement of rooms to accommodate replacement equipment of greater size, higher energy, and with increased workload. If the installation is on an upper floor, room enlargement or contiguous expansion may be impossible. If on the ground floor, expansion onto the surrounding grounds may be most economical, requiring shielding only for walls, and possibly the ceiling, without floor shielding. Expansion over an occupied area may require extra structural support and floor shielding. Expansion underground may require additional excavation, possibly with relocation of sewerage and other services.

[17] See Section 7 for brachytherapy.

view the patient and the control panel from the same protected position. Direct window viewing is used in most superficial and orthovoltage installations. For megavoltage installations the cost of the high density glass and its lead frame may be significant. Indirect viewing by means of mirrors is more economical but may be less satisfactory.

Closed circuit television provides considerable flexibility, as both camera and display (monitor) can be located for maximum convenience[18]. Disadvantages include the need for auxiliary viewing in case of television equipment failure, and the cost of maintenance.

Means for audible communication between the patient and control room *shall* be provided (e.g., voice, buzzer).

When light localization of treatment portals is used, means for adjusting the light level in the room *should* be provided both in the treatment room and at the control panel.

6.2 X-Ray Installations of Less Than 500 kV

The term "grenz-ray therapy" is used to describe treatment with very soft x rays produced at potentials below 20 kV. Special structural shielding is usually not necessary because the ordinary building construction offers adequate protection against this low energy radiation. The operator and other persons (except the patient) *should not* be in the treatment room, and *shall not* be exposed to the unattenuated useful beam.

The term "contact therapy" is used to describe very short source-skin distance irradiation of accessible lesions, usually employing potentials of 40 to 50 kV. Generally, structural shielding is not required when a source-skin distance of 2.0 cm, or less, is employed, because of the short treatment time, i.e., low workload.

The term "superficial therapy" is used to describe treatment with x rays produced at potentials ranging from 50 to 150 kV, and rooms used for this purpose require structural shielding. The control station need not be outside the therapy room. If a protective screen is used to protect the operator, it *shall* be anchored. Viewing *shall* be through a protective window, or by indirect means. The barriers *should* be an integral part of the building.

[18] Therapy equipment control panels and television displays for several facilities may be juxtaposed; several cameras may be used to view the patient from different angles; a zoom lens may be installed for patient close-up views; a pan-tilt mechanism for the camera may be operated from the control panel to view any portion of the treatment room; and additional displays may be located elsewhere.

quently provide more shielding than the recommended minimum (see NCRP Report No. 33 [9]). Unless it is established that such extra shielding is present, the structural shielding design *shall* be based on the assumption that only the recommended minimum is provided. If pertinent data on leakage radiation are available, however, appreciable reduction in secondary barrier requirements may be possible. Unless the leakage is reasonably uniform in all directions, data for many directions (and planes) are necessary, and all possible beam orientations *should* be considered.

When the electrons are not properly directed and/or focused on the target, they may strike other parts of the equipment. In such cases, there may be a substantial increase in the leakage radiation. This possibility *should* be considered in the shielding design and in the requirements for monitoring.

It is usually difficult to treat more than fifty patients with one machine in an eight hour day [see Table 2 (Appendix C)]. If special arrangements are made to increase the workload, such as twin treatment carts which can be alternated, shielding must be correspondingly increased. If more than one work shift is used to increase the utilization of the equipment, added shielding for controlled areas will not be required unless the workload *per shift* is increased. Added shielding, however, may be required for nearby non-controlled areas.

The control station *shall* be located outside the treatment room.

Interlocks and warning lights *shall* be provided (see Sections 6.1.5 and 8.1). The output, particularly from equipment designed to permit extraction of the electron beam, may be so high that a person who is accidentally in the treatment room when the machine is turned "ON" may receive an excessive exposure during the time required to reach an access door. This hazard can be reduced by having "cut-off" or "panic" buttons at appropriate positions about the treatment room, which, when pressed, will cause the irradiation to be terminated. This subject will be dealt with in greater detail in a forthcoming NCRP report [27].

Induced radioactivity in the air and treatment room is negligible for installations operating at up to 10 MV[21].

Ozone production is negligible during x-ray or gamma-ray beam therapy. However, some megavoltage equipment also permits electron beam therapy which may result in significant ozone production, and consideration *should* be given to this possible hazard (see NCRP Report No. 51 [27]).

[21] The target of some megavoltage equipment may become sufficiently radioactive to present a hazard if handled during the servicing of the equipment. Therefore, a survey should be performed before servicing the equipment in the vicinity of the source.

In some models the source housing is designed to swivel the center of the useful beam away from the center of the beam interceptor. If the equipment has this feature, additional structural shielding is usually required. Electrical or mechanical means *shall* be provided to prevent irradiation when the useful beam is directed toward a barrier which does not have the additional thickness required by the absence of the beam interceptor.

TABLE 7-1—*Protective barrier transmission factor (B) per curie for 2.5 mR per hour (corresponding to 100 mR per 40 hours weekly exposure)*

Distance m	^{60}Co	^{226}Ra	^{192}Ir	^{137}Cs	^{198}Au
0.5	0.00048	0.00076	0.00114	0.00188	0.0027
1	0.00192	0.00303	0.00455	0.0075	0.0107
1.5	0.0043	0.0068	0.0102	0.0169	0.024
2	0.0077	0.012	0.0182	0.0301	0.043
2.5	0.012	0.019	0.028	0.047	0.067
3	0.0173	0.027	0.0404	0.068	0.096

Notes: (a) Applying the appropriate value of B, the necessary thickness of shielding material may be obtained from Fig. 11, 12, or 13 (Appendix D).

(b) If protection is required for non-occupational exposure, add one tenth value layer thickness for the shielding material chosen.

(c) For quantities of material other than a curie, the permissible transmission (B) should be adjusted in inverse proportion.

Example:

The required barrier thickness for a radiation worker at a 2-meter distance from a 50 mCi (0.05 Ci) cobalt-60 source is determined from:

$$B = 0.0077 \text{ (from table)} \times \frac{1 \text{ Ci}}{0.05 \text{ Ci}} = 0.154$$

For concrete, the value of B for cobalt-60 indicates a thickness (Figure 12, Appendix D) of 21 cm of concrete. To protect persons other than radiation workers, one tenth value layer of concrete or 20.6 cm would be added, totaling about 42 cm.

difficult to calculate because of self-absorption and the various thicknesses of shielding materials through which the radiation from different sources must pass. However, in most cases, the radiation levels may be approximated by assuming that the sources are located at the center of the safe.

When brachytherapy sources are in use, the protection of nearby persons is generally effected by means of local shielding such as L-blocks, lead bricks and shielded transport containers. Since the shielding of transport containers is often marginal, supplementary shielding *should* be provided if they are used also for storage near occupied areas.

In general, structural shielding is not needed to protect against radiation from brachytherapy sources during the treatment of patients. In most cases, the distance to occupied areas is sufficient to reduce the radiation to adequate levels (see Table 29, Appendix C). Structural shielding, however, is recommended where a large number of brachytherapy cases are involved (see NCRP Report No. 37 [11]). Concrete, rather than lead, is usually the preferred material.

Additional shielding may be required if radiation sensitive instruments or film are in the vicinity of brachytherapy sources.

interlock circuit and causes the useful beam to go to the "OFF" condition, and

(2) the beam does not turn "ON" again when the interlock circuit is restored until the equipment is manually activated from the control panel.

The presence of appropriate warning signs and devices *shall* be determined. Emergency action procedures for gamma-ray beam therapy installations *shall* be posted near the control panel. A red warning signal light (energized only when the useful beam is "ON") *shall* be located: (a) on the control panel, and (b) near the entrance(s) to megavoltage or gamma-ray beam therapy rooms in addition to other appropriate locations in the treatment room (see NCRP Report No. 33 [9]).

"Radiation Area" warning signs *should* be posted in all areas wherein a person, if he were continuously present, could receive an exposure in excess of 5 mR in any one hour or 100 mR in any 5 consecutive days but less than 100 mR in any one hour. Appropriate "High Radiation Area" warning signs *shall* be posted at the entrance to any area wherein a person could receive an exposure of 100 mR or more in any one hour. Exceptions to the posting requirements for "High Radiation Area" signs may be permitted in locations visible to patients when such signs may be a source of apprehension, provided the personnel occupying the areas are otherwise informed of the radiation levels to which they could be exposed, and entrance to the area is strictly controlled.

8.2 Inspection During Construction

Visual inspection during construction is advantageous in ensuring compliance with specifications and revealing faulty materials or workmanship which can be remedied more economically at this stage than later. Inspection *should* include, where applicable:

(a) determination of lead or concrete thickness;

(b) determination of concrete density from samples which were taken at the time of casting of concrete and that "honeycombing" or settling of heavy aggregate does not occur;

(c) observation of the degree of overlap of lead sheets or between lead and other barrier material;

(d) determination of lead glass thickness, density, and number of sheets in each view window;

(e) inspection of the lead shielding behind switch boxes, lock as-

For the determination of the adequacy of secondary protective barriers, measurements *shall* be made employing a suitable phantom to simulate the patient. The near surface of the phantom *should* be placed at the usual source-skin distance.

Certain radiation protective barriers may be tested by the use of a radiation source other than the final one to be employed in the installation. For example, a mobile x-ray unit operated at an appropriate potential may be used for the determination of the radiation attenuation of the barriers for a radiographic or fluoroscopic x-ray installation. The use of a high energy gamma-ray source such as cobalt-60 is inappropriate for testing a lead barrier which is designed for a radiographic or fluoroscopic installation.

8.4 Report of Radiation Protection Survey

The qualified expert *shall* report his findings in writing. The report *shall* indicate whether or not the installation is in compliance with the applicable NCRP recommendations and pertinent governmental regulations.

Exposure rates in nearby occupiable areas *shall* be indicated.

The evaluation of the survey results *shall* be based upon the applicable MPD. Consideration *shall* be given to the type of area (controlled or non-controlled) and the degree of occupancy, the use factor and workload in evaluating the radiation protection of the installation.

If the survey indicates that the applicable MPD could be exceeded, taking into account the expected workload, use factor and occupancy, the qualified expert *shall* recommend appropriate corrective measures. These measures may include an increase in barrier thickness; reduction in use factor and/or workload; changes in operating techniques, equipment, mechanical or electrical restrictions of the beam orientation; or restriction of occupancy.

The report *should* indicate whether a resurvey is necessary after corrections have been made.

A copy of the report *should* be retained by the owner or by the person in charge of the installation. Any recommended limitations of occupancy, operating techniques and/or workload *should* be posted near the control panel.

Written records and data of the survey *should* be retained for a period of at least 5 years by the qualified expert who performed or directed the survey.

purposes of this report, the dose equivalent in rems may be considered numerically equivalent to the absorbed dose in rads and the exposure in roentgens.)

dose rate: Dose per unit time.

exposure: A measure of x or gamma radiation based upon the ionization produced in air by x or gamma rays. The special unit of exposure is the roentgen. (For radiation protection purposes of this report, the number of roentgens may be considered to be numerically equivalent to the number of rads or rems.)

exposure rate: The exposure per unit time.

filter, filtration: Material in the useful beam which absorbs preferentially the less penetrating radiation.

gamma-ray beam therapy: Therapeutic irradiation with collimated gamma rays.

half-life, radioactive: Time for the activity of any particular radionuclide to be reduced to one-half its initial value.

half-value layer *(HVL)*: Thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the exposure rate by one-half.

installation: Radiation sources with associated equipment, and the space in which they are located.

interlock: A device which automatically causes a reduction of the exposure rate upon entry by personnel into a high radiation area. Alternatively, an interlock may prevent entry into a high radiation area.

kilovolt (kV): A unit of electrical potential difference equal to 1000 volts.

kilovolt constant potential: The potential difference in kilovolts of a constant potential generator.

kilovolt peak: The crest value in kilovolts of the potential difference of a pulsating potential generator. When only one-half of the wave is used, the value refers to the useful half of the cycle.

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

leakage radiation: See radiation.

maximum permissible dose equivalent (MPD): For radiation protection purposes, maximum dose equivalents that persons shall be allowed to receive in a stated period of time (See Section 1 and Table 1, Appendix C.) For radiation protection purposes of this report, the dose equivalent in rems may be considered numerically equal to the absorbed dose in rads and the exposure in roentgens.

million electron volts (MeV): Energy equal to that acquired by a particle with one electronic charge in being accelerated through a potential difference of one million volts (one MV).

millicurie (mCi): One-thousandth of a curie.

milliroentgen (mR): One-thousandth of a roentgen.

noncontrolled area: Any space not meeting the definition of controlled area.

normalized output ($\dot{X}_n$): The exposure rate (in roentgens per minute) per unit target current (in milliamperes) and measured at one meter from the source, after transmission through the barrier. The unit is $Rm^2/(mA\ min)$.

occupancy factor (T): The factor by which the workload should be multiplied to correct for the degree of occupancy of the area in question while the source is "ON".

occupational exposure: The exposure of an individual to ionizing radiation in the course of employment in which the individual's normal duties or authorized activities necessarily involve the likelihood of exposure to ionizing radiation.

occupiable area: Any room or other space, indoors or outdoors, that is likely to be occupied by any person, either regularly or periodically during the course of his

radiation protection supervisor: The person directly responsible for radiation protection. (See Section 7.2 of NCRP Report No. 33 [9].)

radiation protection survey: An evaluation of the radiation safety in and around an installation.

rem: The unit of dose equivalent. For radiation protection purposes of this report which covers only x and gamma radiation, the number of rems may be considered equivalent to the number of rads of absorbed dose in tissue or to the number of roentgens of exposure.

Rhm (deprecated): Roentgens per hour at one meter from the effective center of the source (target). In gamma-ray beam therapy, this distance is measured to the nearest surface of the source as its effective center generally is not known.

roentgen (R): A special unit of exposure equal to 2.58×10^{-4} coulomb per kilogram of air.

scattered radiation: See radiation.

secondary protective barrier: See protective barrier.

shall: *Shall* indicates a recommendation that is necessary to meet the currently accepted standards of radiation protection.

should: *Should* indicates an advisory recommendation that is to be applied when practicable.

shutter: (1) In beam therapy equipment, a device fixed to the x-ray or gamma-ray source housing to intercept the useful beam. (2) In diagnostic equipment, an adjustable device used to collimate the useful beam.

source: A discrete amount of radioactive material or the target (focal spot) of the x-ray tube.

sealed source: A radioactive source sealed in a container or having a bonded cover, in which the container or cover has sufficient mechanical strength to prevent contact with and dispersion of the radioactive material under the conditions of use and wear for which it was designed.

source housing: See protective source housing.

source-surface distance *(SSD)*: The distance, measured along the central ray, from the center of the front surface of the source (x-ray focal spot or sealed radioactive source) to the surface of the irradiated object.

stray radiation: See radiation.

survey: See radiation protection survey.

teletherapy: See gamma-ray beam therapy.

tenth-value layer *(TVL)*: Thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the exposure rate to one-tenth.

therapeutic-type protective tube housing:

(a) For x-ray therapy equipment not capable of operating at peak tube potentials of 500 kV or above, the following definition applies: An x-ray tube housing so constructed that the leakage radiation at a distance of one meter from the source does not exceed one roentgen in an hour when the tube is operated at its maximum rated continuous current for the maximum rated tube potential.

(b) For x-ray therapy equipment capable of operating at peak tube potentials of 500 kV or above, the following definition applies: An x-ray tube housing so constructed that the leakage radiation at a distance of one meter from the source does not exceed either one roentgen in an hour or 0.1 percent of the useful beam exposure rate at one meter from the source, whichever is the greater, when the machine is operated at its maximum rated continuous current for the maximum rated accelerating potential.

APPENDIX B

Computation of Barrier Requirements

The basic principles of shielding design are discussed in Section 2. Using these principles and the tables in Appendix C, it is possible to determine directly the barrier requirements for most situations. For other conditions it is necessary to compute the required thicknesses using the graphs of Appendix D. The required steps are shown below.

B.1 Computation of Thickness of Primary Protective Barrier

The curves of Figures 1 through 5 (Appendix D) indicate the attenuation of x rays in a lead or concrete barrier as a function of the barrier thickness. In each graph, the quotient of the exposure at one meter from the target and the workload appears as the ordinate with the value of the weekly workload, W, given in milliampere minutes. It may be noted that the curves are strongly dependent upon the barrier material and the kilovoltage of the radiation. Thus, there is a characteristic curve for each kilovoltage in each type of barrier material.[26]

The weekly exposure, X_u, from the useful beam at the point of interest, which is at a distance, d_{pri}, from the source, is related to the exposure rate at one meter, $\dot{X}_u$, by the following equation

$$X_u = \frac{\dot{X}_u t}{(d_{pri})^2} \tag{1}$$

[26] The question sometimes arises as to whether a family of curves is required for a given kilovoltage in order to provide data for different amounts of filtration. For ordinates in terms of roentgens per milliampere minute, the curves for a range of practical filtrations at a given x-ray potential essentially coincide at other than very small thicknesses of the barrier materials. Thus, a family of curves is not necessary for practical protection design calculations.

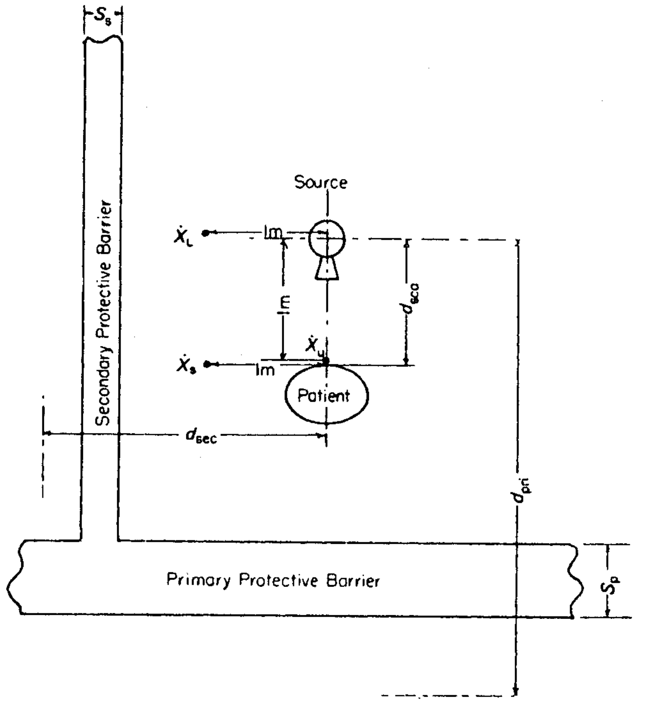

Fig. B-1. Geometry used in deriving equations for computing thickness of primary protective behavior, S_p, and of secondary protective barrier, S_s.

If we define the normalized output, $\dot{X}_n$, as the exposure rate per unit target current, I (in milliamperes), measured at one meter, then $\dot{X}_n = \dot{X}_u/I$ or $\dot{X}_u = \dot{X}_n I$. Substituting for $\dot{X}_u$ in equation 2

$$P = (B_{ux}\dot{X}_n)\frac{It}{(d_{pri})^2} \tag{3}$$

Substituting $It = W$, the weekly workload in milliampere minutes, into the above equation and rearranging terms:

$$B_{ux}\dot{X}_n = P\frac{(d_{pri})^2}{W} \tag{3a}$$

Setting the left hand side of equation 3a equal to K_{ux}, the number of roentgens per milliampere minute in a week for the useful beam normalized at one meter:

$$K_{ux} = \frac{P(d_{pri})^2}{W} \tag{3b}$$

However, in order to recognize that the primary protective barrier

When the radiation is obliquely incident on a barrier, the required thickness of the barrier will be less than that obtained by the above calculations. The difference between these thicknesses depends on (a) the angle of obliquity, θ, between the radiation direction and the normal to the barrier, (b) the barrier material, (c) the required attenuation, and (d) the energy of the radiation. If there were no radiation scattering in the barrier material, the relation between the computed thickness, $S/\cos\theta$, and actual thickness, S, of barrier for obliquely incident radiation would be that illustrated in Figure B-2. However, for large angles of obliquity an incident photon in its scattered path may travel a thickness of less than $S/\cos\theta$ before emerging from the barrier. This effect may necessitate a thickness of barrier greater than S. For most practical situations the effect is small and can be treated as a small increase in the approximate thickness, S (see Reference 13 for more details). If the attenuation required is 1000 and the angle of obliquity is 50 degrees, the increase for concrete barriers is about 2 *HVL* for low energy photons and about 1 *HVL* for high energy photons. For angles of 60 and 70 degrees, each of the above thicknesses should be increased by one and two *HVL* respectively. For lead barriers and a required attenuation of 1000, the

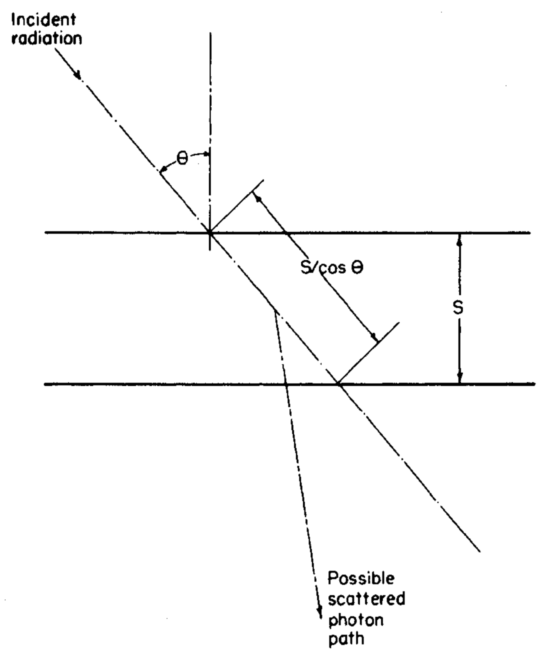

Fig. B-2 Relation between the path length, S/cos θ, of radiation incident on a barrier with an angle of obliquity, θ, and the thickness of the barrier, S.

$$B_{Lx}\ (\text{or } B_{Lg}) = \frac{1000\ P(d_{sec})^2}{WT} \qquad \left[\begin{array}{l}\text{For therapy equipment above}\\ \text{0.5 MV without target}\\ \text{current meter}\end{array}\right] \tag{5d}$$

For x-ray therapy equipment with a target current meter and operating at 500 kV and above, the workload may be expressed as milliampere minutes in a week. Since $\dot{X}_u = \dot{X}_n I$, from equation 5a

$$X_L = \frac{0.001\ \dot{X}_n It}{(d_{sec})^2} \tag{5e}$$

Since $It = W$ (in milliampere minutes per week) and U is equal to unity for leakage radiation, then

$$X_L = \frac{0.001\ \dot{X}_n WT}{(d_{sec})^2} \tag{5f}$$

A barrier having a transmission factor B_{Lx} is required to reduce the weekly exposure to P. Thus

$$P = B_{Lx}X_L = B_{Lx}\frac{0.001\ \dot{X}_n WT}{(d_{sec})^2} \tag{5g}$$

Rearranging and solving for the transmission factor

$$B_{Lx} = \frac{1000\ P(d_{sec})^2}{\dot{X}_n WT} \qquad \left[\begin{array}{l}\text{For therapy equipment above}\\ \text{0.5 MV with a target}\\ \text{current meter}\end{array}\right] \tag{5h}$$

For therapeutic-type protective tube housings of equipment operating below 500 kV, the leakage, L, is limited to 1 roentgen in an hour at 1 m from the source when the tube is operating at the maximum rated continuous tube current, I. The equivalent of equation 5a is therefore

$$X_L = \frac{1}{(d_{sec})^2}\frac{t}{60} \tag{5i}$$

Since $W = It$,

$$X_L = \frac{1}{(d_{sec})^2}\frac{W}{60I} \tag{5j}$$

and it follows that

$$\frac{P}{T} = (B_{Lx})(X_{Lx}) = \frac{(B_{Lx})}{(d_{sec})^2}\frac{W}{60I} \tag{5k}$$

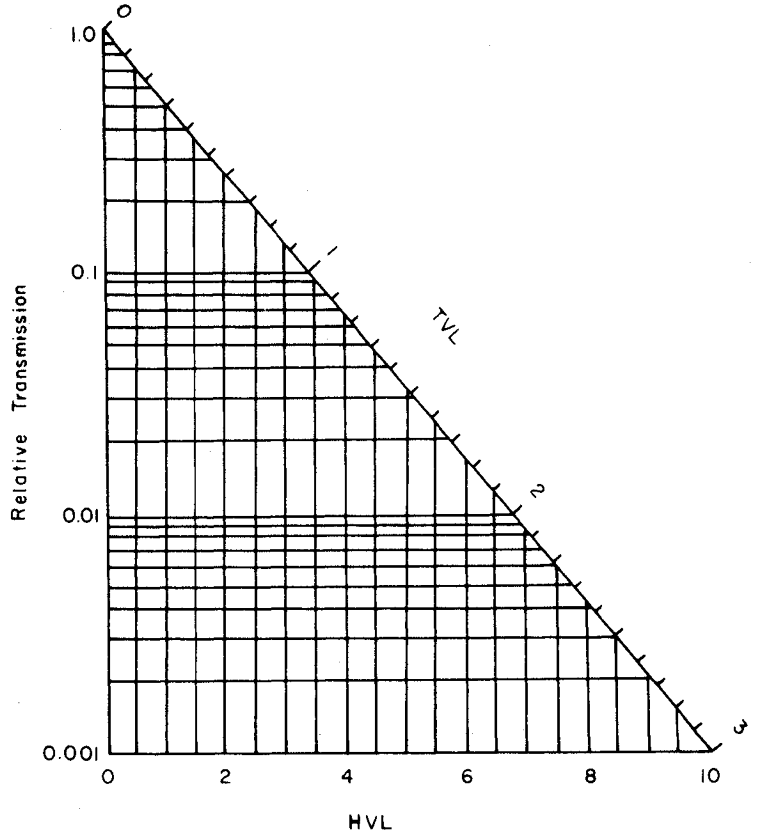

Fig. B-3. Relation between the transmission, B_{Lx} or B_{Lg}, and the number of half-value layers, N, or tenth-value layers, n.

crete. Substituting in Equation (5n), the required barrier thickness *for leakage radiation* is:

$$S_L = (5.2)\ (0.88) = 4.57 \text{ mm lead}$$
$$S_L = (5.2)\ (2.8) = 14.4 \text{ cm concrete}$$

Refer to B.2.2 for an example of the thickness of scattered radiation protective barrier and B.2.3 for an example of the total secondary protective barrier.

B.2.2 *Barrier Against Scattered Radiation*

Radiation scattered from an irradiated object has a much lower exposure rate, $\dot{X}_s$, than that of the incident radiation, $\dot{X}_u$, and usually

TABLE B-2—*Ratio, a, of scattered to incident exposure*[a]

Source	Scattering Angle (from Central Ray)					
	30	45	60	90	120	135
X Rays						
50 kV[b]	0.0005	0.0002	0.00025	0.00035	0.0008	0.0010
70 kV[b]	0.00065	0.00035	0.00035	0.0005	0.0010	0.0013
100 kV[b]	0.0015	0.0012	0.0012	0.0013	0.0020	0.0022
125 kV[b]	0.0018	0.0015	0.0015	0.0015	0.0023	0.0025
150 kV[b]	0.0020	0.0016	0.0016	0.0016	0.0024	0.0026
200 kV[b]	0.0024	0.0020	0.0019	0.0019	0.0027	0.0028
250 kV[b]	0.0025	0.0021	0.0019	0.0019	0.0027	0.0028
300 kV[b]	0.0026	0.0022	0.0020	0.0019	0.0026	0.0028
4 MV[c]	–	0.0027	–	–	–	–
6 MV[d]	0.007	0.0018	0.0011	0.0006	–	0.0004
Gamma Rays						
^{137}Cs[e]	0.0065	0.0050	0.0041	0.0028	–	0.0019
^{60}Co[f]	0.0060	0.0036	0.0023	0.0009	–	0.0006

[a] Scattered radiation measured at one meter from phantom when field area is 400 cm^2 at the phantom surface; incident exposure measured at center of field one meter from the source but without phantom.

[b] From Trout and Kelley (Radiology 104, 161 (1972)). Average scatter for beam centered and beam at edge of typical patient cross-section phantom. Peak pulsating x-ray tube potential.

[c] From Greene and Massey (Brit. J. Radiology 34, 389 (1961)), cylindrical phantom.

[d] From Karzmark and Capone (Brit. J. Radiology 41, 222 (1968)), cylindrical phantom.

[e] Interpolated from Frantz and Wyckoff (Radiology 73, 263 (1959)), these data were obtained from a slab placed obliquely to the central ray. A cylindrical phantom should give smaller values.

[f] From Mooney and Braestrup (AEC Report NYO 2165 (1967)), modified for F = 400 $cm.^2$

one that corresponds to the value of K_{ux} on the pertinent attenuation curve.

Example:

Determine the thickness of scattered radiation protective barrier necessary to protect a controlled area 2.1 meters (7 feet) from the scatterer (patient) using a 250 kV x-ray therapy machine having a weekly workload of 20,000 mA min. The wall in question adjoins an area with an occupancy factor of unity and the treatment distance is 50 cm (0.5 m)

$$P = 0.1 \text{ R}$$
$$d_{sec} = 2.1 \text{ m}$$
$$d_{sca} = 0.5 \text{ m}$$
$$a = 0.0019$$
$$W = 20{,}000 \text{ mA min}$$

Table B-2. The required concrete or lead thicknesses can then be determined from the attenuation curves shown in Figures 14, 15, 16, 17 (Appendix D).

B.2.3 *Barrier Against Stray Radiation*

If the required barrier thickness for leakage and scattered radiations are found to be approximately the same, one *HVL* should be added to the larger one to obtain the required total secondary barrier thickness. If the two differ by at least one *TVL*, the thicker of the two will be adequate.

Example:

Examples of the computation of leakage and scattered radiation protective barriers were given in B.2.1 and B.2.2 for a 250 kV x-ray therapy machine.

TABLE B-3—*Assumptions used in calculating secondary barrier requirements, Appendix C, Tables 5-24*

Installations	I[a]	a[b]	d_{sca}[c]	F[d]
100kV[e] diagnostic fluoroscopic	5	0.0013	0.45	400
125kV[e] diagnostic fluoroscopic	4	0.0015	0.45	400
150kV[e] diagnostic fluoroscopic	3.3	0.0016	0.45	400
100kV[e] diagnostic radiographic	5	0.0013	0.8	1000[f]
125kV[e] diagnostic radiographic	4	0.0015	0.8	1000[f]
150kV[e] diagnostic radiographic	3.3	0.0016	0.8	1000[f]
50kV[e] x-ray therapy	10	0.00035	0.25	400
100kV[e] x-ray therapy	5	0.0013	0.25	400
150kV[e] x-ray therapy	5	0.0016	0.5	400
200kV[e] x-ray therapy	20	0.0019	0.5	400
250kV[e] x-ray therapy	20	0.0019	0.5	400
300kV[e] x-ray therapy	20	0.0019	0.5	400
1000kV[e] x-ray therapy	—[g]	0.001	1	400
2000kV[e] x-ray therapy	—[g]	0.001	1	400
3000kV[e] x-ray therapy	—[g]	0.001	1	400
4000kV[e] x-ray therapy	—[g]	—	—	—
6000kV[e] x-ray therapy	—[g]	0.006	1	400
8000kV[e] x-ray therapy	—[g]	—	—	—
10000kV[e] x-ray therapy	—[g]	—	—	—
^{137}Cs teletherapy	—[g]	0.0028	0.5	400
^{60}Co teletherapy	—[g]	0.0009	0.5	400

[a] I is the maximum rated continuous tube current in milliamperes at the tube potential listed.

[b] a is the ratio of scattered to incident exposure at 1 meter (see Table B-2).

[c] d_{sca} is the distance in meters from the radiation source to the scatterer.

[d] F is the field area at the scatterer in cm^2.

[e] Peak pulsating x-ray tube potential.

[f] Based on 36 × 43 cm (14 × 17 inch) field at 1 meter.

[g] Source housing leakage 0.1 percent of useful beam exposure rate.

APPENDIX C

Tables

TABLE 1—*Maximum permissible dose equivalent recommendations* (MPD)[a]
[The indicated values are for the limited scope of this report. See NCRP Report No. 39 [2] for more complete information.]

	Weekly Dose[b]	Maximum Calendar Quarter Dose	Maximum Yearly Dose	Maximum Accumulated Dose[c]
	rem[d]	*rem*[d]	*rem*[d]	*rem*[d]
Controlled Areas				
Whole body, gonads, red bone marrow, lens of eye	0.1	3	5	5 (*N*-18)[e]
Skin of whole body	–	–	15	–
Hands	–	25	75	–
Forearms	–	10	30	–
Non-controlled Areas	0.01	–	0.5	–

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

[b] For design purposes only.

[c] Long-term accumulation of combined retrospective and prospective whole-body dose equivalent.

[d] The numerical value of the dose equivalent in rem may be assumed to be equal to the numerical value of the exposure in roentgens for the purposes of this report.

[e] N = age in years and is greater than 18.

Table 4—*Occupancy factors for non-occupationally*[a] *exposed persons*[b]

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

Full Occupancy (T = 1)
Work areas such as offices, laboratories, shops, wards, nurses' stations; living quarters; children's play areas; and occupied space in nearby buildings.
Partial Occupancy (T = $^1/_4$)
Corridors, rest rooms, elevators using operators, unattended parking lots.
Occasional Occupancy (T = $^1/_{16}$)[c]
Waiting rooms, toilets, stairways, unattended elevators, janitors' closets, outside areas used only for pedestrians or vehicular traffic.

[a] The occupancy factor of occupationally exposed persons, in general, may be assumed to be one (see text, Section 2, for discussion).

[b] It is advantageous in shielding design to take into account that the occupancy factor in areas adjacent to the radiation room usually is zero for any space more than 2.1 m (7 feet) above the floor as the height of most individuals is less. It is possible, therefore, to reduce the thickness of the wall shielding above this height provided the radiation source is below 2.1 m (7 feet). In determining the shielding requirements for wall areas above 2.1 m (7 feet), consideration must be given to the protection of any persons occupying the floor above the areas adjacent to the radiation room. The wall areas over 2.1 m (7 feet) from the floor of the radiation room must also have sufficient shielding to adequately reduce the scattering from the ceiling of adjacent rooms toward occupants.

[c] It should be noted that the use of an occupancy factor of $^1/_{16}$ may result in full-time exposures in non-controlled areas greater than 2 mR in any one hour or 100 mR in any seven consecutive days.

TABLE 6—*Shielding requirements for radiographic film*

[Indicated thickness required to reduce radiation to 0.2 mR for a weekly workload of 1000 mA min at 100 kV, 400 mA min at 125 kV, or 200 mA min at 150 kV.[a]]

Storage Period	Barrier Type	Distance from Source to Stored Film							
		2.1 m (7 feet)		3.0 m (10 feet)		4.2 m (14 feet)		6.1 m (20 feet)	
		Lead	Concrete[b]	Lead	Concrete[b]	Lead	Concrete[b]	Lead	Concrete[b]
		mm[c]	cm	mm[c]	cm	mm[c]	cm	mm[c]	cm
1 day	Primary with use factor, U,	2.3	19.5	2.1	18	1.8	15.5	1.5	13.5
1 week	of 1/16	3.0	24	2.7	22	2.4	20.5	2.2	18.5
1 month		3.7	29	3.4	27	3.1	24	2.8	23
1 day	Secondary with use factor, U,	1.7	15	1.5	13	1.2	11	1.0	9
1 week	of 1	2.4	19.5	2.1	17.5	1.8	16	1.5	13.5
1 month		3.0	24	2.8	22	2.5	20	2.2	18.5

Note: In the absence of specific information as to the length of film storage period to be expected, it is suggested that the shielding value for the 1 month's storage period be used.

[a] Peak pulsating x-ray tube potential.

[b] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).

[c] See Table 26 for conversion of thickness in millimeters to inches or to surface density.

TABLE 8—*Minimum shielding requirements for 50 kV*[a] *therapy installations*

WUT[b] in mA min		Distance in meters from source to occupied area											
4,000		1.5	2.1	3.0	4.2	6.1	8.4	12.2					
2,000			1.5	2.1	3.0	4.2	6.1	8.4	12.2				
1,000				1.5	2.1	3.0	4.2	6.1	8.4	12.2			
500					1.5	2.1	3.0	4.2	6.1	8.4	12.2		
250						1.5	2.1	3.0	4.2	6.1	8.4	12.2	
125							1.5	2.1	3.0	4.2	6.1	8.4	12.2
62.5								1.5	2.1	3.0	4.2	6.1	8.4
31.3									1.5	2.1	3.0	4.2	6.1
Type of Area	Material	Primary protective barrier thickness[c]											
Controlled	Lead, mm[d]	0.4	0.35	0.3	0.25	0.2	0.2	0.15	0.1	0.1	0.05	0.05	0.05
Noncontrolled	Lead, mm[d]	0.55	0.5	0.45	0.4	0.35	0.3	0.3	0.25	0.2	0.15	0.1	0.1
Controlled	Concrete, cm[e]	4	3.5	3	2.5	2	2	1.5	1	1	0.5	0.5	0.5
Noncontrolled	Concrete, cm[e]	5.5	5	4.5	4	3.5	3	2.5	2.5	2	1.5	1.5	1
		Secondary protective barrier thickness[c]											
Controlled	Lead, mm[d]	0.3	0.25	0.2	0.15	0.1	0.05	0.05	0.05	0	0	0	0
Noncontrolled	Lead, mm[d]	0.4	0.35	0.3	0.25	0.25	0.2	0.15	0.1	0.1	0.05	0.05	0.05
Controlled	Concrete, cm[e]	2.5	2	1.5	1.5	1	0.5	0.5	0.5	0	0	0	0
Noncontrolled	Concrete, cm[e]	3.5	3.5	3	3	2.5	2	1.5	1	0.5	0.5	0.5	0.5

[a] Peak pulsating x-ray tube potential.

[b] *W*—weekly workload in mA min, U— use factor, T—occupancy factor.

[c] Constant potential requires about 20 percent larger thicknesses of lead and about 10 percent larger thicknesses of concrete than those given here for pulsating potential.

[d] See Table 26 for conversion of thickness in millimeters to inches or to surface density.

[e] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).

TABLE 10—*Minimum shielding requirements for 150 kV[a] therapy installations*

WUT[b] in mA min		Distance in meters from source to occupied area											
4,000		1.5	2.1	3.0	4.2	6.1	8.4	12.2					
2,000			1.5	2.1	3.0	4.2	6.1	8.4	12.2				
1,000				1.5	2.1	3.0	4.2	6.1	8.4	12.2			
500					1.5	2.1	3.0	4.2	6.2	8.4	12.2		
250						1.5	2.1	3.0	4.2	6.1	8.4	12.2	
125							1.5	2.1	3.0	4.2	6.1	8.4	12.2
62.5								1.5	2.1	3.0	4.2	6.1	8.4
31.3									1.5	2.1	3.0	4.2	6.1
Type of Area	**Material**	**Primary protective barrier thickness[c]**											
Controlled	Lead, mm[d]	3.15	2.85	2.55	2.3	2.0	1.7	1.45	1.2	0.95	0.7	0.5	0.35
Noncontrolled	Lead, mm[d]	4.2	3.85	3.55	3.25	2.95	2.65	2.4	2.1	1.8	1.55	1.3	1.0
Controlled	Concrete, cm[e]	27	25	22.5	20.5	18.5	16	14	11.5	9.5	7.5	5.5	4
Noncontrolled	Concrete, cm[e]	35	32.5	30	27.5	25.5	23.5	21	19	17	14.5	12.5	10.5
		Secondary protective barrier thickness[c]											
Controlled	Lead, mm[d]	2.05	1.75	1.45	1.15	0.85	0.55	0.35	0.3	0	0	0	0
Noncontrolled	Lead, mm[d]	3.05	2.75	2.45	2.15	1.85	1.55	1.25	0.95	0.65	0.35	0.3	0
Controlled	Concrete, cm[e]	15	13	11	8.5	6.5	4	2.5	2	0	0	0	0
Noncontrolled	Concrete, cm[e]	22.5	20.5	18.5	16	13.5	11.5	9.5	7	5	2.5	2	0

[a] Peak pulsating x-ray tube potential.

[b] W—weekly workload in mA min, U—use factor, T—occupancy factor.

[c] Constant potential requires about 20 percent larger thicknesses of lead and about 10 percent larger thicknesses of concrete than those given here for pulsating potential.

[d] See Table 26 for conversion of thickness in millimeters to inches or to surface density.

[e] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).

TABLE 12—*Minimum shielding requirements for 250 kV*[a] *therapy installations*

WUT[b] in mA min		Distance in meters from source to occupied area											
40,000		1.5	2.1	3.0	4.2	6.1	8.4	12.2					
20,000			1.5	2.1	3.0	4.2	6.1	8.4	12.2				
10,000				1.5	2.1	3.0	4.2	6.1	8.4	12.2			
5,000					1.5	2.1	3.0	4.2	6.1	8.4	12.2		
2,500						1.5	2.1	3.0	4.2	6.1	8.4	12.2	
1,250							1.5	2.1	3.0	4.2	6.1	8.4	12.2
625								1.5	2.1	3.0	4.2	6.1	8.4
Type of Area	Material	Primary protective barrier thickness[c]											
Controlled	Lead, mm[d]	11.45	10.6	9.65	8.8	7.9	7.05	6.2	5.4	4.6	3.9	3.2	2.5
Noncontrolled	Lead, mm[d]	14.55	13.2	12.15	11.8	10.85	9.95	9.05	8.2	7.35	6.5	5.65	4.9
Controlled	Concrete, cm[e]	49	45.5	42.5	40	37	34.5	31.5	29	26	23.5	20.5	18
Noncontrolled	Concrete, cm[e]	58	55.5	52.5	49.5	46.5	43.5	41	38	35	32.5	29.5	27
		Secondary protective barrier thickness[c]											
Controlled	Lead, mm[d]	7.2	6.3	5.4	4.5	3.65	2.8	2.3	1.9	1.55	1.25	1.1	0.05
Noncontrolled	Lead, mm[d]	10.1	9.25	8.35	7.5	6.6	5.7	4.85	3.95	3.1	2.5	2.05	1.65
Controlled	Concrete, cm[e]	31.5	28.5	26.5	23.5	20.5	18	15	12.5	9.5	7.5	4.5	0.5
Noncontrolled	Concrete, cm[e]	41	38	36	33	30	27	24	22	19	16	12.5	10

[a] Peak pulsating x-ray tube potential.

[b] *W*—weekly workload in mA min, U—use factor, T—occupancy factor.

[c] Constant potential requires about 20 percent larger thicknesses of lead and about 10 percent larger thicknesses of concrete than those are given here for pulsating potential.

[d] See Table 26 for conversion of thickness in millimeters to inches or to surface density.

[e] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).

TABLE 14—*Minimum shielding requirements for 1 MV therapy installations*

WUT[a] in mA min		Distance in meters from source to occupied area											
5,000		1.5	2.1	3.0	4.2	6.1	8.4	12.2					
2,500			1.5	2.1	3.0	4.2	6.1	8.4	12.2				
1,250				1.5	2.1	3.0	4.2	6.1	8.4	12.2			
625					1.5	2.1	3.0	4.2	6.1	8.4	12.2		
313						1.5	2.1	3.0	4.2	6.1	8.4	12.2	
156							1.5	2.1	3.0	4.2	6.1	8.4	12.2
78								1.5	2.1	3.0	4.2	6.1	8.4
Type of Area	**Material**	Primary protective barrier thickness											
Controlled	Lead, cm[b]	11	10.5	10	9	9	7	6.5	6	5	4	3.5	3
Noncontrolled	Lead, cm[b]	14	13	12.5	11.5	11	10	9	8.5	7.5	7	6	5
Controlled	Concrete, cm[c]	70	66	62	57	53	48	43	39	35	30	26	21
Noncontrolled	Concrete, cm[c]	85	81	77	72	68	63	59	54	50	45	40	36
		Secondary protective barrier thickness[d]											
Controlled	Lead, cm[b]	6	5.5	5.5	4.5	4	3	2.5	2	1.5	1	0.5	0
Noncontrolled	Lead, cm[b]	9	8	7	6.5	5.5	5	4.5	4	3.5	2.5	2	1.5
Controlled	Concrete, cm[c]	46	42	37	33	28.5	24	19	15	10.5	6	1.5	0
Noncontrolled	Concrete, cm[c]	61	57	52	48	43	39	35	30	25	20.5	16.5	12

[a] *W*—weekly workload in mA min, U—use factor, T—occupancy factor.
[b] See Table 26 for conversion of thickness in millimeters to inches or to surface density.
[c] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).
[d] Shielding for tube housing leakage based on a weekly workload (*WUT*) of 5,000 mA min corresponding to a weekly workload (*WUT*) of 100,000 R at 1 meter ($\dot{X}_n$ = 20 R per mA min at 1 meter).

TABLE 16—*Minimum shielding requirements for 3 MV therapy installations*

WUT[a] in mA min		Distance in meters from source to occupied area											
150		1.5	2.1	3.0	4.2	6.1	8.4	12.2					
75			1.5	2.1	3.0	4.2	6.1	8.4	12.2				
37.5				1.5	2.1	3.0	4.2	6.1	8.4	12.2			
18.75					1.5	2.1	3.0	4.2	6.1	8.4	12.2		
9.5						1.5	2.1	3.0	4.2	6.1	8.4	12.2	
4.75							1.5	2.1	3.0	4.2	6.1	8.4	12.2
2.35								1.5	2.1	3.0	4.2	6.1	8.4
Type of Area	**Material**	**Primary protective barrier thickness**											
Controlled	Lead, cm[b]	30	28	26.5	25	23.5	22	20.5	19	17.5	16	14.5	13
Noncontrolled	Lead, cm[b]	35	33	31.5	30	28.5	27	25	24	22.5	21	19.5	18
Controlled	Concrete, cm[c]	150	146	138	131	124	116	109	101	94	86	79	71
Noncontrolled	Concrete, cm[c]	180	171	169	156	150	141	134	126	118	111	103	96
		Secondary protective barrier thickness[d]											
Controlled	Lead, cm[b]	13	11.5	10	8.5	7	7	5.5	4	2.5	1	0	0
Noncontrolled	Lead, cm[b]	17.5	16.5	15	13.5	12	12	10.5	9	7.5	6	4.5	3
Controlled	Concrete, cm[c]	69	62	54	54	46	38.5	31.5	23.5	15	8	0	0
Noncontrolled	Concrete, cm[c]	93	86	78	78	70	62.5	55.5	48	39.5	32	24.5	17

[a] W—weekly workload in mA min, U—use factor, T—occupancy factor.

[b] See Table 26 for conversion of thickness in millimeters to inches or to surface density.

[c] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).

[d] Shielding for tube housing leakage based on a weekly workload (WUT) of 150 mA min corresponding to a weekly workload (WUT) of 100,000 R at 1 meter ($\dot{X}_n$ = 700 R per mA min at 1 meter).

TABLE 18—*Minimum shielding requirements for 6 MV therapy installations for controlled areas*[a]

WUT[b] in R at 1 meter			Distance in meters from source to occupied area										
160,000			1.5	2.1	3.0	4.2	6.1	8.4	12.2	17			
80,000				1.5	2.1	3.0	4.2	6.1	8.4	12.2	17		
40,000					1.5	2.1	3.0	4.2	6.1	8.4	12.2	17	
20,000						1.5	2.1	3.0	4.2	6.1	8.4	12.2	
10,000							1.5	2.1	3.0	4.2	6.1	8.4	
5,000								1.5	2.1	3.0	4.2	6.1	
2,500									1.5	2.1	3.0	4.2	
Type of Protective Barrier	Material	*TVL* cm	Thickness of barrier in cm										
Primary	Concrete[c]	34.5	202	192	182	172	161	151	141	131	119	109	
Primary	Lead	5.6	33	31	29.5	27.5	26	24.5	22.5	21	19	17.5	
Primary	Iron[e]	9.9	58	55	52	49	46	43	40	37	34	31	
Leakage[d] 0.1 percent	Concrete[c]	34.5	98.5	88	77.5	67.5	57	46.5	36	25.5	15.5	5	
Leakage[d] 0.1 percent	Lead	5.6	16	14.5	12.5	11	9	7.5	6	4	2.5	1	
Leakage[d] 0.1 percent	Iron[e]	9.9	28.5	25.5	22.5	19.5	16.5	13.5	10.5	7.5	4.5	1.5	
Scatter[f]	Concrete[c]												
30°		26.7	98	89.5	82	74	66	58	50	42	34	26	
45°		23.4	72	65	58	51	44	37	30	23	16	8.5	
60°		20.3	58	52	46	40	34	28	21.5	15	9	3	
90°		17.8	46.5	41	36	30.5	25	20	14.5	9	4	0	
135°		14.5	36	31.5	27	22.5	18.5	13.5	9	5	0	0	

[a] For a weekly design level of 100 mR; add one tenth-value layer *(TVL)* for noncontrolled areas, to reduce to 10 mR.
[b] *W*—weekly workload in R at 1 m, U—use factor, T—occupancy factor.
[c] Thickness for primary and leakage protective barriers based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).
[d] Shielding for leakage radiation from tube housing.
[e] Thickness based on iron density of 7.8 g cm^{-3} (488 lb ft^{-3}).
[f] Scatter protective barrier thickness based on Karzmark and Capone [23].

TABLE 20—*Minimum shielding requirements for 10 MV therapy installations for controlled areas*[a]

WUT[b] in R at 1 meter		Distance in meters from source to occupied area									
160,000		1.5	2.1	3.0	4.2	6.1	8.4	12.2	17		
80,000			1.5	2.1	3.0	4.2	6.1	8.4	12.2	17	
40,000				1.5	2.1	3.0	4.2	6.1	8.4	12.2	17
20,000					1.5	2.1	3.0	4.2	6.1	8.4	12.2
10,000						1.5	2.1	3.0	4.2	6.1	8.4
5,000							1.5	2.1	3.0	4.2	6.1
2,500								1.5	2.1	3.0	4.2
Type of Protective Barrier	**Material**	**Thickness of barrier in cm**									
Primary	Concrete[c]	234	222	210	198	186	174	162	150	138	126
Primary	Lead	32.5	30.5	29	27.5	25.5	24	22.5	20.5	19	17.5
Primary	Iron[e]	61.5	58.5	55.5	52	49	46	42.5	39.5	36	33
Leakage[d] 0.1 percent	Concrete[c]	114	102	90	77.5	66	53.5	42	29.5	17.5	6
Leakage[d] 0.1 percent	Lead	15.5	14	12.5	11	9.5	7.5	6	4	2.5	1
Leakage[d] 0.1 percent	Iron[e]	30	26.5	23.5	20.5	17.5	14	11	7.5	4.5	1.5

[a] For a weekly design level of 100 mR; add one tenth-value layer *(TVL)* for noncontrolled areas to reduce to 10 mR (see Table 27).

[b] *W*—weekly workload in R at 1 m, U—use factor, T—occupancy factor.

[c] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).

[d] Shielding for leakage radiation from tube housing.

[e] Thickness based on iron density of 7.8 g cm^{-3} (488 lb ft^{-3}).

TABLE 22—*Minimum concrete shielding requirements for cobalt-60 therapy installations for controlled areas*[a]

WUT[b] in R at 1 meter	Distance in meters from source to occupied area										
120,000	1.5	2.1	3.0	4.2	6.1	8.4	12.2				
60,000		1.5	2.1	3.0	4.2	6.1	8.4	12.2			
30,000			1.5	2.1	3.0	4.2	6.1	8.4	12.2		
15,000				1.5	2.1	3.0	4.2	6.1	8.4	12.2	
7,500					1.5	2.1	3.0	4.2	6.1	8.4	12.2
3,750						1.5	2.1	3.0	4.2	6.1	8.4
1,875							1.5	2.1	3.0	4.2	6.1
950								1.5	2.1	3.0	4.2
475									1.5	2.1	3.0
240										1.5	2.1
120											1.5

Type of Protective Barrier	Approx. *HVL* cm of Concrete	Approx. *TVL* cm of Concrete	Thickness of concrete in centimeters[c]										
Primary	6.2	20.6	125	119	112	106	99.5	93.5	87	80.5	74	67.5	61
Secondary Leakage[d]													
0.1 percent	6.2	20.6	62	55	48	42.5	36	29.5	23	17	10	1	0
0.05 percent	6.2	20.6	55	48	42.5	36	29.5	23	17	10	1	0	0
Scatter[e]													
30°	6.1	20.3	87	81	74.5	68.5	62	57	49	42.5	36.5	29.5	23.5
45°	6.0	19.8	76.5	70.5	64.5	59	53	47	41	35	29	23.5	17.5
60°	5.8	19.2	70	64.5	58.5	52.5	47	41.5	36.5	31	24.5	18	13
90°	4.6	15.4	49.5	45	40.5	36	31.5	27	22	18	13	8.5	4
120°	4.4	14.5	42.5	38.5	34.5	30.5	26	22	18	13.5	9.5	5.5	2

[a] For a weekly design level of 100 mR; add one tenth-value layer *(TVL)* for noncontrolled areas, to reduce to 10 mR.

[b] *W*—weekly workload in R at 1 m, U—use factor, T—occupancy factor.

[c] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).

[d] Refers to leakage radiation from source housing when source in "ON" condition; may be ignored if less than 2.5 mR per h at 1 m.

[e] For large field (20 cm diameter) and a source to skin distance of 40 to 60 cm. This includes scattering from the collimator and from the phantom.

TABLE 24—*Minimum concrete shielding requirements for cesium-137 therapy installations for controlled areas*[a]

WUT[b] in R at 1 meter			Distance in meters from source to occupied area										
24,000			1.5	2.1	3.0	4.2	6.1	8.4	12.2				
12,000				1.5	2.1	3.0	4.2	6.1	8.4	12.2			
6,000					1.5	2.1	3.0	4.2	6.1	8.4	12.2		
3,000						1.5	2.1	3.0	4.2	6.1	8.4	12.2	
1,500							1.5	2.1	3.0	4.2	6.1	8.4	12.2
750								1.5	2.1	3.0	4.2	6.1	8.4
375									1.5	2.1	3.0	4.2	6.1
	Approx.												
Type of Protective Barrier	*HVL* cm of Concrete	*TVL* cm of Concrete	Thickness of concrete in centimeters[c]										
Primary	4.8	15.7	88	83	77.5	72.5	67	62	56.5	51.5	46.5	41.5	36.5
Secondary Leakage[d]													
0.1 percent	4.8	15.7	36.5	31	26	21	15.5	10.5	5	0	0	0	0
0.05 percent	4.8	15.7	31	26	21	15.5	10.5	5	0	0	0	0	0
Scatter[e]													
30°	4.8	15.7	62	56.5	51	45.5	40.5	35	29.5	24	19	13.5	8.5
45°	4.4	14.6	49	44.5	40.5	36	31.5	27	23	18.5	14	9.5	5.5
60°	4.0	13.3	44	40	36	32	27.5	23.5	19.5	15.5	11	7	3
90°	3.7	12.3	38.5	34.5	30.5	27	23	19.5	16	12	8	4.5	0.5
135°	3.4	11.3	33.5	30	26.5	23	19.5	16	12.5	9	5.5	2.5	0

[a] For a weekly design level of 100 mR; add one tenth-value layer *(TVL)* for noncontrolled areas, to reduce to 10 mR.

[b] *W*—weekly workload in R at 1 m, U—use factor, T—occupancy factor.

[c] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).

[d] Refers to leakage radiation from source housing when source in "ON" condition; may be ignored if less than 2.5 mR per h at 1 m.

[e] For large field (20 cm diam) and a source-scatterer distance of 50 cm. This includes only scattering from an obliquely positioned flat scatterer.

TABLE 26—*Commercial lead sheets*

Thickness		Weight in Pounds for a 1 Square Foot Section	
Inches	Millimeter equivalent	Nominal weight	Actual weight
1/64	0.40	1	0.92
3/128	0.60	1 1/2	1.38
1/32	0.79	2	1.85
5/128	1.00	2 1/2	2.31
3/64	1.19	3	2.76
7/128	1.39	3 1/2	3.22
—	1.50	—	3.48
1/16	1.58	4	3.69
5/64	1.98	5	4.60
3/32	2.38	6	5.53
—	2.5	—	5.80
—	3.0	—	6.98
1/8	3.17	8	7.38
5/32	3.97	10	9.22
3/16	4.76	12	11.06
7/32	5.55	14	12.9
1/4	6.35	16	14.75
1/3	8.47	20	19.66
2/5	10.76	24	23.60
1/2	12.70	30	29.50
2/3	16.93	40	39.33
1	25.40	60	59.00

Notes:

1. The density of commercially rolled lead is 11.36 g cm^{-3}.*

2. The commercial tolerances are ±0.005 inches for lead up to 7/128 and ± 1/32 heavier sheets.*

3. It should be noted that lead sheet less than 1/32 inch thick is frequently more expensive than heavier sheet in cost of material and cost of installation.

* Lead Industries Association, Inc., 292 Madison Avenue, New York.

TABLE 28—*Selected gamma-ray sources*

Radionuclide	Atomic Number	Half Life	Gamma Energy MeV	Half-Value Layer[a] Concrete	Half-Value Layer[a] Steel	Half-Value Layer[a] Lead	Tenth-Value Layer[a] Concrete	Tenth-Value Layer[a] Steel	Tenth-Value Layer[a] Lead	Specific Gamma-Ray Constant[b] R cm² per mCi h
				cm	cm	cm	cm	cm	cm	
Cesium-137	55	27 y	0.66	4.8	1.6	0.65	15.7	5.3	2.1	3.2
Cobalt-60	27	5.24y	1.17, 1.33	6.2	2.1	1.20	20.6	6.9	4.0	13
Gold-198	79	2.7 d	0.41	4.1	—	0.33	13.5	—	1.1	2.32
Iridium-192	77	74 d	0.13 to 1.06	4.3	1.3	0.60	14.7	4.3	2.0	5.0
Radium-226	88	1622 y	0.047 to 2.4	6.9	2.2	1.66	23.4	7.4	5.5	8.25[c]

[a] Approximate values obtained with large attenuation.

[b] These values assume that gamma absorption in the source is negligible. Value in R per millicurie-hour at 1 cm can be converted to R per Ci-h at 1 meter by multiplying the number in this column by 0.10.

[c] This value assumes that the source is sealed within a platinum capsule (0.5 mm wall thickness), with units of R per mg h at 1 cm.

APPENDIX D

Figures[28]

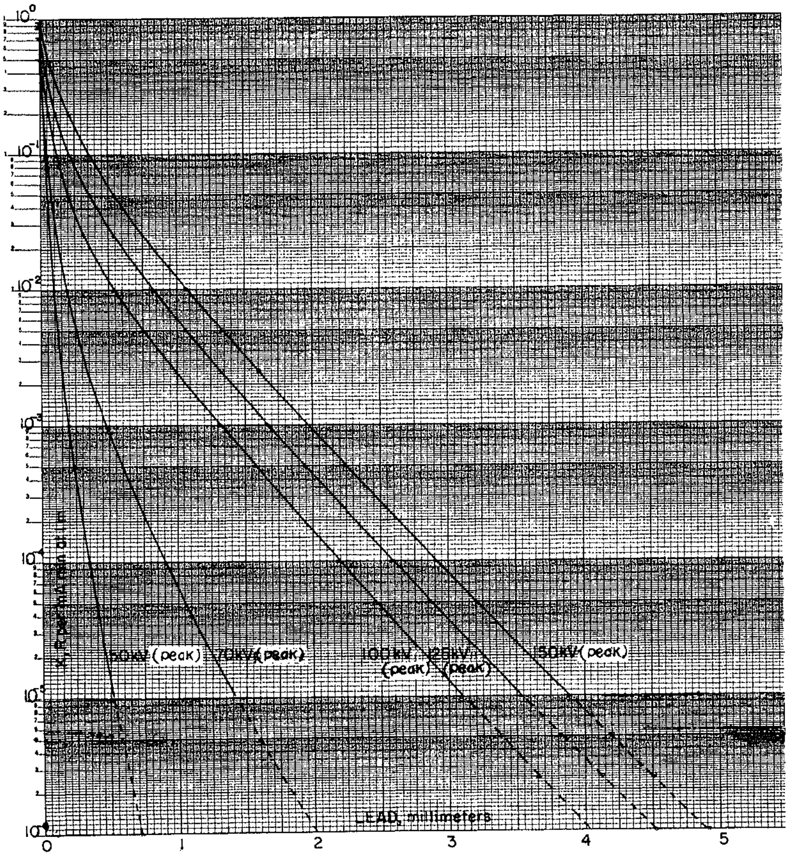

Fig. 1 Attenuation in lead of x rays produced at potentials of 50 to 150 kV peak. The measurements were made with a 90° angle between the electron beam and the axis of the x-ray beam and with pulsed waveform. The filtrations were 0.5 mm of aluminum for 50 kV, 1.5 mm of aluminum for 70 kV, and 2.5 mm of aluminum for 100, 125 and 150 kV (Kelley and Trout [15]).

[Data courtesy of the authors and Radiology.]

[28] Full sized reproductions of the figures are available as an adjunct to this report.

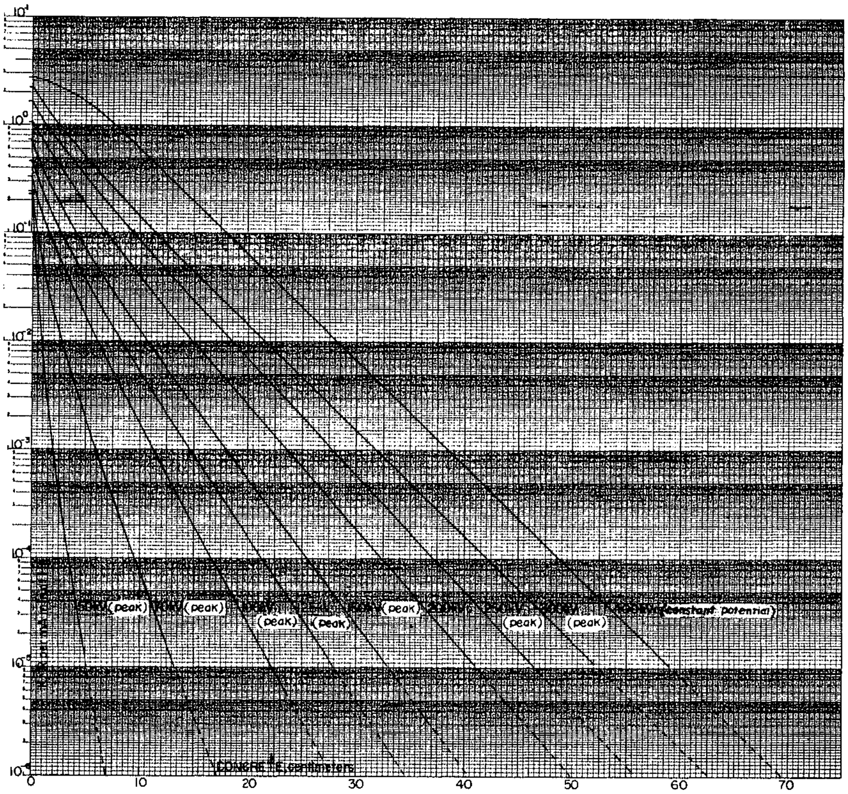

Fig. 3 Attenuation in concrete of x rays produced by potentials of 50 to 300 kV peak; 400 kV constant potential.

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 kV are for a pulsed waveform. The filtrations were 1 mm of aluminum for 50 kV, 1.5 mm of aluminum for 70 kV, 2 mm of aluminum for 100 kV, and 3 mm of aluminum for 125, 150, 200, 250, and 300 kV (Trout *et al.* [17]). The 400 kV curve was interpolated from data obtained with a constant potential generator and inherent filtration of approximately 3 mm of copper (Miller and Kennedy [16]).

[Data courtesy of the authors and Radiology.]

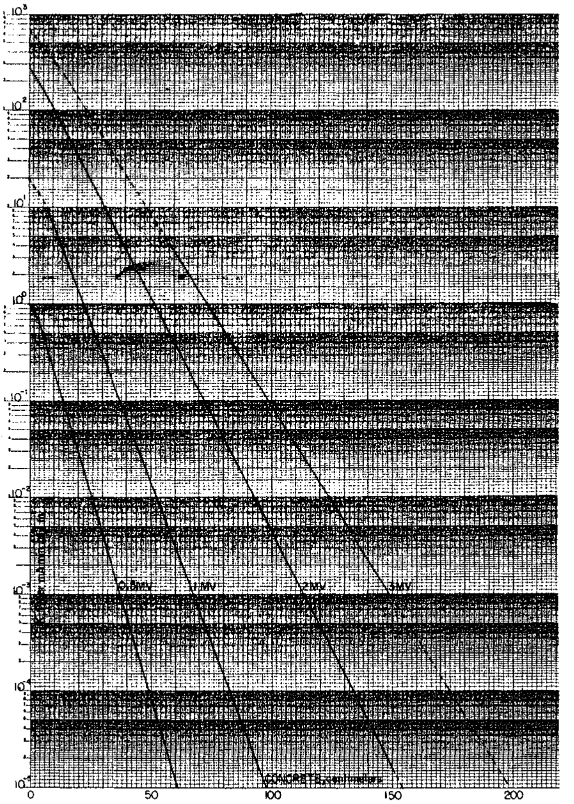

Fig. 5 Attenuation in concrete of x rays produced by potentials of 0.5 to 3 MV constant potential.

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 0.5 and 1 MV 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.* [18]). The 2 MV curve was obtained by extrapolating to broad-beam conditions (E. E. Smith) the data of Evans *et al.* [19]. The inherent filtration was equivalent to 6.8 mm of lead. The 3 MV curve has been obtained by interpolation of the 2 MV curve given herein, and the data of Kirn and Kennedy [21].

[Data courtesy of the authors, Radiology and Nucleonics.]

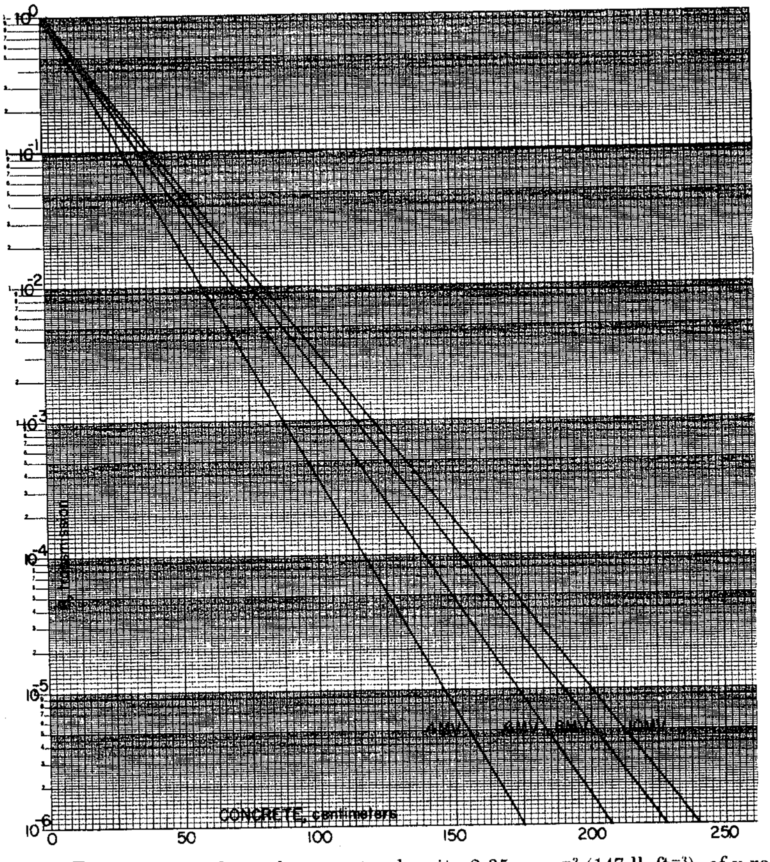

Fig. 7 Transmission through concrete, density 2.35 g cm^{-3} (147 lb ft^{-3}), of x rays produced at 4 to 10 MV. Based on NCRP Report No. 51 [27].

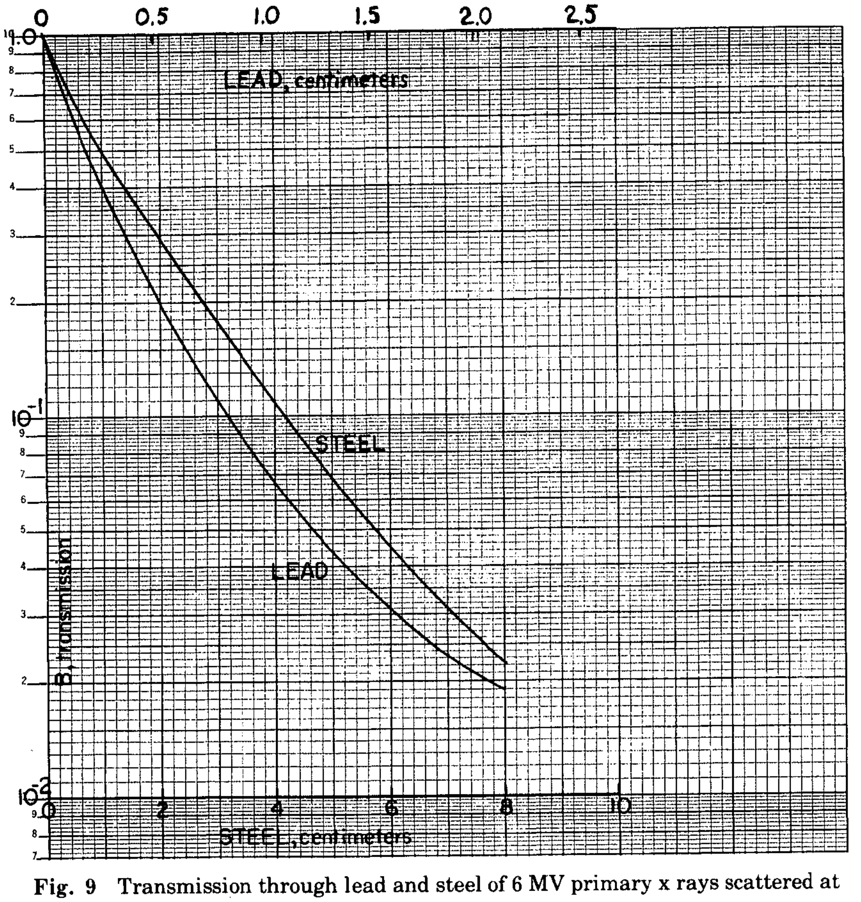

Fig. 9 Transmission through lead and steel of 6 MV primary x rays scattered at 90°.

The measurements were made with 6-MV radiation scattered at 90° from a cylindrical unit density phantom, 27 cm diameter, 30 cm long with its center located 100 cm from the target (Karzmark and Capone [22]).

[Data courtesy of the authors and The British Journal of Radiology.]

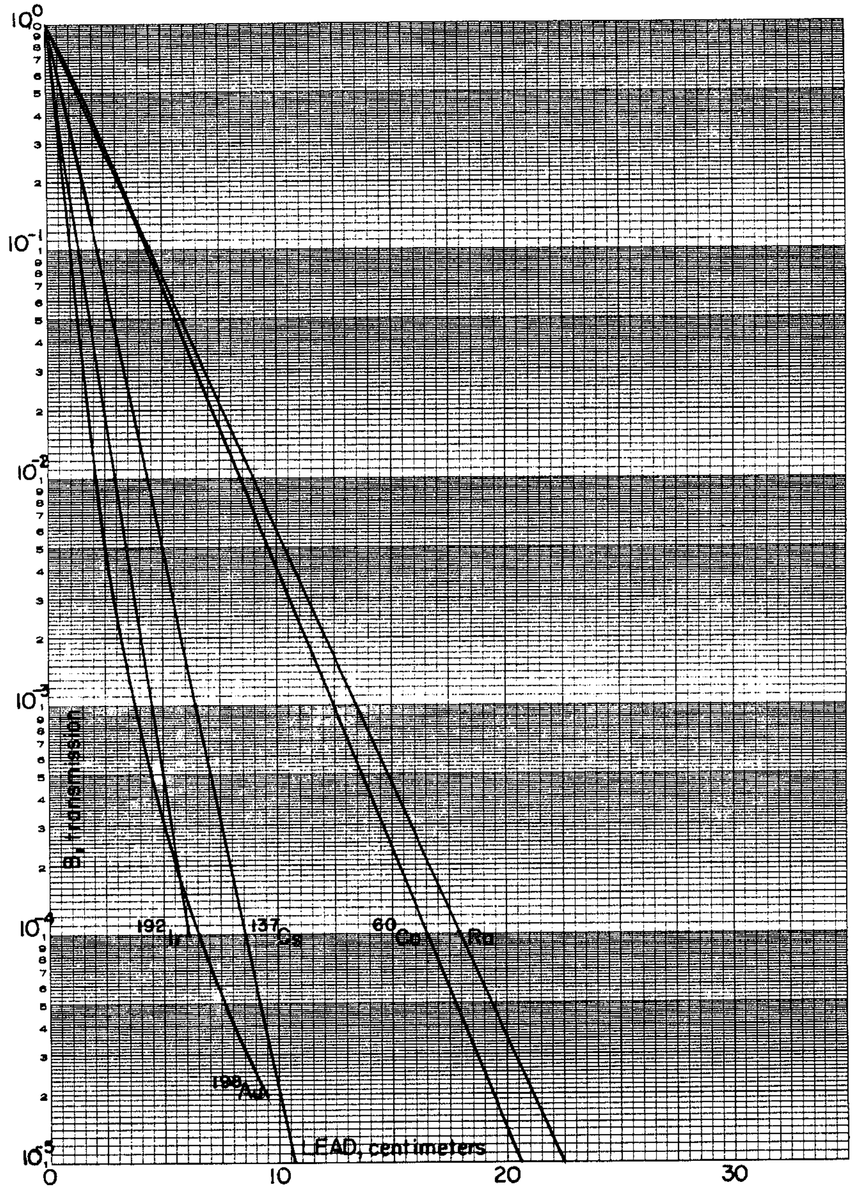

Fig. 11 Transmission through lead of gamma rays from selected radionuclides. Radium (Wyckoff and Kennedy [23]); cobalt-60, cesium-137, gold-198 (Kirn *et al.* [13]); iridium-192 (Ritz [24]).

[Data courtesy of the authors, Radiology, Journal of Research NBS, Non-Destructive Testing (now known as Materials Evaluation) and with permission of The American Society for Nondestructive Testing, Inc.]

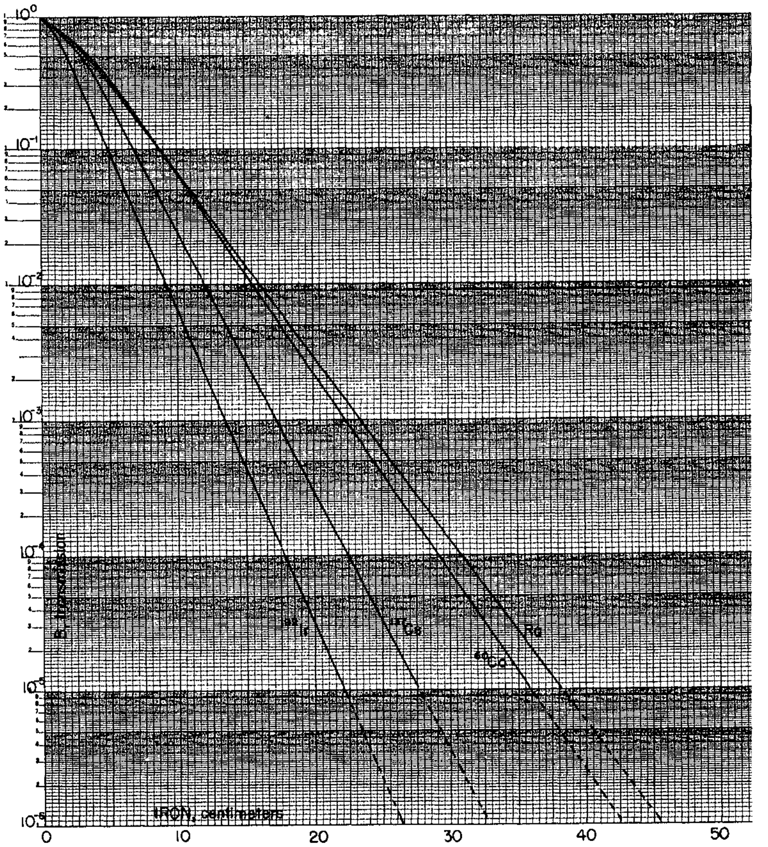

Fig. 13 Transmission through iron of gamma rays from selected radionuclides. Radium (Wyckoff and Kennedy [23]); cobalt-60, cesium-137 (Kirn *et al.* [13]); iridium-192 (Ritz [24]).

[Data courtesy of the authors, Radiology, Journal of Research NBS, Non-Destructive Testing (now known as Materials Evaluation) and with permission of the American Society for Nondestructive Testing, Inc.]

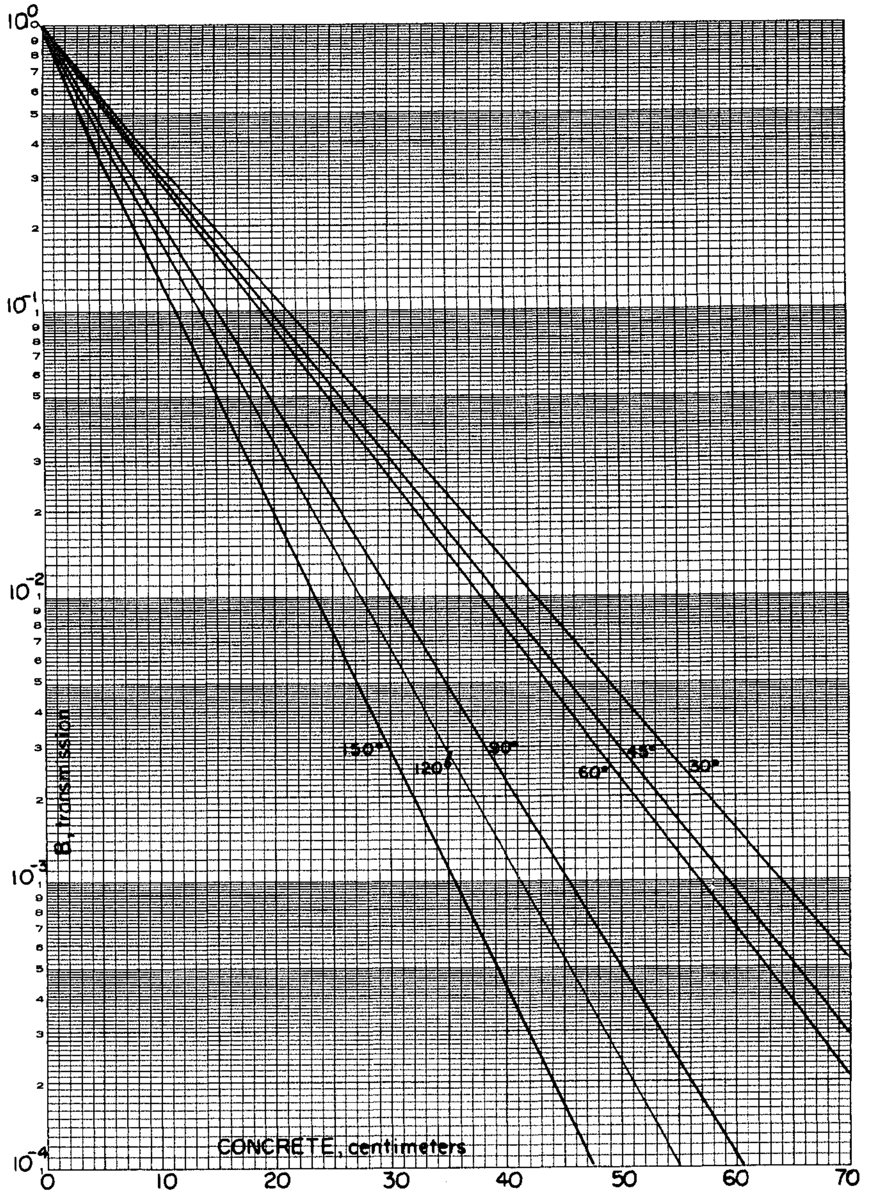

Fig. 15 Transmission through concrete, density 2.35 g cm^{-3} (147 lb ft^{-3}), of cobalt-60 radiation scattered from a cylindrical unit density phantom, 20 cm diameter field, at 1 m from source (Mooney and Braestrup [25]).
[Data courtesy of the authors.]

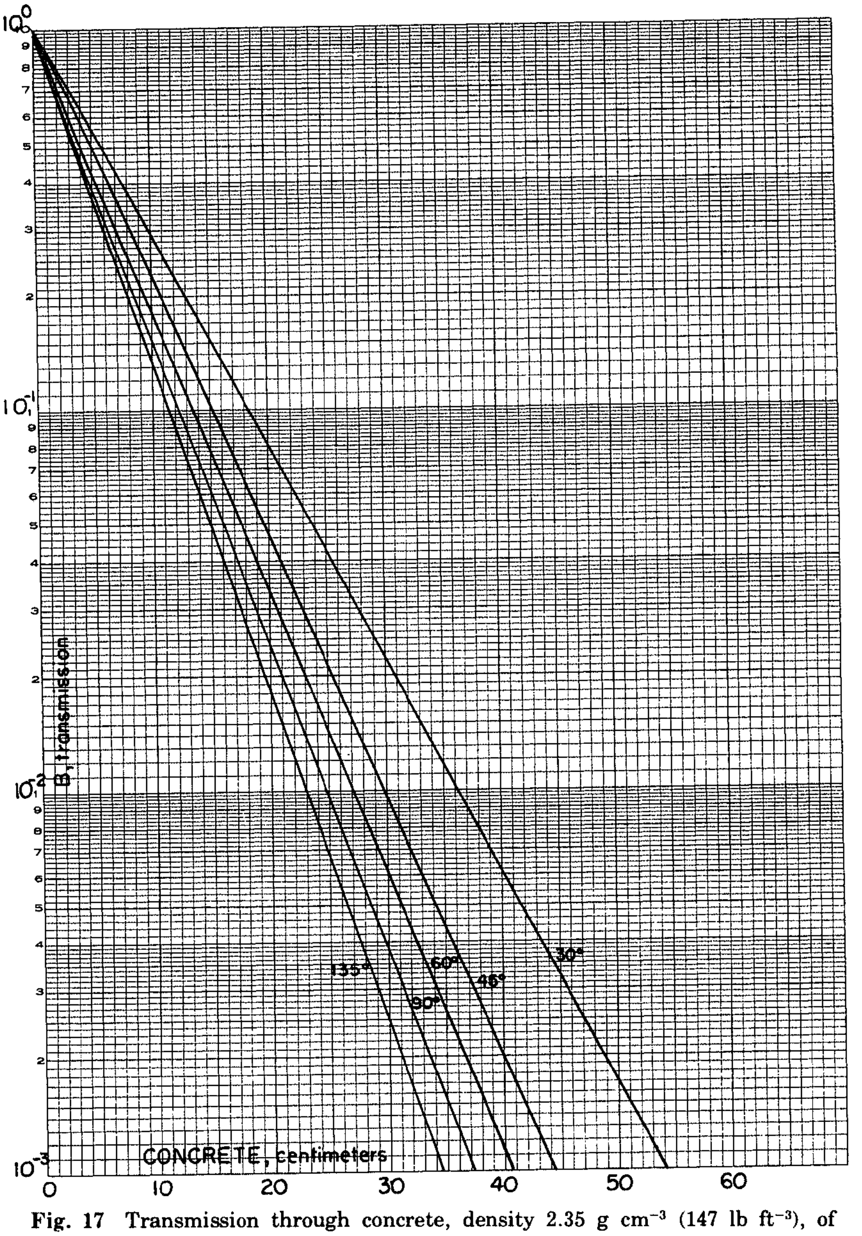

Fig. 17 Transmission through concrete, density 2.35 g cm^{-3} (147 lb ft^{-3}), of cesium-137 scattered radiation (interpolated from Frantz and Wyckoff [26]). [Data courtesy of the authors and Radiology.]

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2. National Council on Radiation Protection and Measurements, *Basic Radiation Protection Criteria,* NCRP Report No. 39 (National Council on Radiation Protection and Measurements, Washington, 1971)
3. C. B. BRAESTRUP AND H. O. WYCKOFF, "Shielding design levels for radiology departments," Radiology 107, 445 (1973)
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7. National Council on Radiation Protection and Measurements, *Dental X-Ray Protection,* NCRP Report No. 35 (National Council on Radiation Protection and Measurements, Washington, 1970)
8. National Council on Radiation Protection and Measurements, *Radiation Protection in Veterinary Medicine,* NCRP Report No. 36 (National Council on Radiation Protection and Measurements, Washington, 1970)
9. National Council on Radiation Protection and Measurements, *Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV—Equipment Design and Use,* NCRP Report No. 33 (National Council on Radiation Protection and Measurements, Washington, 1968)
10. National Council on Radiation Protection and Measurements, *Protection Against Radiation from Brachytherapy Sources,* NCRP Report No. 40 (National Council on Radiation Protection and Measurements, Washington, 1972)
11. National Council on Radiation Protection and Measurements, *Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides,* NCRP Report No. 37 (National Council on Radiation Protection and Measurements, Washington, 1970)
12. International Commission on Radiation Units and Measurements, *Ra-*

[29] Information on the availability of NCRP reports listed is given on page 117.

The NCRP

The National Council on Radiation Protection and Measurements is a nonprofit corporation chartered by Congress in 1964 to:

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2. Provide a means by which organizations concerned with the scientific and related aspects of radiation protection and of radiation quantities, units, and measurements may cooperate for effective utilization of their combined resources, and to stimulate the work of such organizations;
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SC-18: Standards and Measurements of Radioactivity for Radiological Use
SC-22: Radiation Shielding for Particle Accelerators
SC-23: Radiation Hazards Resulting from the Release of Radionuclides into the Environment
SC-24: Radionuclides and Labeled Organic Compounds Incorporated in Genetic Material
SC-25: Radiation Protection in the Use of Small Neutron Generators
SC-26: High Energy X-Ray Dosimetry
SC-28: Radiation Exposure from Consumer Products
SC-30: Physical and Biological Properties of Radionuclides
SC-31: Selected Occupational Exposure Problems Arising from Internal Emitters
SC-32: Administered Radioactivity
SC-33: Dose Calculations
SC-34: Maximum Permissible Concentrations for Occupational and Non-Occupational Exposures
SC-35: Environmental Radiation Measurements
SC-37: Procedures for the Management of Contaminated Persons
SC-38: Waste Disposal
SC-39: Microwaves
SC-40: Biological Aspects of Radiation Protection Criteria
SC-41: Radiation Resulting from Nuclear Power Generation
SC-42: Industrial Applications of X Rays and Sealed Sources
SC-44: Radiation Associated with Medical Examinations
SC-45: Radiation Received by Radiation Employees
SC-46: Operational Radiation Safety
SC-47: Instrumentation for the Determination of Dose Equivalent
SC-48: Apportionment of Radiation Exposure
SC-50: Surface Contamination
SC-51: Radiation Protection in Pediatric Radiology and Nuclear Medicine Applied to Children
SC-52: Conceptual Basis of Calculations of Dose Distributions
SC-53: Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Radiation
SC-54: Bioassay for Assessment of Control of Intake of Radionuclides

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22	*Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (1959) [Includes Addendum 1 issued in August 1963]
23	*Measurement of Neutron Flux and Spectra for Physical and Biological Applications* (1960)
25	*Measurement of Absorbed Dose of Neutrons, and of Mixtures of Neutrons and Gamma Rays* (1961)
27	*Stopping Powers for Use with Cavity Chambers* (1961)
30	*Safe Handling of Radioactive Materials* (1964)
32	*Radiation Protection in Educational Institutions* (1966)
35	*Dental X-Ray Protection* (1970)
36	*Radiation Protection in Veterinary Medicine* (1970)
37	*Precautions in the Management of Patients Who Have Received Therapeutic Amounts of Radionuclides* (1970)
38	*Protection Against Neutron Radiation* (1971)
40	*Protection Against Radiation from Brachytherapy Sources* (1972)
41	*Specification of Gamma-Ray Brachytherapy Sources* (1974)
42	*Radiological Factors Affecting Decision-Making in a Nuclear Attack* (1974)
44	*Krypton-85 in the Atmosphere—Accumulation, Biological Significance, and Control Technology* (1975)

74 *Biological Effects of Ultrasound: Mechanisms and Clinical Implications* (1983)

75 *Iodine-129: Evaluation of Releases from Nuclear Power Generation* (1983)

76 *Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment* (1984)

77 *Exposures from the Uranium Series with Emphasis on Radon and Its Daughters* (1984)

78 *Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters in the United States* (1984)

79 *Neutron Contamination from Medical Electron Accelerators* (1984)

80 *Induction of Thyroid Cancer by Ionizing Radiation* (1985)

81 *Carbon-14 in the Environment* (1985)

82 *SI Units in Radiation Protection and Measurements* (1985)

83 *The Experimental Basis for Absorbed-Dose Calculations in Medical Uses of Radionuclides* (1985)

84 *General Concepts for the Dosimetry of Internally Deposited Radionuclides* (1985)

85 *Mammography—A User's Guide* (1986)

86 *Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields* (1986)

87 *Use of Bioassay Procedures for Assessment of Internal Radionuclide Deposition* (1987)

88 *Radiation Alarms and Access Control Systems* (1986)

89 *Genetic Effects from Internally Deposited Radionuclides* (1987)

90 *Neptunium: Radiation Protection Guidelines* (1988)

92 *Public Radiation Exposure from Nuclear Power Generation in the United States* (1987)

93 *Ionizing Radiation Exposure of the Population of the United States* (1987)

94 *Exposure of the Population in the United States and Canada from Natural Background Radiation* (1987)

95 *Radiation Exposure of the U.S. Population from Consumer Products and Miscellaneous Sources* (1987)

96 *Comparative Carcinogenicity of Ionizing Radiation and Chemicals* (1989)

97 *Measurement of Radon and Radon Daughters in Air* (1988)

98 *Guidance on Radiation Received in Space Activities* (1989)

99 *Quality Assurance for Diagnostic Imaging* (1988)

100 *Exposure of the U.S. Population from Diagnostic Medical Radiation* (1989)

Volume III.	NCRP Reports Nos. 32, 35, 36, 37
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Volume V.	NCRP Reports Nos. 42, 44, 46
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NCRP Commentaries

No.	Title
1	*Krypton-85 in the Atmosphere—With Specific Reference to the Public Health Significance of the Proposed Controlled Release at Three Mile Island* (1980)
2	*Preliminary Evaluation of Criteria for the Disposal of Transuranic Contaminated Waste* (1982)
3	*Screening Techniques for Determining Compliance with Environmental Standards—Releases of Radionuclides to the Atmosphere* (1986), Revised (1989)
4	*Guidelines for the Release of Waste Water from Nuclear Facilities with Special Reference to the Public Health Significance of the Proposed Release of Treated Waste Waters at Three Mile Island* (1987)
5	*Review of the Publication, Living Without Landfills* (1989)
6	*Radon Exposure of the U.S. Population—Status of the Problem* (1991)

12 *Health and Ecological Implications of Radioactively Contaminated Environments*, Proceedings of the Twenty-sixth Annual Meeting held on April 4-5, 1990 (including Taylor Lecture No. 14) (1991)

13 *Genes, Cancer and Radiation Protection*, Proceedings of the Twenty-seventh Annual Meeting held on April 3-4, 1991 (including Taylor Lecture No. 15) (1992)

14 *Radiation Protection in Medicine*, Proceedings of the Twenty-eighth Annual Meeting held on April 1-2, 1992 (including Taylor Lecture No.16) (1993)

Lauriston S. Taylor Lectures

No.	Title
1	*The Squares of the Natural Numbers in Radiation Protection* by Herbert M. Parker (1977)
2	*Why be Quantitative about Radiation Risk Estimates?* by Sir Edward Pochin (1978)
3	*Radiation Protection—Concepts and Trade Offs* by Hymer L. Friedell (1979) [Available also in *Perceptions of Risk*, see above]
4	*From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review* by Harold O. Wyckoff (1980)
5	*How Well Can We Assess Genetic Risk? Not Very* by James F. Crow (1981) [Available also in *Critical Issues in Setting Radiation Dose Limits*, see above]
6	*Ethics, Trade-offs and Medical Radiation* by Eugene L. Saenger (1982) [Available also in *Radiation Protection and New Medical Diagnostic Approaches*, see above]
7	*The Human Environment—Past, Present and Future* by Merril Eisenbud (1983) [Available also in *Environmental Radioactivity*, see above]
8	*Limitation and Assessment in Radiation Protection* by Harald H. Rossi (1984) [Available also in *Some Issues Important in Developing Basic Radiation Protection Recommendations*, see above]
9	*Truth (and Beauty) in Radiation Measurement* by John H. Harley (1985) [Available also in *Radioactive Waste*, see above]
10	*Biological Effects of Non-ionizing Radiations: Cellular Properties and Interactions* by Herman P. Schwan (1987) [Available also in *Nonionizing Electromagnetic Radiations and Ultrasound*, see above]

5 *NCRP Statement on Dose Limit for Neutrons* (1980)
6 *Control of Air Emissions of Radionuclides* (1984)
7 *The Probability That a Particular Malignancy May Have Been Caused by a Specified Irradiation* (1992)

Other Documents

The following documents of the NCRP were published outside of the NCRP Report, Commentary and Statement series:

Somatic Radiation Dose for the General Population, Report of the Ad Hoc Committee of the National Council on Radiation Protection and Measurements, 6 May 1959, Science, February 19, 1960, Vol. 131, No. 3399, pages 482-486

Dose Effect Modifying Factors In Radiation Protection, Report of Subcommittee M-4 (Relative Biological Effectiveness) of the National Council on Radiation Protection and Measurements, Report BNL 50073 (T-471) (1967) Brookhaven National Laboratory (National Technical Information Service Springfield, Virginia)

The following documents are now superseded and/or out of print:

NCRP Reports

No.	Title
1	*X-Ray Protection* (1931) [Superseded by NCRP Report No. 3]
2	*Radium Protection* (1934) [Superseded by NCRP Report No. 4]
3	*X-Ray Protection* (1936) [Superseded by NCRP Report No. 6]
4	*Radium Protection (1938)* [Superseded by NCRP Report No. 13]
5	*Safe Handling of Radioactive Luminous Compound* (1941) [Out of Print]
6	*Medical X-Ray Protection Up to Two Million Volts* (1949) [Superseded by NCRP Report No. 18]
7	*Safe Handling of Radioactive Isotopes* (1949) [Superseded by NCRP Report No. 30]
9	*Recommendations for Waste Disposal of Phosphorus-32 and Iodine-131 for Medical Users* (1951) [Out of Print]
10	*Radiological Monitoring Methods and Instruments* (1952) [Superseded by NCRP Report No. 57]
11	*Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water* (1953) [Superseded by NCRP Report No. 22]
12	*Recommendations for the Disposal of Carbon-14 Wastes* (1953) [Superseded by NCRP Report No. 81]

53 *Review of NCRP Radiation Dose Limit for Embryo and Fetus in Occupationally-Exposed Women* (1977) [Out of Print]

56 *Radiation Exposure from Consumer Products and Miscellaneous Sources* (1977) [Superseded by NCRP Report No. 95]

58 *A Handbook of Radioactivity Measurements Procedures*, 1st ed. (1978) [Superseded by NCRP Report No. 58, 2nd ed.]

66 *Mammography* (1980) [Out of Print]

91 *Recommendations on Limits for Exposure to Ionizing Radiation* (1987) [Superseded by NCRP Report No. 116]

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