NCRP REPORT No. 49

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

Recommendations of the
NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS

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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 the Committee and the consultants for the time and effort devoted to the preparation of this report.

Lauriston S. Taylor
President, NCRP

Bethesda, Maryland
January 15, 1976

Contents

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.

able increase in cost of the structural shielding [3]. In such cases the use of the lower weekly exposure value for design purposes is consistent with the "lowest practicable level" concept for radiation exposure. The use of this lower design factor, however, must not be considered a reduction in the MPD as discussed above.

This report is intended primarily for use in planning and designing new facilities and in remodeling existing facilities. Since corrections or additions after facilities are completed can be expensive, it is important that structural shielding be properly designed and installed in the original construction process. It is also advisable that the planning include consideration of possible future needs for new equipment, higher radiation energies, and increased workloads.

It is recommended that the shielding be designed by a qualified expert (see definition given in Appendix A) to ensure that the required degree of radiation protection is achieved economically. This objective will be furthered by providing the qualified expert with all pertinent information regarding the proposed radiation equipment and its use, type of building construction and occupancy of nearby areas, such as is listed in Appendix E. If possible, the expert should be consulted during the early planning stages; often the shielding requirements affect the choice of location of radiation facilities and type of building construction. It is highly desirable that final shielding drawings and specifications be reviewed by the qualified expert and by the pertinent federal, state or local agency (if applicable) before construction is begun. While some other aspects of x- and gamma-ray facilities, such as interlocks, warning signs and lights, electrical safety and room lighting, are mentioned in this report, these aspects are not represented as a complete treatment of these topics.

Recent availability of new data used to calculate the shielding in radiation facilities has resulted in revision from previous recommendations of some of the shielding requirement tables in Appendix C. However, installations designed before the publication of this report and meeting the requirements of the Appendix C shielding tables in NCRP Report No. 34 [1] need not be re-evaluated.

While specific recommendations are given, alternate methods may prove equally satisfactory in providing radiation protection. The final assessment of the adequacy of the design and construction of structural shielding should be based on the radiation survey of the completed installation. If the radiation survey shows deficiencies, additional shielding or modifications of equipment and procedures are required.

Exposure, and its special unit the roentgen, are defined in Appendix A. For radiation protection purposes of this report, the number of 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.

2. Barrier Thickness Requirements

The principal objective of radiation protection is to ensure that the dose received by any individual is as low as practicable and, in any case (except for medically required doses to patients), does not exceed the applicable maximum permissible value. A secondary objective is to prevent damage or impairment of function of radiation-sensitive films and instruments. These objectives may be achieved by any one, or a combination, of the following methods:

(a) providing sufficient *distance* between the individual or object and the source or sources of radiation.
(b) limiting the *time* of exposure, and
(c) interposing a protective (attenuating) *barrier* between the individual or object and the source or sources of radiation.

Distance involves the inverse square relationship[3]; the distances are determined by the positions of persons (or radiation-sensitive devices) relative to the source. It is usually assumed that the individual is at least 30 cm (12 inches) away from the barrier.

The *time* factor is determined by the period during which an individual is in a radiation field. Consequently it involves both the time that the source is "ON"[4] and the fraction of the "ON" time during which a person is in the radiation field. Generally the protective housing for gamma-ray beam sources is so constructed that the MPD cannot be exceeded for individual exposure due only to source housing leakage radiation when the source is "OFF". Similar considerations apply to x-ray sources under "standby" conditions.

In most applications covered by this report protective *barriers* are

[3] The statement that the exposure rate from the source varies inversely as the square of the distance from the source is based on the assumptions that the source dimensions are small compared to the distance and that absorption in the intervening medium is negligible. The first assumption is valid for calculating the requirement for the primary barrier; the absorption in air is generally insignificant if the radiation energy is more than 50 keV and the distance is less than 30 m (100 feet).

[4] Here the "ON" time means the time that (a) the x-ray beam is "ON", or (b) the beam control mechanism of gamma-ray beam equipment is in the "ON" position, or (c) a sealed source is outside of its shielded storage container.

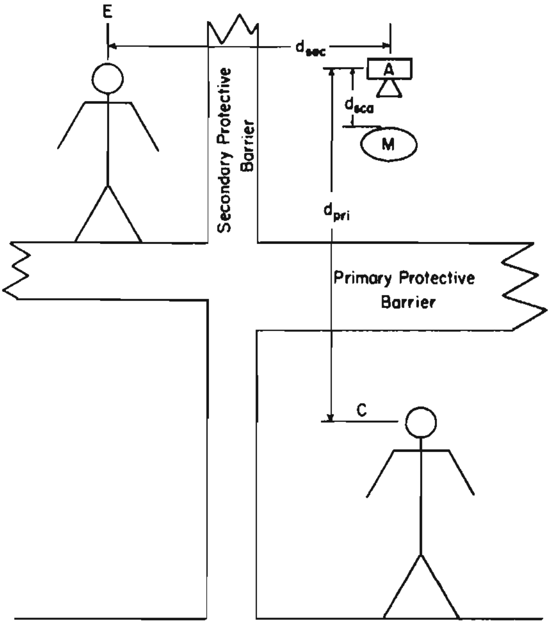

Fig. 2-1. Elevation view of radiation room and its surroundings with indication of distances of interest for radiation shielding calculations. A is the radiation source, M the patient, and C and E positions that may be occupied by persons.

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.

radiation scattered from the patient is usually more significant than that scattered from the primary barrier.

Tables giving minimum protective barrier requirements are included in Appendix C of this report for weekly exposure limits, P, equal to 0.1 and 0.01 roentgen, the maximum design levels for controlled and noncontrolled areas, respectively.

It has been shown [3] that the cost of shielding for typical radiographic and therapeutic x-ray installations will only increase approximately 25 percent if the shielding design for controlled areas is based on a weekly exposure of 0.01 roentgen rather than the maximum design value of 0.1 roentgen. The use of the lower weekly exposure for design purposes is consistent with the "as low as practicable" concept.

Tables 2, 3 and 4 (Appendix C) give suggested values of weekly workload, W, use factor, U, and occupancy factor, T, respectively, for use in those cases where more specific information is not available at the time of planning. The occupancy factors listed in Table 4 are to be applied only to nonoccupationally exposed persons (for whom P = 0.01 R).

For occupationally exposed persons, the occupancy factor, T, usually is assumed to be unity. For example, a corridor which is used by the public and which is outside a radiation room would have an occupancy factor of 1/4 for the public, but of unity for occupationally exposed persons. Occupational exposure means 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.

Occupationally exposed persons may be assumed to spend their entire work period in *controlled* areas. The fraction of each person's time which will be spent at any one location often cannot be predicted. Thus, it must be assumed that all positions from which persons are not specifically excluded are likely to be occupied by a given person for unspecified periods of time. With these assumptions, all accessible portions of the controlled area *should* be designed with an occupancy factor of unity for *occupationally exposed persons*. However, if the portion of time spent by any person at all locations can be predicted, the occupancy factor, T, for some areas may be less than unity, but the weekly exposure *shall not* average, over a period of one year, more than 0.1 R.

Areas which are not part of the radiologic department or suite *should not* be declared *controlled areas* for the purpose of permitting reduction in the degree of protection of occupants. Areas within the department or suite which are not directly related to the use of radiation sources *should not* be declared controlled areas.

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.

3. Shielding Materials

3.1 General

Most materials (see Table 25, Appendix C) may be used for radiation shielding if employed in a thickness sufficient to attenuate the radiation by the required degree. Although the two materials most often used for shielding are lead and concrete, others may prove to be more advantageous under certain circumstances. In selecting shielding material the following factors should be considered:

(a) Required thickness and weight of material
(b) Possibility of multiple use (e.g., use of material that serves for both shielding and structural purposes)
(c) Uniformity of shielding
(d) Permanence of shielding
(e) Optical transparency (when required)
(f) Quality control requirements
(g) Cost of material, including its installation and maintenance
(h) Appearance

These factors are discussed below.

3.2 Choice of Material

The choice between lead and concrete is usually made for the reason of economy and depends upon the energy of radiation to be attenuated. For example, a concrete primary protective barrier for a 100 kV x-ray installation would have to be about 80 times as thick and about 17 times as heavy as lead to provide the same degree of shielding. On the other hand, for a 1 MV x-ray installation, the concrete thickness would be only about six times as great, about 25 percent heavier than an equivalent lead barrier and considerably less costly. Where space is an important consideration, it is sometimes advantageous to use lead or steel in place of part, or all, of the concrete in a barrier for high energy radiation. For many years it has been a general rule that lead is more economical than concrete as 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.

3.2.2 *Concrete.*

(a) *Common Poured (Cast) Concrete*[7]. The principal advantage of concrete is that it is a standard building material commonly used, especially in floors and ceilings of modern buildings. The radiation attenuation of a concrete barrier depends upon its thickness, density and composition. The concrete barrier thicknesses indicated in the shielding tables in this report are based on a concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}). For other concrete densities, a correction must be applied to the thicknesses indicated in the tables to ensure that the area density (g cm^{-2}, lb ft^{-2}) remains the same. Variations in concrete density arise from differences in the densities of the components, from foaming or tamping techniques used in the casting of the concrete, or from different proportions used in the mix. The elemental composition of the concrete depends upon the source of supply of its components. For common concrete, however, the difference in the elemental composition does not modify the attenuation of photons significantly if allowance is made for differences in density.

(b) *Loaded Concrete.* Where space is limited, high density concrete may be used to advantage. It is produced by introducing into the mixture loading material such as barytes, magnetite, ilmenite, steel, ferrophosphorus or lead. The shielding property of common concrete can be greatly increased by the addition of such materials. The cost of using loaded concrete, however, is considerably higher than that of common concrete.

The casting of loaded concrete at the site presents special problems including the need for more careful mixing to ensure uniform distribution of loading material. Quality control is needed to ensure that no part of the cast barrier has a density of less than that specified. In addition, extra heavy equipment and forms are required to handle the greater weight.

(c) *Solid Blocks.* Both common and loaded concrete solid blocks are available in standard dimensions. Quality control is simplified as the density can readily be checked before the blocks are laid. Mortar (without voids) having a density not less than that of the block, *should* be used in protective barriers of block construction. For multiple course construction, the joints *should* be staggered.

3.2.3 *Other Masonry Material.* Most mineral-base building materials (solid cinder blocks, bricks, plaster, granite, marble[8]) have a

[7] Steel reinforcement increases the effective shielding, because steel offers greater attenuation than the concrete it displaces.

[8] Measurements indicate that the concrete equivalence of marble at 100 kV is about 15 percent greater than calculated from the density ratio [4].

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.

(b) *Lead Glass*. Glass with a high lead content is commonly used for shielding purposes. It is available with densities ranging from about 3.3 to 6.2 g cm^{-3} and in a variety of thicknesses. Due to its deep yellow color and relatively low light transmission, the higher density glass (refractive index 1.97) is not commonly used for observation windows if more than a few sheets are required. Non-browning lead glass (density 3.3 g cm^{-3}, refractive index 1.59) has a light yellow color and a 1/4 inch thick sheet has a lead equivalence of about 2 mm for 100 kV x rays. Since high density lead glass darkens with exposure to radiation, it is sometimes covered on the exposed side with a sheet of non-browning lead glass to reduce this effect.

(c) *Liquids*. Prior to the availability of thick lead glass, water and other solutions, such as optical grade zinc bromide solution, in a glass and steel container were commonly used in observation windows. These windows, however, require periodic checks for any loss of fluid. Furthermore, liquids occasionally become turbid with age and require replacement.

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* have mortar (without voids) of at least the same density as the block, and for multiple course construction the joints *should* be staggered.

Joints between different kinds of protective material *should* be constructed so that the overall protection of the barrier is not impaired. Typical examples are shown in Figure 4-1; the extension of the lead into the concrete is required to attenuate the radiation scattered in the concrete. Baffles are usually required for door sills exposed to the useful beam. Typical designs are shown in Figure 4-2.

4.3 Voids in Protective Barriers

Openings in protective barriers for doors, windows, ventilating ducts, conduits, pipes, etc. may require radiation baffles to ensure that the required degree of overall protection is maintained. Whenever possible, the opening *should* be located in a secondary barrier where the required shielding thickness is less. The design of the baffles will depend upon a number of factors. These include:

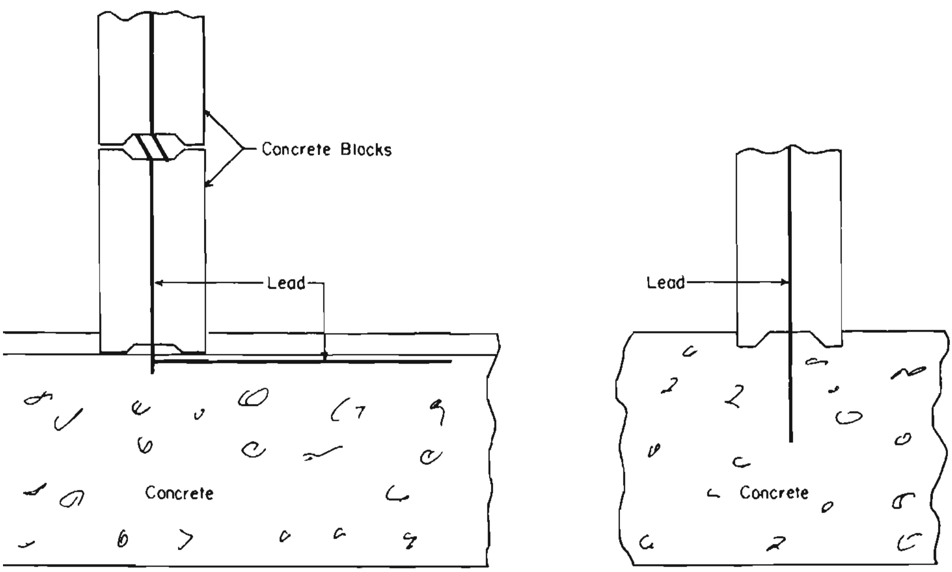

Fig. 4-1. Typical joints between different kinds of protective material. The length of the horizontal or vertical extension of the lead will depend on the energy and direction of the radiation; diagnostic installations usually do not require extension of the lead.

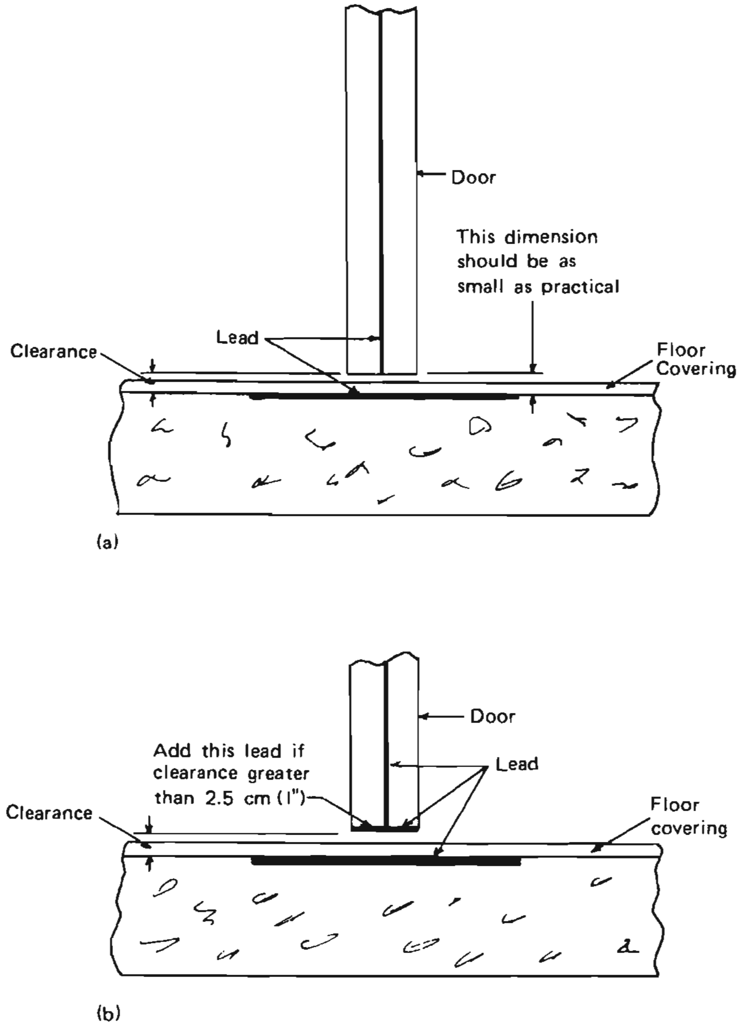

Fig. 4-2. Typical lead baffles under doors exposed to the useful beams generally not required for diagnostic installations.

(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.

Figures 4-3, 4-4, 4-5, 4-6 and 4-7 show typical baffle designs. In 4-3, 4-4 and 4-5 the opening is in a secondary protective barrier and, therefore, exposed to scattered and leakage radiation only. In Figures 4-6 and 4-7 the opening is located in a primary protective barrier.

The illustrated methods of protection are intended as guides only; effective protection at minimum cost can be achieved only by consideration of all pertinent factors of each individual installation. Generally, the most economical shielding material for a baffle is lead because the amount of radiation scattered from lead is less than that from lighter materials and the scattered radiation is more readily attenuated in lead. Since lead is not structurally self-supporting, it *should* be mounted so that there will be no sagging.

Since the primary protective barrier in diagnostic and superficial (low voltage) therapy x-ray rooms need not extend above 2.1 m (7 feet)

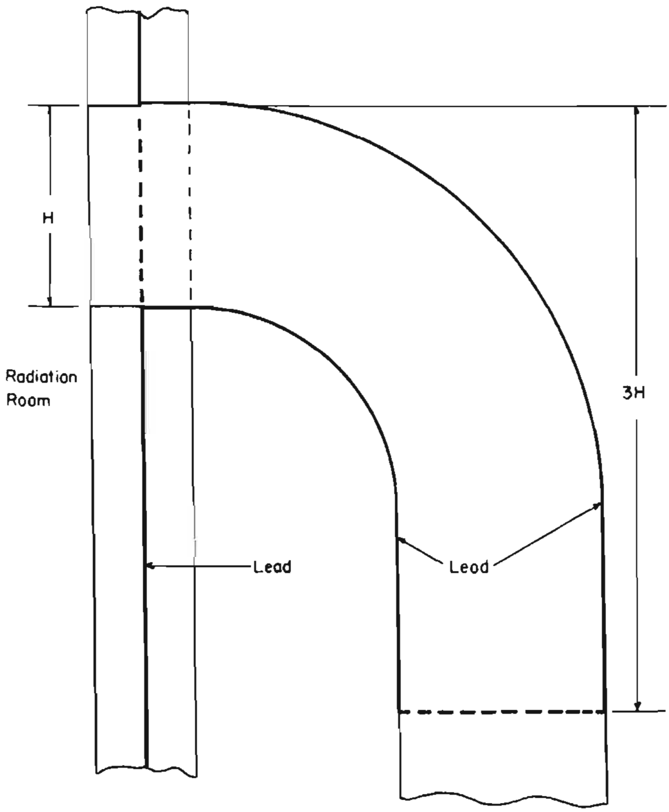

Fig. 4-3. Typical baffle design for openings in secondary protective barrier.

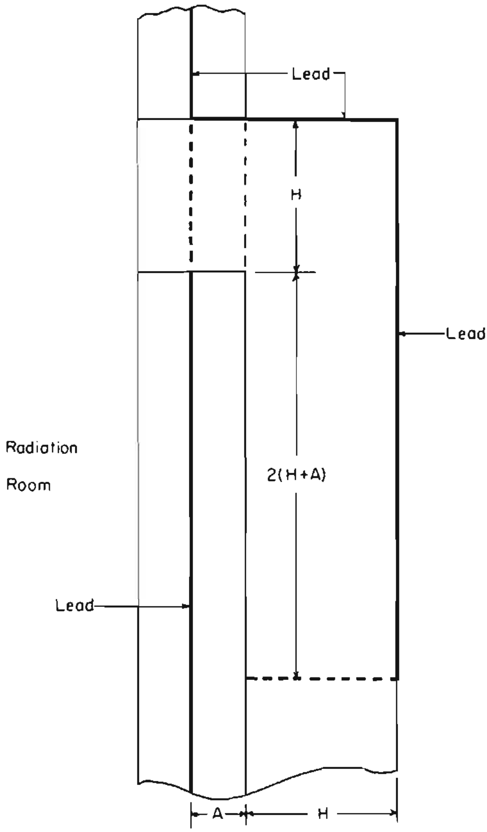

Fig. 4-4. Typical baffle design for openings in secondary protective barrier.

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).

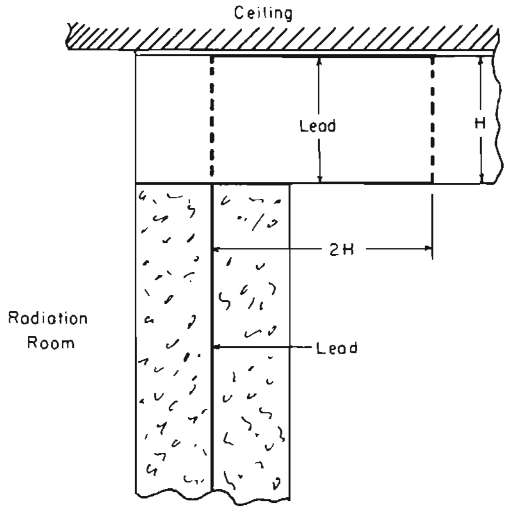

Fig. 4-5. Typical baffle design for openings in secondary protective barrier.

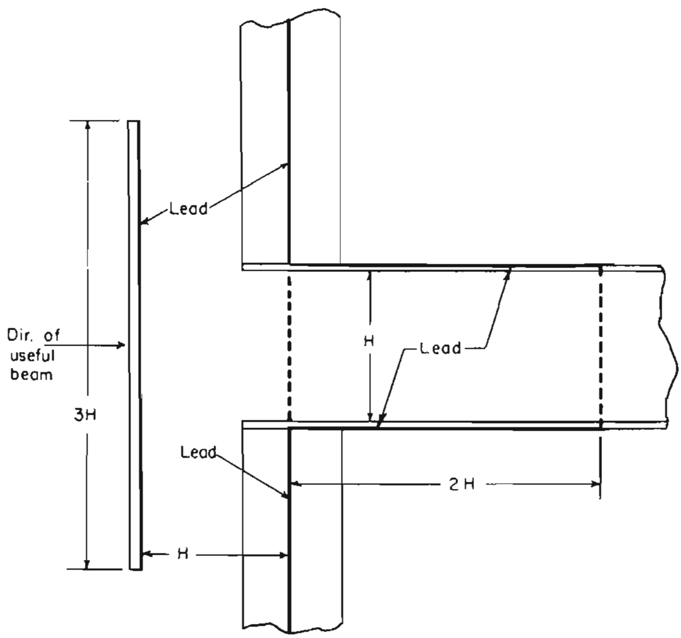

Fig. 4-6. Typical baffle design for openings in primary protective barrier for orthovoltage installations.

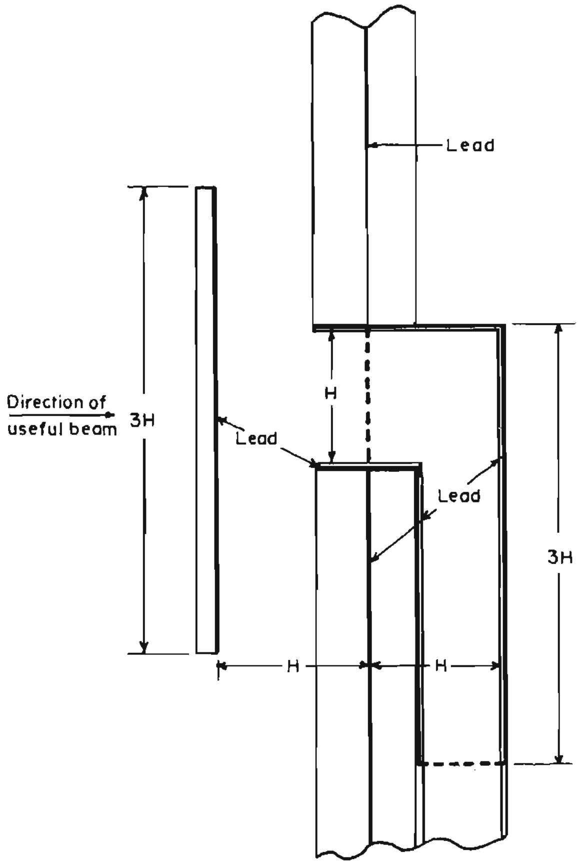

Fig. 4-7. Typical baffle design for openings in primary protective barrier for orthovoltage installations.

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.

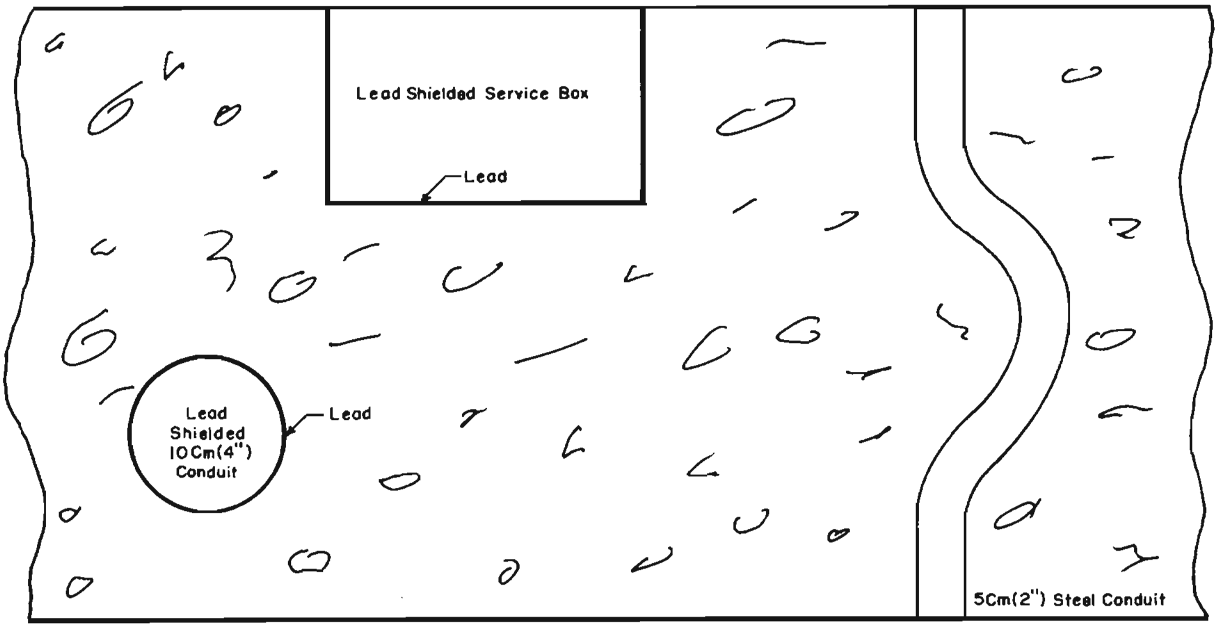

Fig. 4-8. Lead shielding of service box and conduit in concrete barrier. On the right are shown bends required for a conduit passing through the barrier.

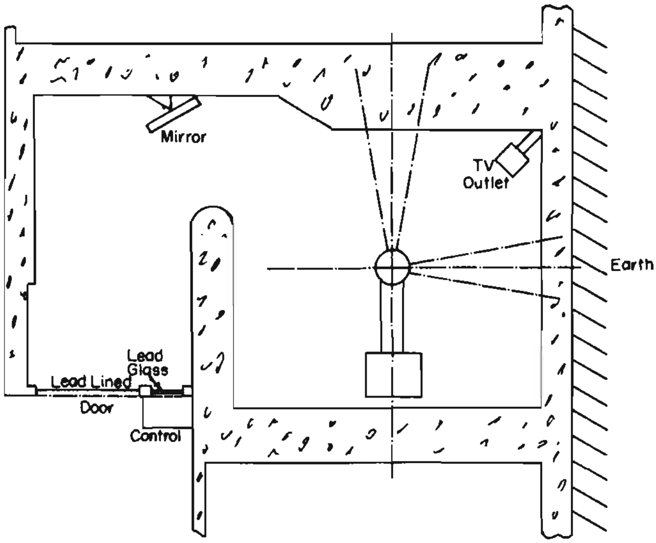

Fig. 4-9. Typical maze design for megavoltage therapy installation. The door and window are exposed only to radiation which has been scattered at least twice.

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.

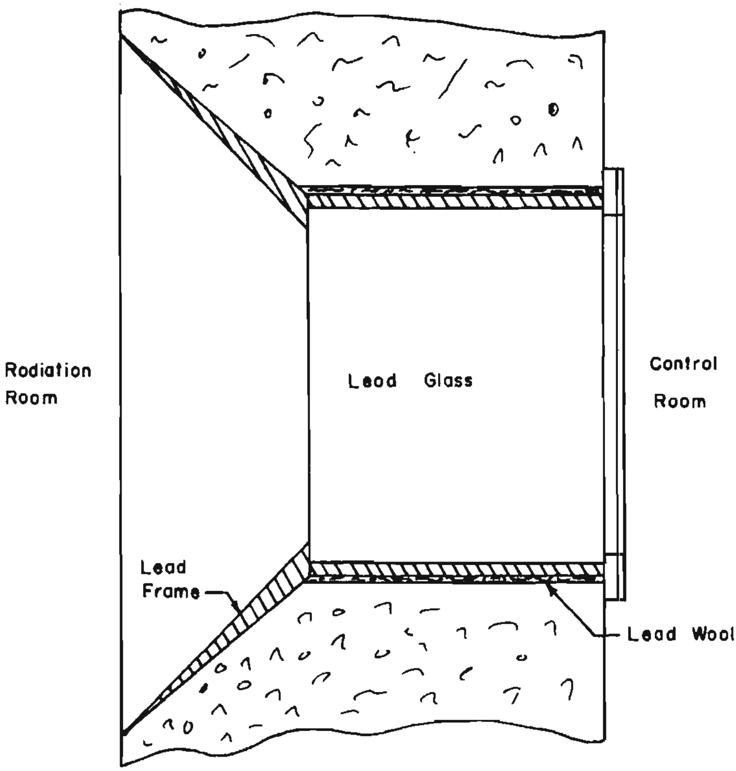

Fig. 4-10. Lead glass observation window with lead frame.

ally is the most economical, as the shielding of the door can be greatly reduced, usually to less than 6 mm of lead, it it is exposed to multiple scattered radiation only. The required lead equivalence of the door will depend upon radiation energy, maze design, weekly workload, and beam orientations. A typical maze design is shown in Figure 4-9. The principal objections to the use of a maze are increased space requirements and less convenient access to the treatment room, particularly for stretcher patients.

4.5 Observation Windows

Various methods of observing the patient during irradiation are considered in Sections 5.3.2 and 6.1.6. Where direct viewing is used for megavoltage installations, the design of the window presents

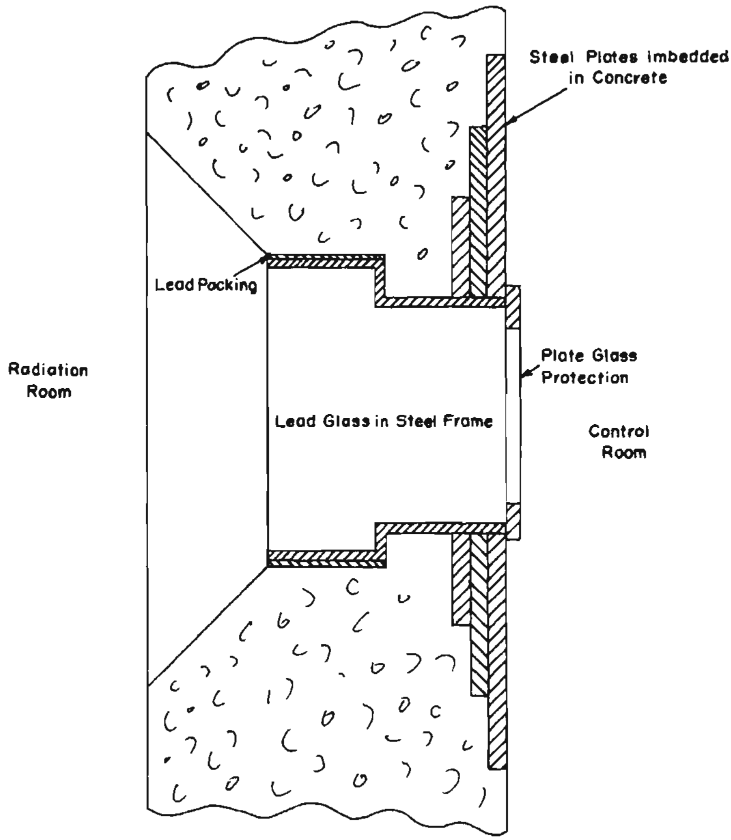

Fig. 4-11. Alternate lead glass observation window design for megavoltage installations.

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.

5. Diagnostic Installations[13]

5.1 General

X-ray tube potentials used in diagnostic installations generally range from 25 to 150 kV, with most examinations performed at 60 to 100 kV[14]. The amount of structural shielding required is, therefore, relatively low compared with that for high-voltage therapy installations. Frequently, the shielding provided by conventional building construction is sufficient. This often is the case, particularly for concrete floors and for concrete ceilings. When supplementary shielding is required, lead is generally used. However, there is little, if any, saving to be achieved by using a lead thickness of less than about one millimeter. In many instances, it may be more economical to employ greater thickness of concrete in the floor than to provide lead shielding.

5.1.1 *Location.* While the degree of occupancy of areas adjacent to the x-ray room determines, to a considerable extent, the amount of structural shielding required, the saving resulting from locating the room remote from occupied areas is usually outweighed by other considerations. The location of the installation is generally determined by such factors as the accessibility to related medical services, patient convenience and traffic control. Outside walls and, particularly, windows may require shielding to protect distant areas even if the nearest occupied area is not immediately adjacent.

5.1.2 *X-Ray Tube Potential and Workload.* All the factors determining shielding requirements, including the tube potential and workload, are discussed in Appendix B. For a given weekly workload (mA

[13] Recommendations concerning dental and veterinary x-ray installations are covered in NCRP Report No. 35 [7] and NCRP Report No. 36 [8], respectively.

[14] Diagnostic procedures have been performed experimentally with megavoltage equipment. Generally such equipment is used primarily for therapy, in which case the shielding requirements depend on the therapy workload and may be determined from Tables 14 to 20 (Appendix C). The shielding requirements for megavoltage installations used only for diagnostic purposes may be determined by use of the appropriate curves in Figures 4 through 10 (Appendix D).

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 enable the personnel to function in the darkened room. (This type of fluoroscopic equipment is becoming obsolete.)

5.2 Fluoroscopic Installations

Fluoroscopic equipment is usually operated at 60 to 100 kV, with weekly workloads ranging from 100 to 2000 mA min. While a primary barrier is incorporated in the viewing device, secondary structural protective barriers are required against leakage radiation and radiation scattered from the patient and various parts of the equipment. Table 7 (Appendix C) gives the thicknesses of the required secondary barriers.

Vertical fluoroscopes are often installed in small rooms. By locating the fluoroscope so that the door is exposed to multiple scattered radiation only, lead lining of the door may not be necessary. Generally, shielding does not have to be added to the floor and ceiling.

The shielding requirements for combination radiographic-fluoroscopic installations are usually determined by the radiographic use of the room.

5.3 Radiographic Installations

5.3.1 *Use Factor*. Radiographic equipment usually is operated at 25 to 150 kV with weekly workloads of 10 to 1000 mA min. Typical workloads are indicated in Table 2 (Appendix C). The equipment generally is arranged to allow many different beam orientations. When specific information for a given installation is not available, the use factor, U, for walls (including those with a cassette holder or plate changer) may be assumed to be 1/4 (see Table 3, Appendix C). If there is a possibility that most of the exposures are to be made with the beam directed only at certain wall areas, higher use factors *should* be used. The use factor for the ceiling may be assumed to be zero, since the beam is rarely oriented toward the ceiling.

When mobile equipment is to be used routinely in one location, shielding *shall* be provided as for a fixed radiographic installation.

5.3.2 *Operator's Control Station*. The operator's control station *should* be in a separate room, or in a protected booth, or behind a fixed shield which will intercept the useful beam and scattered radiation from the patient. Typical designs of control stations are shown in Figure 5-1. When a door is required to shield the operator from

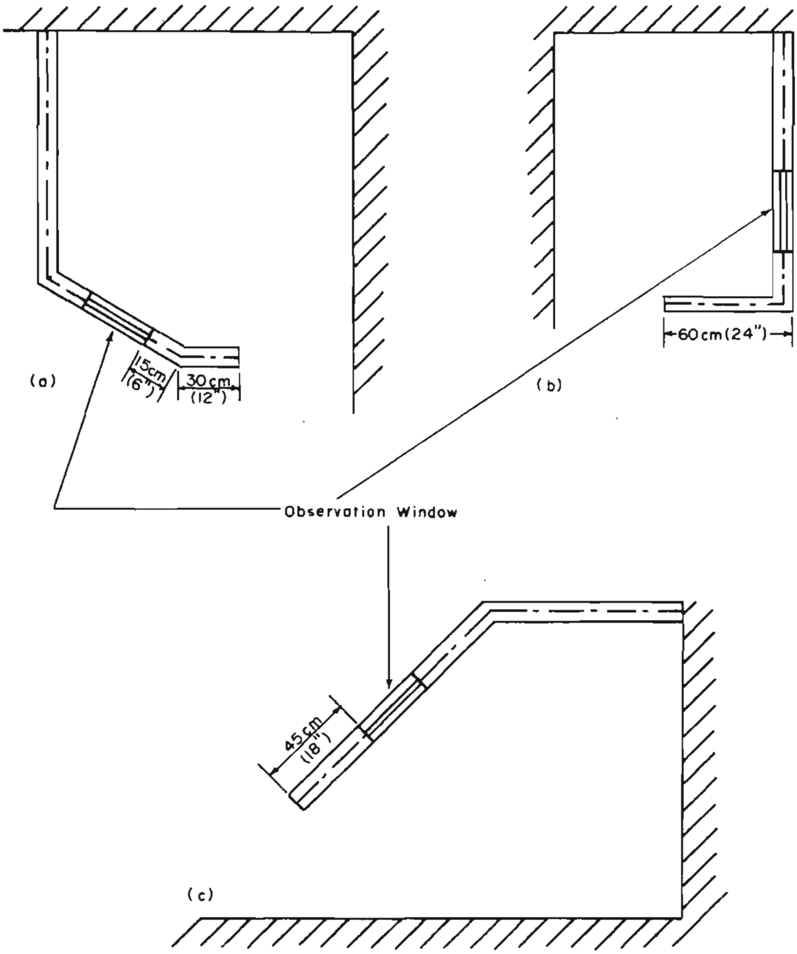

Fig. 5-1. Typical designs of control stations.

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 communication with a patient can generally be achieved by locating the x-ray control station within the radiographic room. When a protective door is not required, the edge of the observation window *should* be at least 45 cm (18 inches) from the edge of the control partition. Further, consideration *should* be given to the location of the opening of the control booth to minimize the exposure of the operator to scattered radiation. These factors have been considered in the design of a typical installation shown in Figure 5-2.

5.4 Photofluorographic (Photo-Roentgen) Installations

Photofluorographic equipment utilizes a camera to photograph the image produced on a fluorescent screen. When the x-ray tube orientation is restricted so that the useful beam may be directed only toward the camera, a primary protective barrier is required only for the wall behind the camera. The primary protective barrier *should* extend at least 30 cm (12 inches) beyond the perimeter of the entire wall area which can be struck by the useful beam. The use factor for this area is one. All other wall, floor and ceiling areas can be

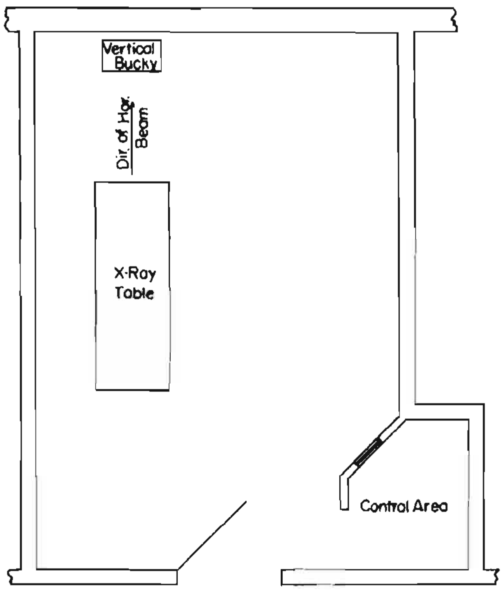

Fig. 5-2. Typical design for installation with control panel located within the radiographic room.

secondary 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.

non-radiologic procedures and the collection of physiologic and hemodynamic data. The methods for determining the shielding requirements are the same as those for conventional radiographic installations. See Section 5.3.2 for operator's control station protection requirements.

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.

Future need for additional services (electrical, water, vacuum, oxygen) *should* be considered during initial planning.

6.1.3 *Size of Treatment Room.* The desirable size of a treatment room depends upon the type of the therapy equipment, the type of patient (ambulatory only or including bed patients), and the use of special equipment for research and teaching. Making the room larger than necessary may permit the installation of additional ancillary equipment, or replacement of the original therapy equipment by a larger unit requiring more shielding. However, larger rooms cost more to build, require more walking for the staff, and encourage use for extraneous purposes.

6.1.4 *Access to Treatment Room.* A shielded door opening directly into the treatment room is most satisfactory when protection requirements are moderate. For megavoltage installations, a door with adequate shielding which permits direct access to the treatment room may weigh several tons and require an expensive motor drive. When such doors offer the only access to the room, at least one *shall* be provided with auxiliary means for being opened in case of power failure or mechanical breakdown.

A maze which allows only multiple scattered radiation to reach the door will usually provide an overall economy by greatly reducing the shielding requirements for the door. However, a maze requires more floor space, and reduces the convenience of access, especially for stretchers and equipment.

Height and width of doorways, elevators, and mazes must be adequate to permit delivery of equipment into treatment rooms, unless other entry is available. Gamma-ray beam therapy installations also require access for replacement sources in large, heavy shipping containers.

6.1.5 *Interlocks and Warning Signals.* Effective means *shall* be provided to prevent access to the treatment room during exposure. For installations of 150 kV or higher, each access door to the treatment room *shall* be provided with a "fail-safe" interlock. It is recommended that the interlock system be so designed that the failure of any one component will not jeopardize the safety of the system, e.g., the use of series-connected double switch assemblies at access doors, and dual interlock relays. If an access door is opened when the machine is "ON", the interlock *shall* cause the irradiation to be terminated. It *shall* then be possible to restore the machine to full operation *only* from the control panel.

For megavoltage or gamma-ray beam therapy installations, see Section 8.1.7 regarding warning light requirements.

6.1.6 *Communication with Patient.* The operator *shall* be able to 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.

The term "orthovoltage therapy" (deep therapy) is used to describe treatment with x rays produced at potentials ranging from 150 to 500 kV. The control station *shall* be outside the therapy room[19]. Interlocks *shall* be provided for access doors (see Section 6.1.5). Restricting the beam orientation will limit the area requiring primary protective barriers to that which can be struck by the useful beam plus a suitable margin[20]. All primary protective barriers *shall* be designed for a use factor of at least $^1/_{16}$. Mechanical or electrical means *shall* be provided to prevent the useful beam from striking secondary protective barriers.

6.3 X-Ray Installations of 0.5 to 10 MV (Megavoltage or Supervoltage)

Primary protective barriers for megavoltage installations will usually be of concrete several feet thick, or the equivalent. Therefore, to ensure economical construction, careful consideration of room location, beam orientation, and use factor is necessary.

Restricting the beam orientation will limit the area requiring primary protective barriers to that which can be struck by the useful beam plus a suitable margin[20]. In the design of primary protective barriers, due consideration *should* be given to possible future changes in techniques which may increase the use factor. The use factor *shall not* be assumed to be less than $^1/_{16}$. Mechanical or electrical means *shall* be provided to prevent the useful beam from striking secondary protective barriers.

When the room is below grade, the possibility of beam orientation toward the ground surface should be considered. The upper edge of the largest projected beam *should* be far enough below the surface to prevent significant scattered radiation from reaching the surface.

Protective type source housings for megavoltage equipment fre-

[19] The control station may be located in a booth within the room if the door, walls, and ceiling of the booth are adequately shielded, and if interlocks are provided for the door between the booth and the treatment room, as well as for other access door(s) to the treatment room.

[20] A primary protective barrier that does not extend over an entire wall (floor or ceiling) *should* include an extended margin beyond the maximum projected beam size to guard against misalignment of the beam. Consideration should also be given to forward small angle scatter from the patient, etc., for which the usual secondary barriers may be inadequate. The width of the margin will depend upon the room dimensions, type and location of equipment, and the energy of the radiation. For an orthovoltage therapy installation with an average size treatment room, a 30 cm (12 inches) margin is usually adequate.

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.

When megavoltage equipment is provided with a beam interceptor, pertinent recommendations of Section 6.4 apply.

6.4 Gamma-Ray Beam Therapy Installations (Teletherapy)

The two nuclides most commonly used for gamma-ray beam therapy are cobalt-60 and cesium-137. Since their photon energies are in the MeV range, the considerations of Section 6.3 apply with only limited additions. While detailed discussion of the design of gamma-ray beam therapy equipment is not pertinent to this report (see NCRP Report No. 33 [9]), certain design features of the equipment may affect structural shielding requirements. When a room is planned for a specific type of equipment, the structural shielding design will be most appropriate if adequate data are available concerning:

(a) possible orientations of unattenuated useful beam and possible beam orientations with beam interceptor, if present,
(b) leakage radiation of source housing in "ON" condition,
(c) attenuation of the useful beam and scattered radiation by the beam interceptor, if present,
(d) minimum angle through which radiation is scattered from isocenter without attenuation by the beam interceptor, if present,
(e) source-axis distance for isocentric equipment.

With gamma-ray beam equipment utilizing an isocentric mounting, the counter-weight is frequently designed to serve also as a beam interceptor in order to reduce the structural shielding requirements. When a beam interceptor is provided, it *should* transmit not more than 0.1 percent of the useful beam[22]. It also *should* reduce, by the same factor, the radiation scattered by the patient through an angle of up to 30 degrees from the isocenter. Unless it is established that the beam interceptor attenuates radiation scattered more than 30 degrees, the computation of radiation barrier thickness *should* be based on the assumption that there is no interceptor attenuation beyond 30 degrees (see Section 4.2.1 (f) of NCRP Report No. 33 [9]).

Some gamma-ray beam equipment is made with the counterweight not intercepting the useful beam, and, therefore, not significantly reducing structural shielding requirements.

[22] Greater transmission is acceptable provided the manufacturer's specifications indicate the actual value so that allowance can be made for it in the design of the structural shielding.

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.

7. Brachytherapy[23]

Brachytherapy is a method of radiation therapy in which sealed gamma or beta sources are utilized to irradiate tissue at distances of up to a few centimeters either by surface, intracavity, or interstitial application. The sources most commonly used are in the form of metallic capsules (tubes), needles and seeds (cells) for interstitial, intracavity and surface use and in the form of applicators or plaques specifically designed for surface application. The sources usually are radium-226, radon-222, cobalt-60, gold-198 or iridium-192, although any radioactive material with appropriate radiation energy, half-life and physical properties could be used (see Table 28, Appendix C). With this method of treatment, structural shielding alone is insufficient to ensure adequate protection. Proper operating procedures are of prime importance.

In general, local shielding rather than structural shielding is preferable in protection against radiation from brachytherapy sources. When in storage, the sources *shall* be so shielded that individuals and radiation-sensitive objects in the vicinity will be adequately protected. Occasionally a shielded storage safe will require supplementary structural shielding if it is placed against a wall immediately adjacent to a non-controlled area.

Where it is necessary to locate a storage room or a workroom for brachytherapy sources close to a room in which low-level radiation counting equipment is used, the intervening walls may require structural shielding. As in the case of all relatively high energy radiation (in excess of about 0.3 MeV), concrete shielding is usually more advantageous than lead, unless space or weight is a critical consideration.

Table 7-1 shows the transmission factor, B, for various sources and for different distances. The factor B may be employed to determine the required thickness of the shielding material [Figures 11, 12, or 13 (Appendix D)].

When a large number of brachytherapy sources are located in a storage safe, the exact radiation levels at the outside of the safe are

[23] See NCRP Report No. 40 [10] for an extensive discussion of protection in brachytherapy.

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.

8. Radiation Protection Survey[24]

8.1 General

All new installations and existing installations not previously surveyed *shall* have a radiation protection survey performed by or under the direction of a *qualified expert*.

The radiation protection survey may include visual inspection during construction, followed by radiation scanning and measurement and evaluation. Approval or disapproval *should* be judged on the basis of compliance with the applicable NCRP recommendations and pertinent federal, state and local regulations.

All occupiable areas near a radiation installation *shall* be evaluated for the purpose of determining whether or not any person is likely to receive more than the applicable MPD. In the case of installations operating below 150 kV, radiation measurements *shall* be made unless there is sufficient information to determine that no person can receive more than one quarter of the applicable MPD. For installations capable of operating at 150 kV, or above, radiation measurements *shall* be made in all cases.

If the survey shows that supplementary shielding is required, a resurvey *shall* be performed after its installation. In addition, a resurvey *shall* be made after every change which might decrease the radiation protection significantly.

The testing of safety devices such as door interlock switches, limit switches for beam orientation, mechanical stops, etc. *shall* be performed after the installation is completed, using the radiation equipment for which the facility has been designed. These devices *shall* also be checked periodically.

The testing of the beam control mechanism *shall* include a demonstration that with the beam in the "ON" condition:

(1) The action of opening the door to the radiation room breaks the

[24] For further information see NCRP Report No. 33 [9] and the forthcoming NCRP report on instrumentation and monitoring methods for radiation protection. For dental installations see NCRP Report No. 35 [7].

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-

semblies, etc., recessed in protective barriers;
(f) inspection of location and action of door interlock switches and warning lights;
(g) verification of specified lead dimensions in baffles or in barriers.

8.3 Radiation Scanning and Measurement

Radiation scanning is a screening procedure involving qualitative measurements to determine the location of radiation fields which may require further quantitative measurement for protection evaluation. Particular attention *should* be paid to the detection and location of defects in the shielding construction.

For radiation scanning of a protective barrier a Geiger-Mueller, scintillation or other sensitive rate meter with a fast response *should* be used. The use of an audible indicator with the meter will save considerable time during the scan. Where scanning indicates that a quantitative measurement is required a calibrated ion chamber or other instrument having small energy dependence *should* be used to determine the exposure rate in the areas being surveyed. The survey results at the point of interest *should* be expressed as milliroentgens per 100 milliampere-seconds for radiographic installations and as milliroentgens per hour for therapeutic and fluoroscopic installations.

Radiation measurement involves a quantitative determination of radiation levels; it *shall* be performed when scanning reveals radiation fields of significant levels. Such quantitative measurements *shall* be made with properly calibrated radiation measuring devices.

In the choice of instruments used for the measurement the following factors *should* be considered: (a) calibration and stability, (b) sensitivity, (c) energy dependence, (d) rate dependence, (e) size of sensitive volume, (f) time constant, and (g) directional dependence.

For the determination of the adequacy of protective barriers, measurements *shall* be made with those beam orientations and field sizes used in patient treatment and diagnosis which result in the greatest exposure at the point of measurement[25].

For the determination of the adequacy of primary protective barriers, measurements *shall* be made without a phantom, using the maximum field size.

[25] It is reasonable to assume that persons will not remain within 30 cm (12 inches) of the barrier.

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.

APPENDIX A

Definitions

The following definitions apply to certain terms used in this report. For more rigorous definitions of some of these terms, see ICRU Report 19 [12].

absorbed dose: The mean energy imparted to matter by ionizing radiation per unit mass of matter. The special unit of absorbed dose is the rad. One rad equals 10^{-2} joule per kilogram (100 ergs per gram).

activity: The number of spontaneous nuclear transformations (a change of nuclide or an isomeric transition) occurring in a given quantity of material per unit time. See curie.

attenuation: The reduction of exposure rate upon passage of radiation through matter. This report is concerned with broad beam attenuation, i.e., that occurring when the field area is large at the barrier and the point of measurement is near the exit surface.

barrier: See protective barrier.

brachytherapy: A method of radiation therapy in which an encapsulated source is utilized to deliver gamma or beta radiation at a distance up to a few centimeters either by surface, intracavitary or interstitial application.

collimator zone: The portion of the source housing of a gamma-ray beam apparatus which includes the beam defining mechanism.

concrete equivalence: The thickness of concrete of density 2.35 g cm^{-3} (147 lb ft^{-3}) affording the same attenuation, under specified conditions, as the material in question.

constant potential: Unidirectional potential (or voltage) which has little, or no, periodic variation.

controlled area: A defined area in which the exposure of persons to radiation is under the supervision of a Radiation Protection Supervisor. (This implies that a controlled area is one that requires control of access, occupancy and working conditions for radiation protection purposes.)

curie (Ci): The special unit of activity equal to a nuclear transformation rate of 3.7×10^{10} per second (exactly).

diagnostic-type protective tube housing: An x-ray tube housing so constructed that the leakage radiation measured at a distance of 1 meter from the source cannot exceed 100 mR in 1 hour when the tube is operated at its maximum continuous rated current for the maximum rated tube potential.

dose equivalent (*H*): A quantity used for radiation protection purposes that expresses on a common scale for all radiations the irradiation incurred by exposed persons. It is defined as the product of the absorbed dose in rads and certain modifying factors. The special unit of dose equivalent is the rem. (For radiation protection 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 work, habitation or recreation and in which an ionizing radiation field exists because of radiation sources in the vicinity.

owner: A person, organization, or institution having title to or administrative control over one or more installations or sources of radiation.

phantom: As used in this report, for radiation protection purposes, a volume of tissue-equivalent material used to simulate the absorption and scattering characteristics of the patient's body or of a portion thereof.

primary beam: See radiation: useful beam.

primary protective barrier: See protective barrier.

protective barrier: A barrier of radiation attenuating material(s) used to reduce radiation exposure.

primary protective barrier: Barrier sufficient to attenuate the useful beam to the required degree.

secondary protective barrier: Barrier sufficient to attenuate the stray radiation to the required degree.

protective source housing: An enclosure, for a gamma-beam therapy source, so constructed that the leakage radiation does not exceed specified limits with the source in the "OFF" and in the "ON" conditions.

(a) Beam "OFF" condition. The housing *shall* be so constructed that at one meter from the source, the maximum and average exposure rates do not exceed 10 mR h^{-1} and 2 mR h^{-1}, respectively, when the beam control mechanism is in the "OFF" position.

(b) Beam "ON" condition. The leakage radiation measured at one meter from the source *shall not* exceed 0.1 percent of the useful beam exposure rate at that distance when the beam control mechanism is in the "ON" position, except for the portion of the housing which includes the collimator zone. This limit, however, does not apply to source housings when the leakage radiation at one meter is less than 1 R h^{-1}, nor does it apply to apparatus used exclusively for whole-body irradiation.

qualified expert: With reference to *radiation protection,* a person having the knowledge and training to advise regarding radiation protection needs, to measure ionizing radiation, and to evaluate safety techniques (for example, persons having relevant certification from the American Board of Radiology or American Board of Health Physics, or those having equivalent qualifications). With reference to *shielding design,* a person having particular knowledge and training in the field of medical x-ray and gamma-ray shielding.

rad: A special unit of absorbed dose equal to 10^{-2} J kg^{-1} (100 ergs g^{-1}).

radiation (ionizing): Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, by interaction with matter. In this report "radiation" refers to x rays and gamma rays.

leakage radiation: All radiation coming from within the source or tube housing except the useful beam. (Note: Leakage radiation includes the portion of the direct radiation not absorbed by the protective source or tube housing as well as the scattered radiation produced within the housing.)

scattered radiation: Radiation that, during passage through matter, has been deviated in direction. (It may have been modified also by a decrease in energy.)

stray radiation: The sum of leakage and scattered radiation.

useful beam: Radiation which passes through the window, aperture, cone or other collimating device of the source housing. Sometimes called "primary beam."

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.

(c) In either case, small areas of reduced protection are acceptable provided the average reading over any 100 cm^2 area at one meter distance from the source does not exceed the values given above.

use factor (beam direction factor) (U): Fraction of the time during which the radiation under consideration is directed at a particular barrier.

useful beam: See radiation.

user: Any individual who personally utilizes or manipulates a source of radiation.

workload *(W)*: The degree of use of an x-ray or gamma-ray source. For x-ray equipment operating below 4 MV, the weekly workload is usually expressed in milliampere minutes. For gamma-ray beam therapy sources, and for x-ray equipment operating at 4 MV or above, the workload is usually stated in terms of the weekly exposure of the useful beam at one meter from the source and is expressed in roentgens (Rm^2).

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.

TABLE B-1—*Quantities used*[a] *in calculations of barrier thickness*

Quantity[b]	Symbol	Units
Weekly design exposure rate[c]	P	R
Weekly workload:		
X-ray equipment with current meter	W	mA min[d]
Megavoltage and gamma sources	W	R at 1 m[e]
Use factor	U	–
Occupancy factor	T	–
Distance from radiation source:		
To person to be protected	d_{pri}, d_{sec}	m
To scatterer	d_{sca}	m
Field area	F	cm^2
Normalized output	$\dot{X}_n$	R per mA min at 1 m
Exposure rate at 1 meter from the source of the:		
Useful beam	$\dot{X}_u$	R per min
Leakage radiation	$\dot{X}_L$	R per min
Exposure rate at 1 meter from the scatter for:		
Scattered radiation	$\dot{X}_s$	R per min at 1 m
Quotient of exposure at unit distance and workload	K_{ux}	R per mA min at 1 m
Transmission factor for:		
Useful beam:		
x rays	B_{ux}	–
gamma rays	B_{ug}	–
Leakage radiation:		
x rays	B_{Lx}	–
gamma rays	B_{Lg}	–
Scattered radiation:		
x rays	B_{sx}	–
gamma rays	B_{sg}	–
Leakage of source housing	L	R per h at 1 m
Exposure	X_u, X_L, X_s	R
Tube current	I	mA
Weekly beam ON-time	t	min
Barrier thickness:		
Primary	S_p	mm (lead) cm (concrete)
Secondary	S_s	mm (lead) cm (concrete)
Half value layer	HVL	mm or cm
Tenth value layer	TVL	mm or cm

[a] It is assumed that the acceleration potential is known for x-ray sources and that the energy is known for gamma-ray sources.

[b] See definitions in Appendix A.

[c] As this report deals with x and gamma radiation only, the number of roentgens may be considered equal to the number of rems (see Table 1 in Appendix C).

[d] This unit is used for x rays produced by potentials below 4 MV, and for higher potentials when the equipment has a target-current meter.

[e] This unit is used for all gamma-ray sources and for x rays produced by potentials of 4 to 10 MV, when the equipment does not have a target-current meter.

where t is the number of minutes of beam ON-time in a week. (See Table B-1 for a tabulation of the quantities and units used in calculation of barrier thickness.) If X_u is greater than the permissible weekly exposure, P, a primary barrier of sufficient thickness, S_p, to give a transmission factor of B_{ux} (for x rays), must be inserted into the beam between the source and the point of interest (see Figure B-1). Then,

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

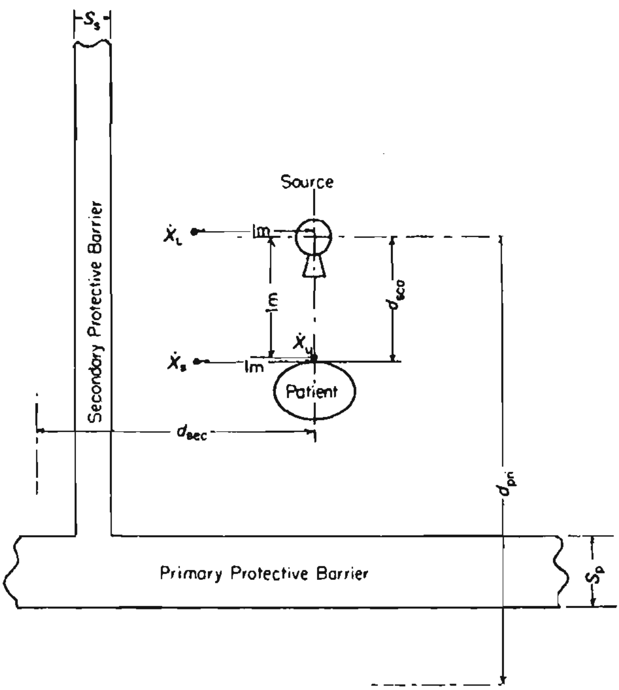

Fig. B-1. Geometry used in deriving equations for computing thickness of primary protective behavior, S_p, and of secondary protective barrier, S_s.

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 might be irradiated for only a fraction, U, of the total beam ON-time and that the anticipated occupancy of the point of interest may be a fraction, T, of the time which the beam is ON and the barrier protecting the point of interest is irradiated, the value of W in the denominator of equation 3b must be modified by multiplying it by the product, UT. That is,

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

from which the value of K_{ux} is computed, so that the barrier thickness, S_p, can be obtained from the appropriate curve on Figures 1–5 (Appendix D).

For gamma-ray beam equipment and for x-ray equipment which does not have a current meter, the workload, W, is expressed as roentgens in a week at one meter, and

$$B_{ug} \text{ or } B_{ux} = \frac{P(d_{pri})^2}{WUT} \tag{4}$$

where B_{ug} is the transmission factor for the useful gamma-ray beam and B_{ux} is the transmission factor for the useful x-ray beam. The curves showing the relation between B_{ug} or B_{ux} and the required barrier thickness, S_p, are to be found in Figures 6 through 8 and 11 through 13 (Appendix D).

Example:

Determine the thickness of primary protective barrier necessary to protect a controlled area 2.1 m (7 feet) from the target of a 250 kV x-ray therapy machine, having a weekly workload of 20,000 mA min. The wall in question has a use factor of 1/4 assigned to it, and the occupancy factor of the area to be protected is unity. Then

$$\begin{aligned} P &= 0.1\ \text{R} \\ d_{pri} &= 2.1\ \text{m} \\ W &= 20{,}000\ \text{mA min} \\ U &= 1/4 \\ T &= 1 \end{aligned}$$

Substituting in Equation (3c):

$$K_{ux} = \frac{(0.1)\,(2.1)^2}{(20{,}000)\,(1/4)(1)} = 0.000088$$

The 250 kV curves of Figures 2 and 3 (Appendix D) show that the required barrier thickness for K_{ux} is 7.9 mm of lead or 37 cm (14.7 inches) of concrete. The same values are given in Table 12 (Appendix C).

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

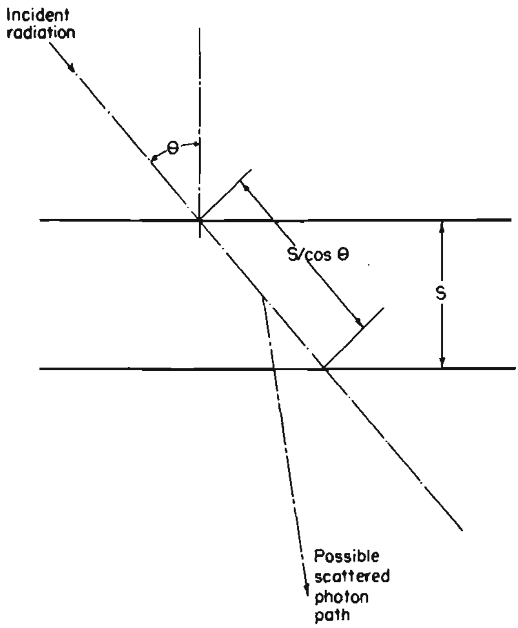

Fig. B-2 Relation between the path length, S/cos θ, of radiation incident on a barrier with an angle of obliquity, θ, and the thickness of the barrier, S.

increase is only about 1 HVL at 60 degrees. The above approximate determinations are for radiation incident at a single angle. If the beam is very divergent, one should not use the angle of obliquity for the central ray because some of the radiation will have a somewhat smaller angle of obliquity. Use of the minimum angle of obliquity will provide more attenuation than is required. Thus, judgment must be used in selecting the proper angle for divergent beams.

B.2 Computation of Secondary Protective Barriers

Secondary protective barriers shield against both leakage and scattered radiation. As these two types of radiation are of different qualities, it is necessary to compute the barrier thickness requirements for each separately.

B.2.1 *Barrier Against Leakage Radiation*

The protective source housing and the therapeutic-type protective tube housing for x-ray therapy equipment operating at 500 kV or above, have in their design a limitation on the amount of leakage radiation (0.1 percent of the useful beam exposure rate, $\dot{X}_u$, at one meter from the source). Thus, the weekly leakage exposure, X_L, at the point of interest, which is at a distance d_{sec} from the source of radiation (see Figure B-1), would be

$$X_L = \frac{0.001\ \dot{X}_u t}{(d_{sec})^2} \tag{5a}$$

where t is the number of minutes of beam ON-time in a week.

Since $(\dot{X}_u)$ (t) is equal to W, in R in a week at one meter (see Section B.1),

$$X_L = \frac{0.001\ WUT}{(d_{sec})^2} \tag{5b}$$

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

$$P = (B_{Lx})(X_L) = \frac{B_{Lx}\ (0.001\ WUT)}{(d_{sec})^2} \tag{5c}$$

Since U is equal to unity for leakage radiation,

$$\mathrm{B}_{L\mathrm{x}} \text{ (or } \mathrm{B}_{L\mathrm{g}}) = \frac{1000\, P(d_{\mathrm{sec}})^2}{WT} \qquad \left[\begin{array}{l}\text{For therapy equipment above}\\ \text{0.5 MV without target}\\ \text{current meter}\end{array}\right] \tag{5d}$$

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 $\dot{X}_{\mathrm{u}} = \dot{X}_{\mathrm{n}} I$, from equation 5a

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

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

$$X_L = \frac{0.001\, \dot{X}_{\mathrm{n}} W\mathrm{T}}{(d_{\mathrm{sec}})^2} \tag{5f}$$

A barrier having a transmission factor $\mathrm{B}_{L\mathrm{x}}$ is required to reduce the weekly exposure to P. Thus

$$P = \mathrm{B}_{L\mathrm{x}} X_L = \mathrm{B}_{L\mathrm{x}} \frac{0.001\, \dot{X}_{\mathrm{n}} W\mathrm{T}}{(d_{\mathrm{sec}})^2} \tag{5g}$$

Rearranging and solving for the transmission factor

$$\mathrm{B}_{L\mathrm{x}} = \frac{1000\, P(d_{\mathrm{sec}})^2}{\dot{X}_{\mathrm{n}} W\mathrm{T}} \qquad \left[\begin{array}{l}\text{For therapy equipment above}\\ \text{0.5 MV with a target}\\ \text{current meter}\end{array}\right] \tag{5h}$$

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

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

Since $W = It$,

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

and it follows that

$$\frac{P}{\mathrm{T}} = (\mathrm{B}_{L\mathrm{x}})(X_{L\mathrm{x}}) = \frac{(\mathrm{B}_{L\mathrm{x}})}{(d_{\mathrm{sec}})^2} \frac{W}{60I} \tag{5k}$$

Rearranging equation 5k and solving for B_{Lx},

$$B_{Lx} = \frac{P(d_{sec})^2 60I}{WT} \quad \text{[Therapy below 0.5 MV]} \tag{5l}$$

For a diagnostic-type protective tube housing, where L equals 0.1 roentgen in an hour at 1 m from the source

$$B_{Lx} = \frac{P(d_{sec})^2 (600I)}{WT} \quad \text{[Diagnostic]} \tag{5m}$$

The thickness of barrier, S_L, to protect from leakage radiation at the point of interest can be computed as follows using the value of B_{Lx} or B_{Lg} together with Figure B-3 and the table of half-value layers and tenth-value layers (Table 27, Appendix C).[27] The value of B_{Lx} or B_{Lg} is entered as the ordinate of Figure B-3; the value of N or n is read on the appropriate abscissa. The leakage barrier thickness, S_L, is computed by

$$S_L = \mathrm{N}\,(HVL) \text{ or } \mathrm{n}\,(TVL) \tag{5n}$$

where numerical values of *HVL* or *TVL* are obtained from Table 27 (Appendix C) for the appropriate energy.

Example:

Determine the thickness of leakage protective barrier necessary to protect a controlled area 2.1 meters (7 feet) from the target of 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 x-ray machine has a continuous tube current rating at 250 kV of 20 mA. Then

$$\begin{aligned} P &= 0.1 \text{ R} \\ d_{sec} &= 2.1 \text{ m} \\ W &= 20{,}000 \text{ mA min} \\ \mathrm{T} &= 1 \\ I &= 20 \text{ mA} \end{aligned}$$

Substituting in Equation (5l):

$$B_{Lx} = \frac{(0.1)\ (2.1)^2\ (60)\ (20)}{(20{,}000)\ (1)} = 0.0265$$

From Figure B-3 a transmission of 0.0265 corresponds to 5.2 *HVL*'s. From Table 27 of Appendix C, the *HVL* for 250 kV is 0.88 mm lead and 2.8 cm con-

[27] This procedure is valid at energies where significant buildup in the shielding material does not occur. At energies where buildup is significant, i.e., the broad beam half-value layer is greater at low attenuation than at high attenuation, shielding against leakage radiation *should* be determined using the appropriate transmission curve from Appendix D.

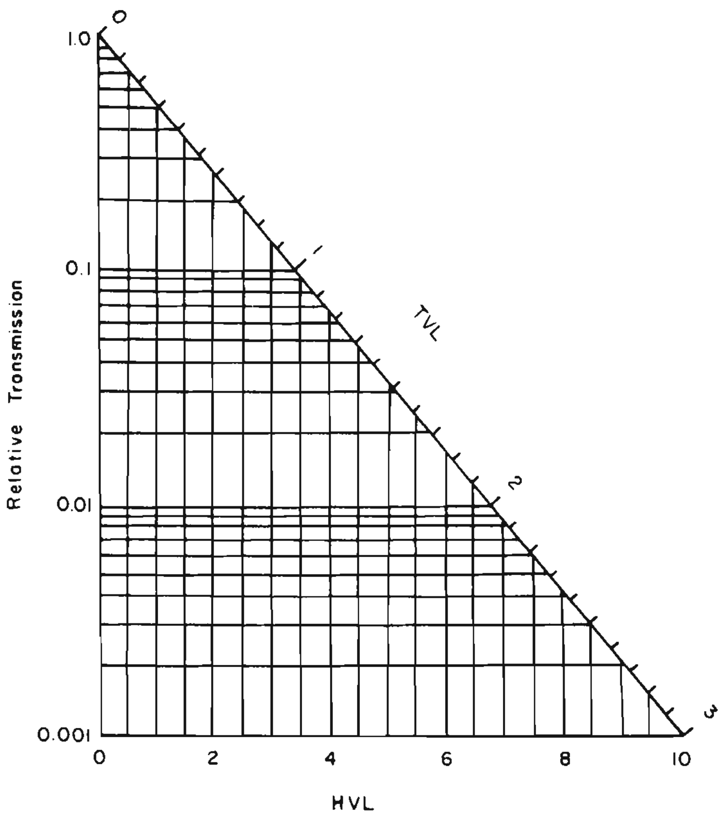

Fig. B-3. Relation between the transmission, B_{Lx} or B_{Lg}, and the number of half-value layers, N, or tenth-value layers, n.

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 is of lower energy. The ratio, a, of the scattered to incident exposure is a function of energy and scattering angle. The numerical values given in Table B-2 are for a field area, F, of 400 cm^2 at the phantom surface. Since the exposure rate $\dot{X}_s$, of scattered radiation, measured at one meter from a scatterer 1 m from the source is proportional to F:

$$\dot{X}_s = a \cdot \dot{X}_u \frac{F}{400} \tag{6a}$$

The exposure from the scatterer, X_s, at the point of interest, which is at a distance of d_{sec} from the scatterer, is related to the scatter exposure rate at one meter, $\dot{X}_s$, by the following equation

$$X_s = \frac{\dot{X}_s t}{(d_{sec})^2} \tag{6b}$$

Substituting for $\dot{X}_s$:

$$X_s = \frac{a\dot{X}_u}{(d_{sec})^2} \frac{Ft}{400} \tag{6c}$$

In the event that the scatterer is located at a distance (d_{sca}) from the source, equation 6c must be modified in terms of the inverse square of this source-skin distance.

$$X_s = \frac{a\dot{X}_u}{(d_{sec})^2} \cdot \frac{1}{(d_{sca})^2} \cdot \frac{Ft}{400} \tag{6d}$$

Proceeding as in the derivation of Equation 3:

$$P = B_{sx} \cdot X_s = B_{sx} \cdot \frac{\dot{X}_n It}{(d_{sca})^2} \cdot \frac{a}{(d_{sec})^2} \cdot \frac{F}{400}$$

It = WT, since U = 1 for scattered radiation; solving for $(B_{sx} \cdot \dot{X}_n)$, the secondary protective barrier transmission factor:

$$B_{sx} \cdot \dot{X}_n = \frac{P}{aWT} \cdot (d_{sca})^2 \cdot (d_{sec})^2 \cdot \frac{400}{F} \tag{6e}$$

For x rays generated at voltages of 500 kV and below it is usually assumed that the barrier penetrating capability of scattered photons is the same as that of the useful beam. The value of $B_{sx} \cdot \dot{X}_n$ can then be set equal to K_{ux}.

$$K_{ux} = \frac{P}{aWT} (d_{sca})^2 \cdot (d_{sec})^2 \cdot \frac{400}{F} \tag{6f}$$

Thus, the barrier thickness required to reduce the exposure to P is the

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)

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

$$T = 1$$
$$F = 400 \text{ cm}^2$$

Substituting in Equation 6f

$$K_{ux} = \frac{(0.1)\,(0.5)^2\,(2.1)\,(400)}{(0.0019)\,(20{,}000)\,(1)\,(400)} = 0.0029$$

The 250 kV curves in Figures 2 and 3 (Appendix D) show that the required barrier thickness for K_{ux} is 3.8 mm of lead or 23.5 cm of concrete.

For installations using x rays of 500 kV or less, the exposure from leakage radiation is of about the same magnitude as that from scattered radiation. However, the leakage radiation is more penetrating than the scattered radiation, so a greater barrier thickness may be required for leakage radiation than for scattered radiation and therefore be the determining factor for the secondary protective barrier.

For x-ray beams of 1 to 3 MV the scattered radiation is less penetrating than is the useful beam. For 90° scattered radiation the value of the ratio of scatter to incident exposure, a, is about 1×10^{-3} and the transmission of the scattered radiation through the barrier is about the same as for a 500 kV *useful* beam. However, because of the much higher output with increasing operating voltage, the value of $\dot{X}_n$ for voltages higher than 500 kV is larger than the value for 500 kV x rays, $(\dot{X}_n)_{0.5}$. Consequently, in order to use Equation 6f for scattered radiation from these higher voltage x-ray beams, the value of $(\dot{X}_n)_{0.5}$, and hence the value of K_{ux} must be normalized by multiplying the right hand side of Equation 6f by the factor appropriate for the higher operating voltage. The factors for 1 MV, 2 MV, and 3 MV are, respectively, 1/20, 1/300, and 1/700.

The barriers required for scattered radiation from *4 to 10 MV x-ray beams* may be calculated using Equation 6e, Table B-2 and the attenuation curves of Figures 9 and 10 (Appendix D). However, the barrier requirements for the leakage radiation (Equation 5d) will generally be greater, and therefore be the determining factor for the secondary protective barriers.

The transmission factor, B_{sg}, needed to calculate the thickness of secondary protective barriers for scattered radiation from ^{137}Cs and ^{60}Co gamma-ray beams is given by

$$B_{sg} = \frac{P}{aWT} \cdot (d_{sec})^2 \cdot (d_{sca})^2 \cdot \frac{400}{F} \qquad (6g)$$

The values for the ratio, a, in this equation can be obtained from

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 cm².

[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.

For the conditions assumed in those examples, the protective barriers required for leakage and scattered radiations were:

Barrier against leakage radiation: 4.57 mm of lead or 14.6 cm of concrete.

Barrier against scattered radiation: 3.8 mm of lead or 23.5 cm of concrete.

From Table 27 (Appendix C) the *TVL* for 250 kV is 2.9 mm of lead and 9.4 cm of concrete. Since the computed protective barrier requirements for leakage and scattered radiations differ by less than one *TVL*, one *HVL* should be added to the larger. From Table 27 (Appendix C), the *HVL*'s are 0.88 mm of lead and 2.8 cm of concrete resulting in a secondary protective barrier of 5.45 mm of lead or 26.3 cm of concrete. These same values, rounded off as described in Section 2, "Barrier Thickness Requirements", of this report, are given in Table 12 (Appendix C).

B.2.4 *Computation of Secondary Barrier Requirements for Typical Radiation Installations, Tables 5 through 24 (Appendix C)*

The shielding requirements for secondary barriers for typical radiation installations given in Tables 5 through 24 of Appendix C were ıputed using typical assumptions for the factors. The assumptions ed in these computations include those shown in Table B-3.

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 2—*Typical weekly workloads for busy installations*

Diagnostic	Daily Patient Load	Weekly workload (*W*) mA min		
		100 kV[a] or less	125 kV[a]	150 kV[a]
Admission Chest:				
(Miniature, with photo-timing grid)	100	100	–	–
Chest:				
(14 × 17: 3 films per patient, no grid)	60	150	–	–
Cystoscopy	8	600	–	–
Fluoroscopy including spot filming	24	1,500	600	300
Fluoroscopy without spot filming	24	1,000	400	200
Fluoroscopy with image intensification including spot filming	24	750	300	150
General Radiography	24	1,000	400	200
Special Procedures	8	700	280	140
Therapy		**Weekly workload (*W*)**		
Superficial (up to 150 kV[a])	32	3,000 mA min		
Orthovoltage (200–500 kV[a])	32	20,000 mA min		
Megavoltage (0.5 MV–10 MV)	50	100,000 R at a meter[b]		
Cesium				
50 cm *SSD*	16	8,000 R at a meter[b]		
50 cm *SSD*	32	15,000 R at a meter[b]		
60 cm *SSD*	32	24,000 R at a meter[b]		
Cobalt				
70 cm *SSD*	32	30,000 R at a meter[b]		
80 cm *SSD*	32	40,000 R at a meter[b]		
100 cm *SSD*	32	60,000 R at a meter[b]		

[a] Peak pulsating x-ray tube potential.
[b] R per week at a meter = R m^2 per week.

TABLE 3—*Use factors for primary protective barriers*[a]

[To be used only if specific values for a given installation are not available.]

	Radiographic Installations	Therapy Installations
Floor	1	1
Walls	1/4	1/4
Ceiling	—[b]	—[c]

[a] The use factor for secondary protective barriers is usually 1.

[b] The shielding requirements for the ceiling of a radiographic installation are determined by the secondary barrier requirements rather than by the use factor which is generally extremely low.

[c] The use factor for the ceiling of a therapy installation depends on the type of equipment and techniques used, but usually is not more than 1/4.

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 5—*Minimum shielding requirements for radiographic installations*

WUT[a] in mA min			Distance in meters from source to occupied area										
100 kV[b]	125 kV[b]	150 kV[b]											
1,000	400	200	1.5	2.1	3.0	4.2	6.1	8.4	12.2				
500	200	100		1.5	2.1	3.0	4.2	6.1	8.4	12.2			
250	100	50			1.5	2.1	3.0	4.2	6.1	8.4	12.2		
125	50	25				1.5	2.1	3.0	4.2	6.1	8.4	12.2	
62.5	25	12.5					1.5	2.1	3.0	4.2	6.1	8.4	12.2
Type of Area	Material		Primary protective barrier thickness[e]										
Controlled	Lead, mm[c]		1.95	1.65	1.4	1.15	0.9	0.65	0.45	0.3	0.2	0.1	0.1
Noncontrolled	Lead, mm[c]		2.9	2.6	2.3	2.05	1.75	1.5	1.2	0.95	0.75	0.55	0.35
Controlled	Concrete, cm[d]		18	15.5	13.5	11.5	9.5	7	5.5	4	2.5	1.5	0.5
Noncontrolled	Concrete, cm[d]		25	23	20.5	18.5	16.5	14	12	10	8		
			Secondary protective barrier thickness[e]										
Controlled	Lead, mm[c]		0.55	0.45	0.35	0.3	0	0	0	0	0	0	0
Noncontrolled	Lead, mm[c]		1.3	1.05	0.75	0.55	0.45	0.35	0.3	0.05	0	0	0
Controlled	Concrete, cm[d]		5	3.5	2.5	2	0	0	0	0	0	0	0
Noncontrolled	Concrete, cm[d]		11.5	9.5	7.5	5.5	4	3	2	0.5	0	0	0

[a] *W*—weekly workload in mA min, U—use factor, T—occupancy factor.
[b] Peak pulsating x-ray tube potential.
[c] See Table 26 for conversion of thickness in millimeters to inches or to surface density.
[d] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).
[e] Barrier thickness based on 150 kV.

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 7—*Minimum shielding requirements for fluoroscopic installations*

WT[a] in mA min			Distance in meters from source to occupied area											
100 kV[b]	125 kV[b]	150 kV[b]												
2,000	800	400	1.5	2.1	3.0	4.2	6.1	8.4	12.2					
1,000	400	200		1.5	2.1	3.0	4.2	6.1	8.4	12.2				
500	200	100			1.5	2.1	3.0	4.2	6.1	8.4	12.2			
250	100	50				1.5	2.1	3.0	4.2	6.1	8.4	12.2		
125	50	25					1.5	2.1	3.0	4.2	6.1	8.4	12.2	
62.5	25	12.5						1.5	2.1	3.0	4.2	6.1	8.4	12.2
Type of Area	Material		Secondary protective barrier thickness											
Controlled	Lead, mm[c]		0.75	0.6	0.45	0.35	0.3	0.05	0	0	0	0	0	0
Noncontrolled	Lead, mm[c]		1.6	1.3	1.05	0.75	0.6	0.45	0.4	0.35	0.05	0	0	0
Controlled	Concrete, cm[d]		7.5	5.5	4	3	2.5	0.5	0	0	0	0	0	0
Noncontrolled	Concrete, cm[d]		14	12	10	8	6	4.5	3.5	2.5	0.5	0	0	0

[a] W—weekly workload in mA min, T—occupancy factor.
[b] Peak pulsating x-ray tube potential.
[c] See Table 26 for conversion of thickness in millimeters to inches or surface density.
[d] Thickness based on concrete density of 2.35 g cm^{-3} (147 lb ft^{-3}).

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 9—*Minimum shielding requirements for 100 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	6.0	8.4	12					
2,000			1.5	2.1	3.0	4.2	6.0	8.4	12				
1,000				1.5	2.1	3.0	4.2	6.0	8.4	12			
500					1.5	2.1	3.0	4.2	6.0	8.4	12		
250						1.5	2.1	3.0	4.2	6.0	8.4	12	
125							1.5	2.1	3.0	4.2	6.0	8.4	12
62.5								1.5	2.1	3.0	4.2	6.0	8.4
31.3									1.5	2.1	3.0	4.2	6.0
Type of Area	Material	Primary protective barrier thickness[c]											
Controlled	Lead, mm[d]	2.4	2.15	1.85	1.6	1.35	1.1	0.85	0.65	0.45	0.3	0.2	0.1
Noncontrolled	Lead, mm[d]	3.35	3.05	2.75	2.5	2.2	1.95	1.7	1.4	1.2	0.95	0.7	0.5
Controlled	Concrete, cm[e]	18	16	14.5	13	11.5	10	8.5	7	5.5	4	2.5	1.5
Noncontrolled	Concrete, cm[e]	24	22	20.5	18.5	17	15	13.5	12	10.5	9	7.5	6
		Secondary protective barrier thickness[c]											
Controlled	Lead, mm[d]	1.9	1.6	1.3	1.05	0.75	0.5	0.25	0.25	0	0	0	0
Noncontrolled	Lead, mm[d]	2.45	2.2	1.95	1.65	1.4	1.1	1.1	0.85	0.5	0.3	0.3	0.3
Controlled	Concrete, cm[e]	11.5	10	8	6.5	5	3	2	2	0	0	0	0
Noncontrolled	Concrete, cm[e]	17	15	13.5	12	10.5	8.5	7	5.5	3.5	2	2	2

[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 11—*Minimum shielding requirements for 200 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]	6.6	6.1	5.5	5.0	4.5	4.0	3.6	3.1	2.7	2.3	1.9	1.6
Noncontrolled	Lead, mm[d]	8.4	7.6	7.2	6.8	6.2	5.8	5.2	4.7	4.2	3.7	3.2	2.8
Controlled	Concrete, cm[e]	43.5	40.5	37.5	35	32.5	29.5	27	24.5	21.5	19.5	17	14.5
Noncontrolled	Concrete, cm[e]	52	50	46.5	44	41.5	39	36	33.5	30.5	28	25.5	23
		Secondary protective barrier thickness[c]											
Controlled	Lead, mm[d]	4.25	3.7	3.2	2.7	2.15	1.7	1.4	1.15	0.9	0.75	0.6	0.05
Noncontrolled	Lead, mm[d]	6.0	5.45	4.95	4.4	3.9	3.4	2.85	2.35	1.8	1.5	1.25	1.0
Controlled	Concrete, cm[e]	27	24.5	22	19.5	17	14	11.5	9.5	7	5	3.5	0.5
Noncontrolled	Concrete, cm[e]	35.5	33	30.5	28	25.5	23	20	17.5	15	12.5	10	8

[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 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 13—*Minimum shielding requirements for 300 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]	17.65	16.25	14.85	13.45	12.05	10.75	9.4	8.2	6.9	5.8	4.7	3.75
Noncontrolled	Lead, mm[d]	22.5	21.1	19.6	18.15	16.7	15.3	13.85	12.55	11.2	9.85	8.55	7.35
Controlled	Concrete, cm[e]	55	51.5	48.5	45	42	39	36	33.5	30	27	24	21
Noncontrolled	Concrete, cm[e]	64.5	62	59	56	53	49.5	46.5	43.5	40	37	34	31
		Secondary protective barrier thickness[c]											
Controlled	Lead, mm[d]	12.0	10.55	9.05	7.6	6.1	4.65	3.55	2.95	2.5	2.1	1.8	1.6
Noncontrolled	Lead, mm[d]	16.9	15.45	13.95	12.5	11.05	9.55	8.1	6.6	5.15	3.75	3.1	2.65
Controlled	Concrete, cm[e]	33	30	27	24	21	18	14.5	11.5	9	6	3.5	1.5
Noncontrolled	Concrete, cm[e]	43	40	37	34	31	28	25	22.5	19	15.5	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 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 15—*Minimum shielding requirements for 2 MV therapy installations*

WUT[a] in mA min		Distance in meters from source to occupied area											
350		1.5	2.1	3.0	4.2	6.1	8.4	12.2					
175			1.5	2.1	3.0	4.2	6.1	8.4	12.2				
87.5				1.5	2.1	3.0	4.2	6.1	8.4	12.2			
44					1.5	2.1	3.0	4.2	6.1	8.4	12.2		
22						1.5	2.1	3.0	4.2	6.1	8.4	12.2	
11							1.5	2.1	3.0	4.2	6.1	8.4	12.2
5.5								1.5	2.1	3.0	4.2	6.1	8.4
Type of Area	Material	Primary protective barrier thickness											
Controlled	Lead, cm[b]	22	21	19.5	18.5	17	16	15	13.5	12.5	11	10	9
Noncontrolled	Lead, cm[b]	26	25	24	22.5	21.5	30	19	18	16.5	15.5	14	13
Controlled	Concrete, cm[c]	118	111	105	98	92	86	80	74	67.5	61	57	49.5
Noncontrolled	Concrete, cm[c]	138	132	126	119	113	107	101	95	89	82.5	78	70.5
		Secondary protective barrier thickness[d]											
Controlled	Lead, cm[b]	11	10	8.5	7.5	6	6	4.5	3.5	2	1	0	0
Noncontrolled	Lead, cm[b]	15.5	14	12.5	11.5	10	10	9	7.5	6.5	5	4	2.5
Controlled	Concrete, cm[c]	63	55.5	49.5	44	37	31	24.5	18.5	12.5	6	0	0
Noncontrolled	Concrete, cm[c]	84.5	76.5	70.5	65.5	58	52	46	39.5	33.5	27	20.5	14.5

[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 350 mA min corresponding to a weekly workload (*WUT*) of 100,000 R at 1 meter ($\dot{X}_n$ = 300 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 17—*Minimum shielding requirements for 4 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]	29.2	171	162	153	144	136	127	118	109	101	92
Primary	Lead	5.3	31	29.5	28	26.5	24.5	23	21.5	19.5	18	16.5
Primary	Iron[e]	9.1	53.5	50.5	48	45	42.5	39.5	37	34	31.5	28.5
Leakage[d] 0.1 percent	Concrete[c]	29.2	83	75	66	57	48	39	31	22	13	4
Leakage[d] 0.1 percent	Lead	5.3	15	13.5	12	11.5	10	8.5	7	5.5	4	2.5

[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] Shielding for leakage radiation from tube housing.
[e] Thickness based on iron density of 7.8 g cm^{-3} (488 lb ft^{-3}).

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 19—*Minimum shielding requirements for 8 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]	223	212	200	189	177	166	154	143	131	120
Primary	Lead	33	31.5	29.5	28	26	24.5	23	21	19.5	17.5
Primary	Iron[e]	60.5	57.5	54	51	48	45	41.5	38.5	35.5	32.5
Leakage[d] 0.1 percent	Concrete[c]	108	96.5	85.5	74	62.5	51.5	39.5	28.5	16.5	5.5
Leakage[d] 0.1 percent	Lead	16	14.5	12.5	11	9.5	7.5	6	4	2.5	1
Leakage[d] 0.1 percent	Iron[e]	29.5	26.5	23	20	17	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 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 21* —*Minimum lead shielding requirements for cobalt-60 therapy installations for controlled areas*[a] *(revised as of February 1, 1977)*

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 lead	Approx. TVL cm of lead	Thickness of lead in centimeters										
Primary	1.2	4.0	23.5	22	21	20	18.5	17.5	16	15	14	12.5	11.5
Secondary Leakage[c]													
0.1 percent	1.2	4.0	11.5	10	9	8	6.5	5.5	4	3	1.5	0.5	0
0.05 percent	1.2	4.0	10	9	8	6.5	5.5	4	3	1.5	0.5	0	0
Scatter[d]													
30°	1.0	3.35	14	13	12	11	10	9	8	7	6	4.5	3.5
45°	0.87	2.9	10.5	9.5	9	8	7.5	6.5	5.5	5	4	3.5	2.5
60°	0.74	2.45	8.5	8	7	6.5	5.5	5	4.5	3.5	3	2.5	1.5
90°	0.44	1.45	5	4.5	4	3.5	3	2.5	2.5	2	1.5	1	0.5
120°	0.20	0.65	2	2	1.5	1.5	1	1	1	0.5	0.5	0.5	0.5

[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] 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.

[d] 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 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 23—*Minimum lead 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
Type of Protective Barrier	Approx *HVL* cm of Lead	Approx *TVL* cm of Lead	Thickness of lead in centimeters										
Primary	0.65	2.16	11	10	9.5	9	8.5	7.5	7	6	5.5	5	4.5
Secondary Leakage[c]													
0.1 percent	0.65	2.16	4.5	4	3	2.5	2	1	0.5	0	0	0	0
0.05 percent	0.65	2.16	4	3	2.5	2	1	0.5	0	0	0	0	0
Scatter[d]													
30°	0.55	1.8	6	5.5	5	4.5	3.5	3	2.5	2	1.5	1	0.5
45°	0.45	1.5	4.5	4	3.5	3	3	2.5	2	1.5	1	0.5	0.5
60°	0.38	1.3	3.5	3	3	2.5	2	1.5	1.5	1	0.5	0.5	0.5
90°	0.22	0.7	2	1.5	1.5	1	1	1	0.5	0.5	0.5	0.5	0.5
135°	0.13	0.4	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	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] Refers to leakage radiation of source housing when source in "ON" condition; may be ignored if less than 2.5 mR per h at 1 m.

[d] 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 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
Type of Protective Barrier	Approx. *HVL* cm of Concrete	Approx. *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 25—*Densities of commercial building materials*

Material	Range of Density[a]	Average Density[b]	
		$g\ cm^{-3}$	$lb\ ft^{-3}$
Barium sulfate (natural barite)	–	4.5	280
Barytes concrete	3.6 to 4.1	3.6	210
Brick, soft	1.4 to 1.9	1.65	103
hard	1.8 to 2.3	2.05	128
Earth, dry, packed	–	1.5	95
Ferrophosphorus aggregate concrete	6.0	4.8	300
Granite	2.6 to 2.7	2.65	165
Ilmenite aggregate concrete	4.4 to 4.7	3.85	240
Lead	–	11.36	709
Lead glass	–	3.27	205
Lead glass, high density	–	6.22	387
Limestone	2.1 to 2.8	2.46	153
Marble	2.6 to 2.86	2.7	170
Sand, dry, packed	1.6 to 1.9	–	100–120
Sand plaster	–	1.54	96
Concrete	2.25 to 2.4	2.35	147
Steel	–	7.8	489
Tile	1.6 to 2.5	1.9	118

[a] Density values for the concrete aggregates are given for the aggregate only.
[b] Density values are given for the concrete made from the specified aggregate.
Note: Concrete blocks and cinder blocks vary too much to be listed.
Reference: Mark's Mechanical Engineering Handbook, 5th ed. (McGraw-Hill, New York, 1941); excerpts from a table (pp. 522–523), Approximate Specific Gravity and Density.

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 27—*Half-value and tenth-value layers*

Approximate values obtained at high attenuation for the indicated peak voltage values under broad-beam conditions; with low attenuation these values will be significantly less.

Peak Voltage (kV)	Attenuation Material					
	Lead (mm)		Concrete (cm)		Iron (cm)	
	HVL	*TVL*	*HVL*	*TVL*	*HVL*	*TVL*
50	0.06	0.17	0.43	1.5		
70	0.17	0.52	0.84	2.8		
100	0.27	0.88	1.6	5.3		
125	0.28	0.93	2.0	6.6		
150	0.30	0.99	2.24	7.4		
200	0.52	1.7	2.5	8.4		
250	0.88	2.9	2.8	9.4		
300	1.47	4.8	3.1	10.4		
400	2.5	8.3	3.3	10.9		
500	3.6	11.9	3.6	11.7		
1,000	7.9	26	4.4	14.7		
2,000	12.5	42	6.4	21		
3,000	14.5	48.5	7.4	24.5		
4,000	16	53	8.8	29.2	2.7	9.1
6,000	16.9	56	10.4	34.5	3.0	9.9
8,000	16.9	56	11.4	37.8	3.1	10.3
10,000	16.6	55	11.9	39.6	3.2	10.5
Cesium-137	6.5	21.6	4.8	15.7	1.6	5.3
Cobalt-60	12	40	6.2	20.6	2.1	6.9
Radium	16.6	55	6.9	23.4	2.2	7.4

TABLE 28 —*Selected gamma-ray sources*

Radionuclide	Atomic Number	Half Life	Gamma Energy MeV	Half-Value Layer[a]			Tenth-Value Layer[a]			Specific Gamma-Ray Constant[b] R cm² per mCi h
				Concrete	Steel	Lead	Concrete	Steel	Lead	
				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.

TABLE 29—*Relation between distance and millicurie-hours for an exposure of 0.1 R from an unshielded source*

Millicurie-Hours	Gamma-Ray Source				
	Radium	Cobalt-60	Cesium-137	Iridium-192	Gold-198
	Distance to Source in Meters				
10	0.28	0.37	0.18	0.22	0.15
30	0.49	0.64	0.31	0.39	0.27
100	0.91	1.16	0.57	0.70	0.48
300	1.55	1.98	0.98	1.22	0.83
1,000	2.87	3.65	1.77	2.26	1.52
3,000	4.9	6.35	3.08	3.87	2.70
10,000	9.1	11.6	5.7	7.07	4.82

APPENDIX D

Figures[28]

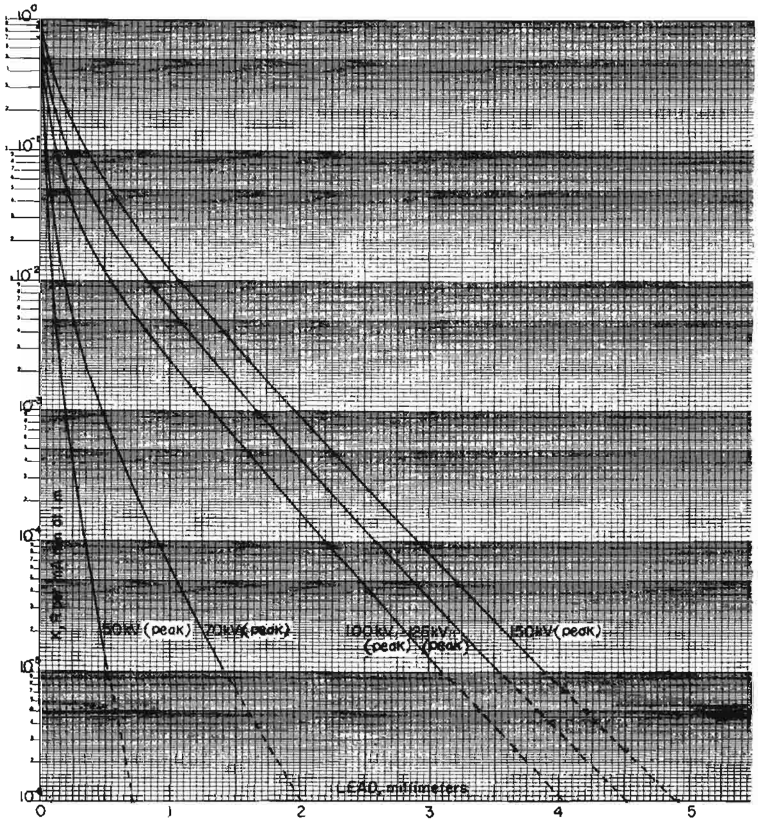

Fig. 1 Attenuation in lead of x rays produced at potentials of 50 to 150 kV peak. The measurements were made with a 90° angle between the electron beam and the axis of the x-ray beam and with pulsed waveform. The filtrations were 0.5 mm of aluminum for 50 kV, 1.5 mm of aluminum for 70 kV, and 2.5 mm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

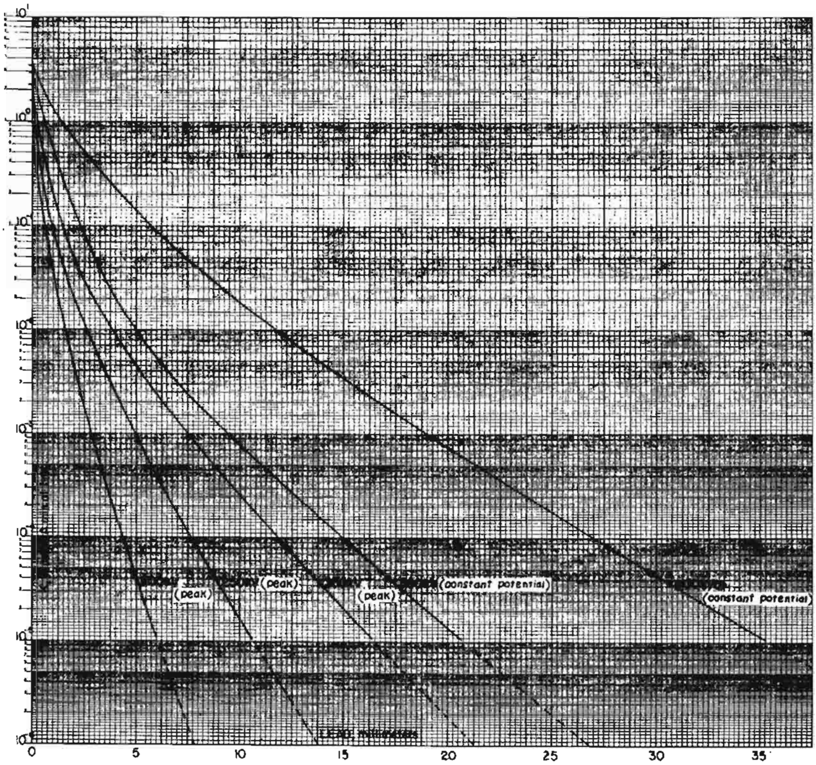

Fig. 2 Attenuation in lead of x rays produced by potentials of 200, 250 and 300 kV peak; 300 and 400 kV constant potential.

The measurements were made with a 90° angle between the electron beam and the axis of the x-ray beam. The 200, 250, and 300 kV curves are for a pulsed waveform and filtration of 3 mm of aluminum (Kelley and Trout [15]). The 300 kV and 400 kV curves were 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.]

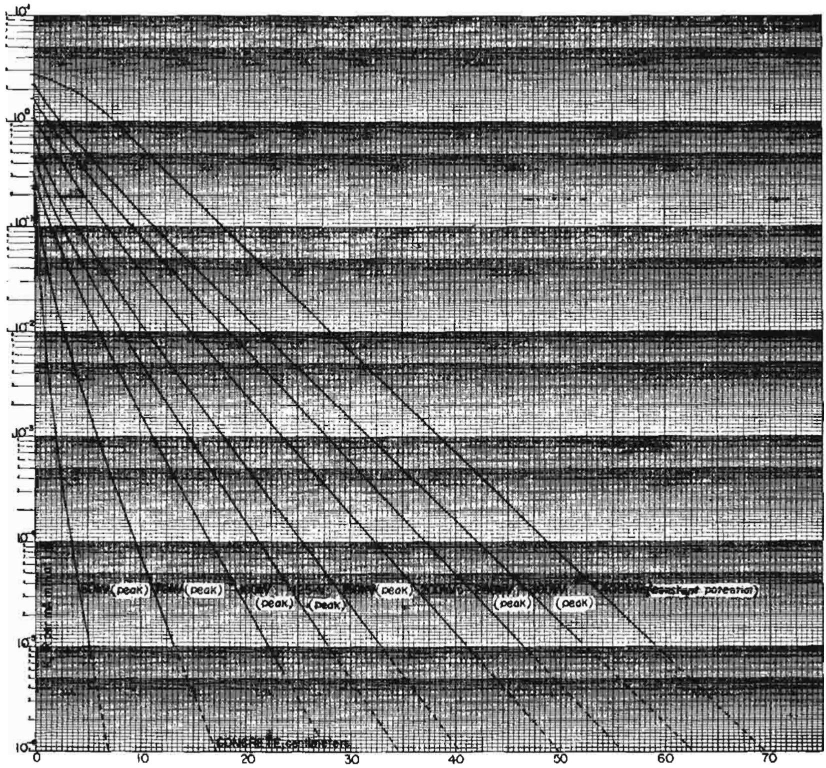

Fig. 3 Attenuation in concrete of x rays produced by potentials of 50 to 300 kV peak; 400 kV constant potential.

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.]

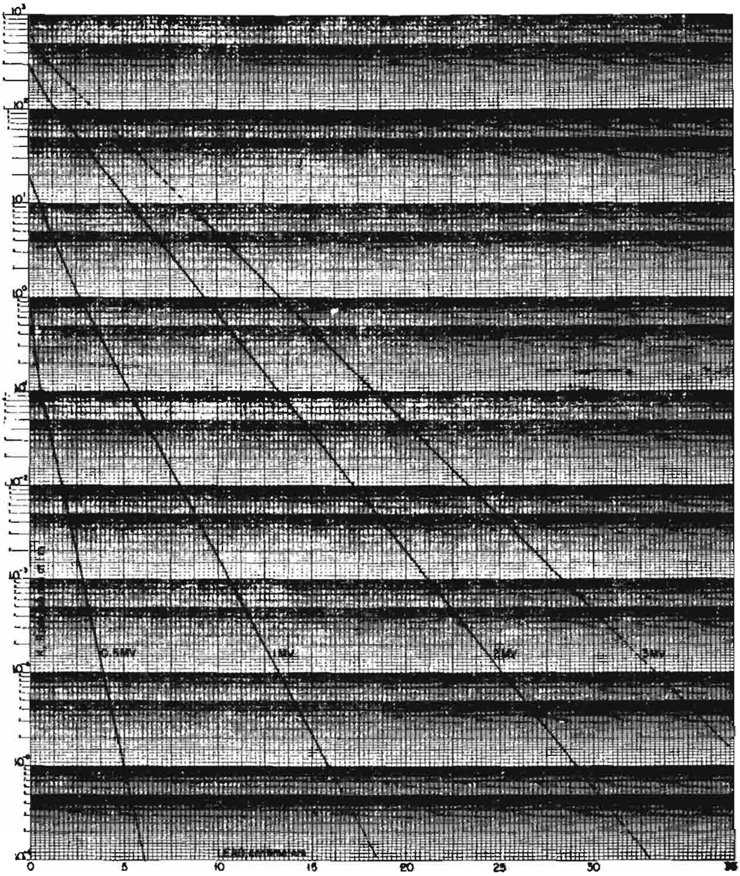

Fig. 4 Attenuation in lead of x rays produced by potentials of 0.5 to 3 MV constant potential.

The measurements were made with 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 2.88 mm of tungsten, 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) from 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 Miller and Kennedy [20].

[Data courtesy of the authors, Radiation Research, Radiology and Academic Press.]

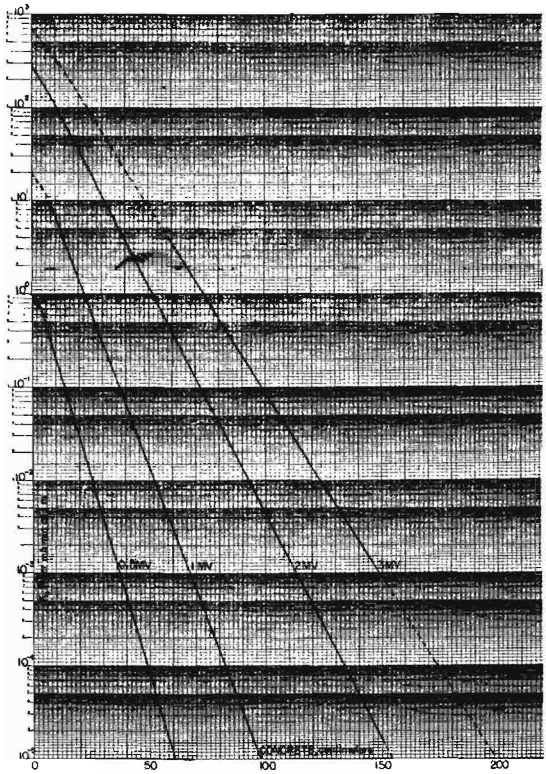

Fig. 5 Attenuation in concrete of x rays produced by potentials of 0.5 to 3 MV constant potential.

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.]

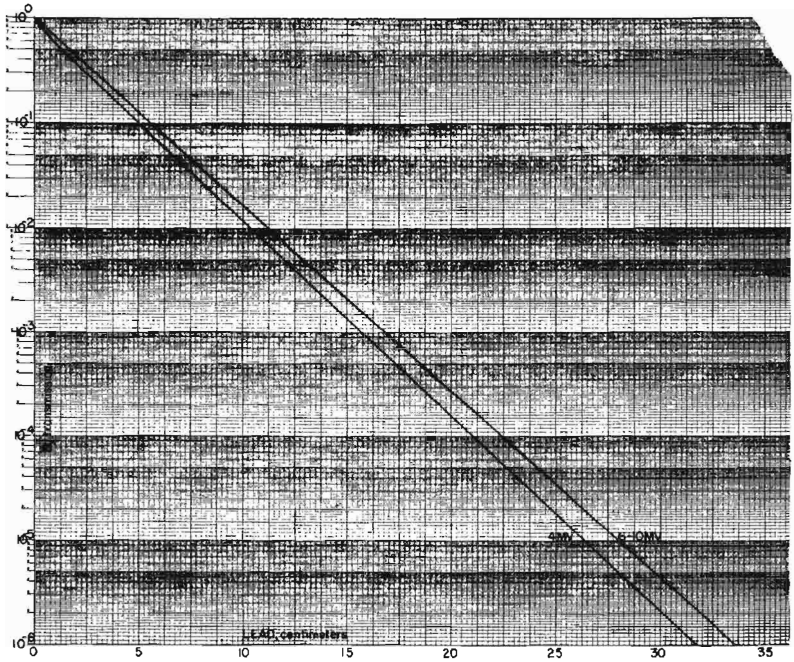

Fig. 6 Transmission through lead of x rays produced at 4 to 10 MV. Based on NCRP Report No. 51 [27].

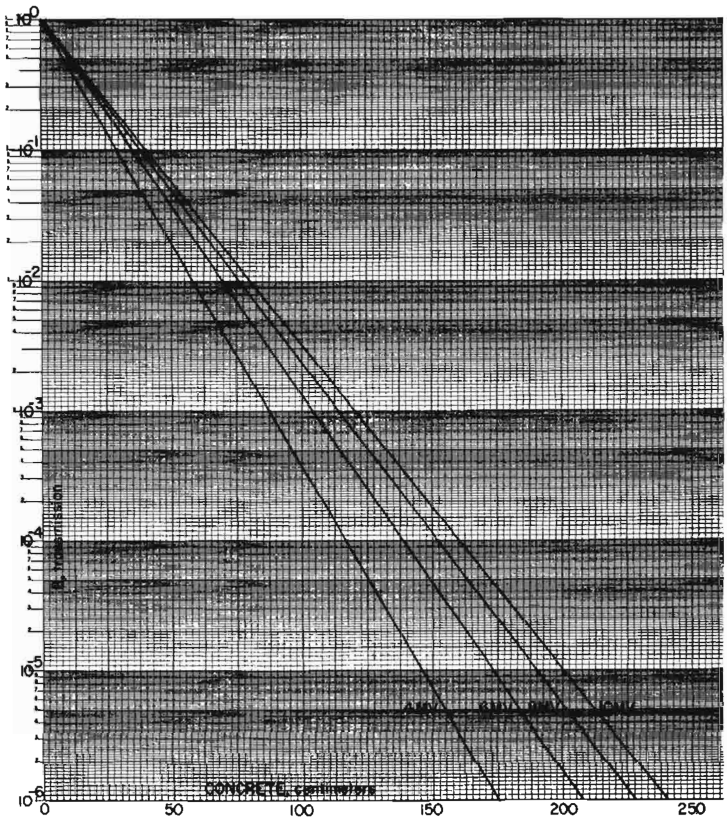

Fig. 7 Transmission through concrete, density 2.35 g cm^{-3} (147 lb ft^{-3}), of x rays produced at 4 to 10 MV. Based on NCRP Report No. 51 [27].

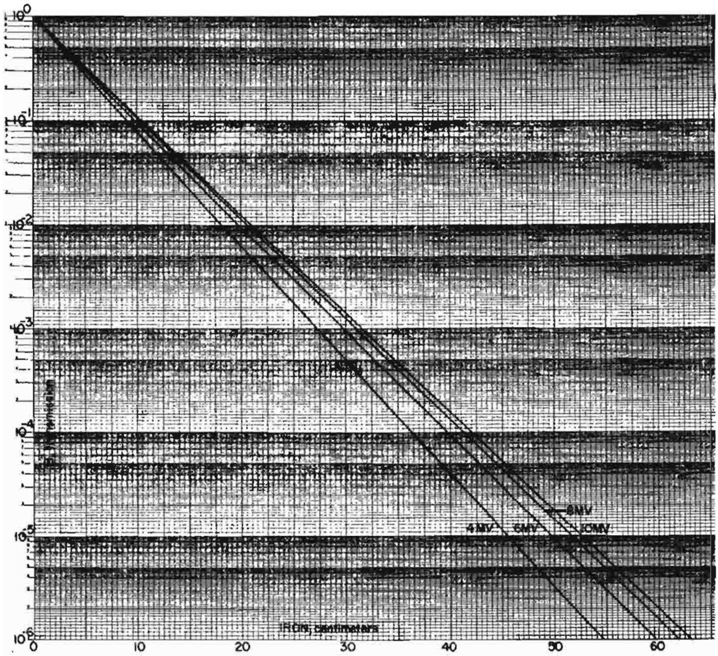

Fig. 8 Transmission through iron, density 7.8 g cm^{-3} (488 lb ft^{-3}), of x rays produced at 4 to 10 MV. Based on NCRP Report No. 51 [27].

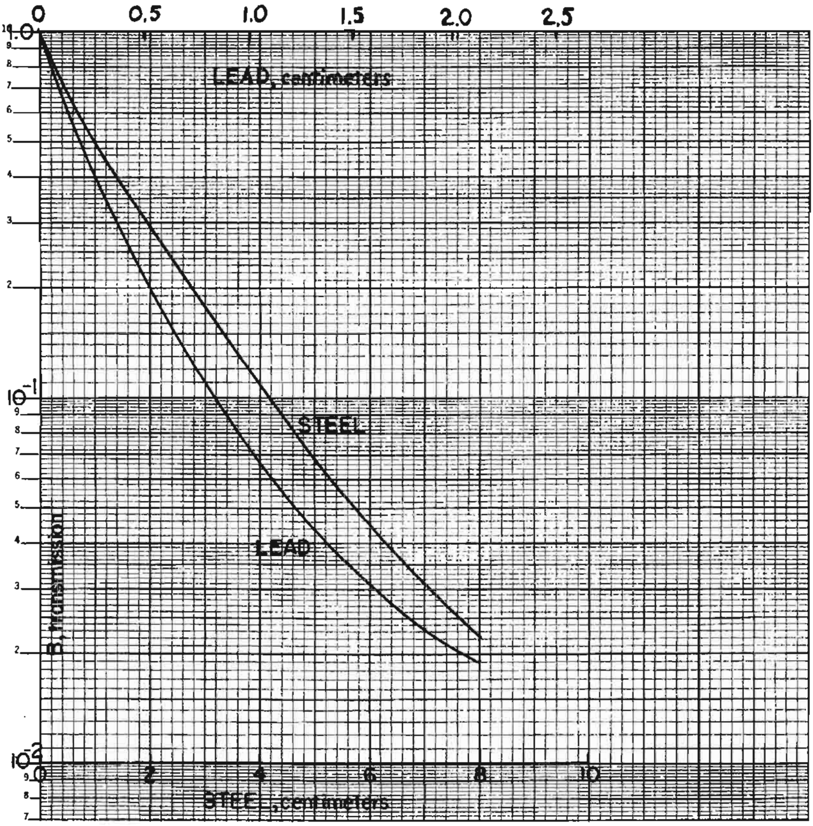

Fig. 9 Transmission through lead and steel of 6 MV primary x rays scattered at 90°.

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.]

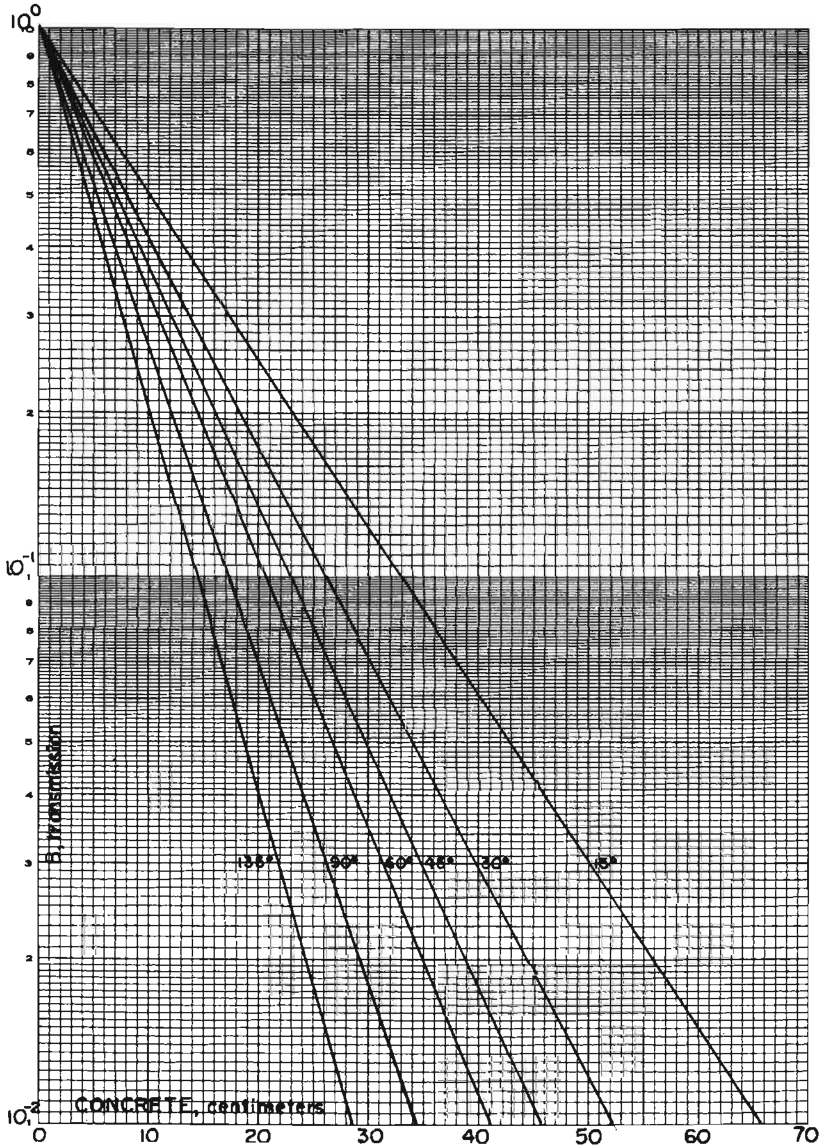

Fig. 10 Transmission through concrete, density 2.35 g cm^{-3} (147 lb ft^{-3}), for 6 MV primary x rays scattered at six different angles from a unit density phantom.

The measurements were made with 6 MV radiation scattered 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.]

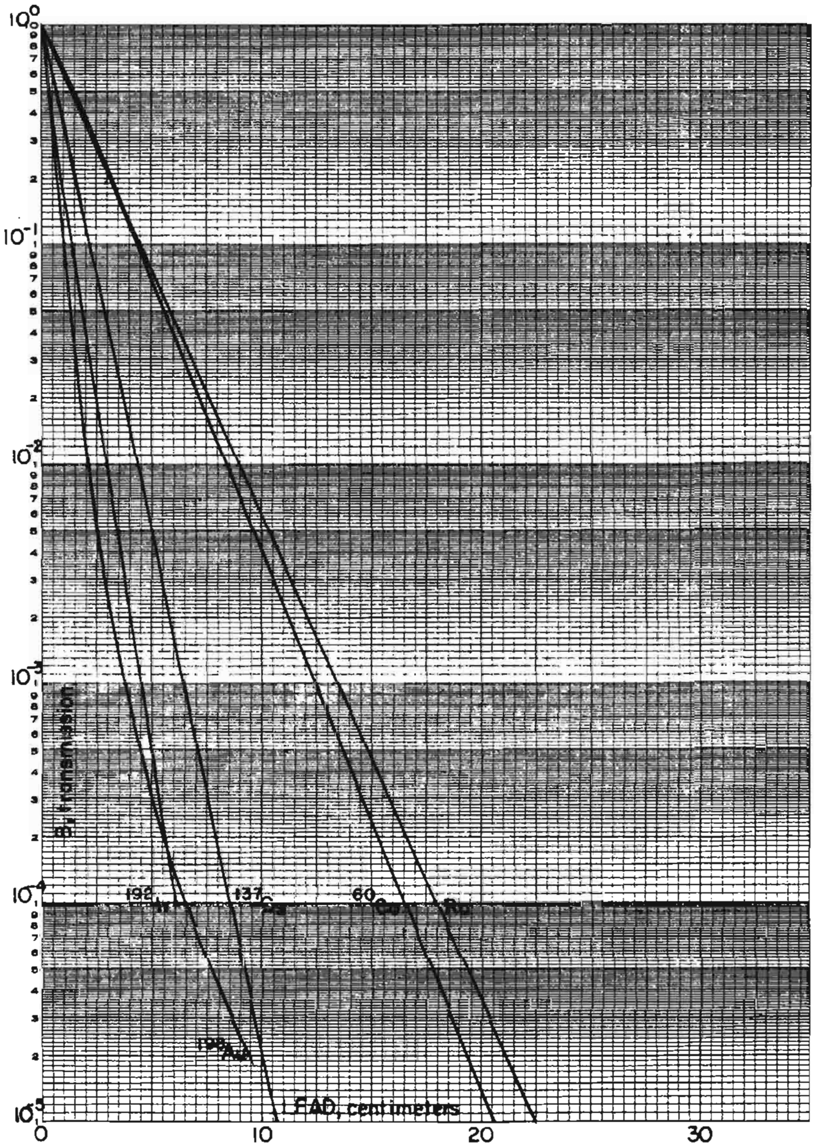

Fig. 11 Transmission through lead of gamma rays from selected radionuclides. Radium (Wyckoff and Kennedy [23]); cobalt-60, cesium-137, gold-198 (Kirn *et al.* [13]); iridium-192 (Ritz [24]).

[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.]

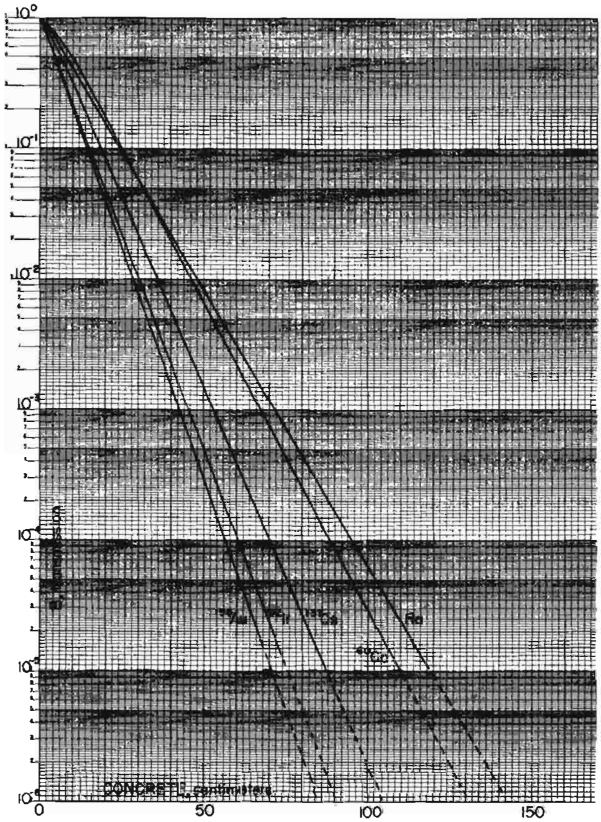

Fig. 12 Transmission through concrete, density 2.35 g cm^{-3} (147 lb ft^{-3}), of gamma rays from selected radionuclides.

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.]

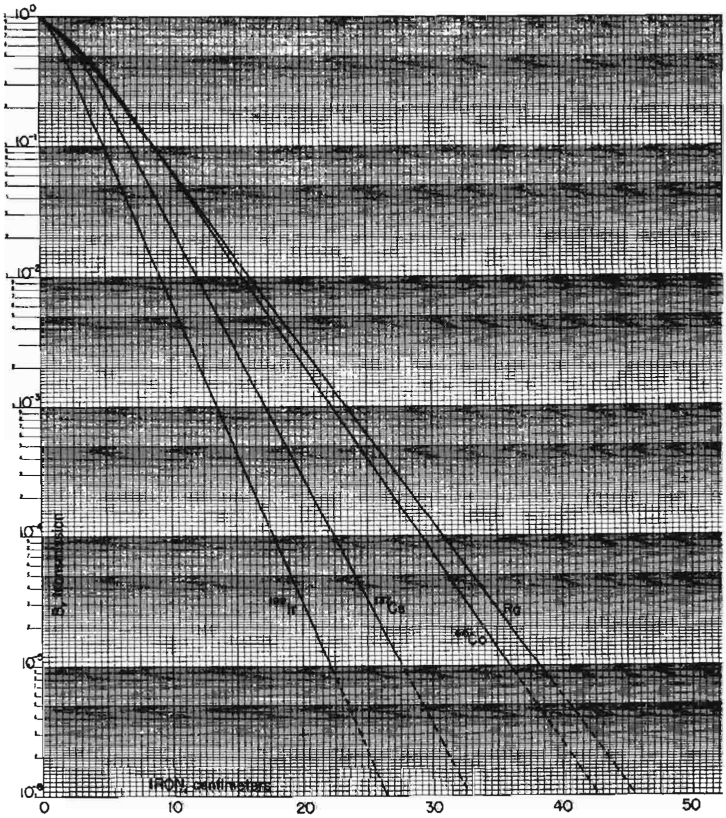

Fig. 13 Transmission through iron of gamma rays from selected radionuclides. Radium (Wyckoff and Kennedy [23]); cobalt-60, cesium-137 (Kirn *et al.* [13]); iridium-192 (Ritz [24]).

[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.]

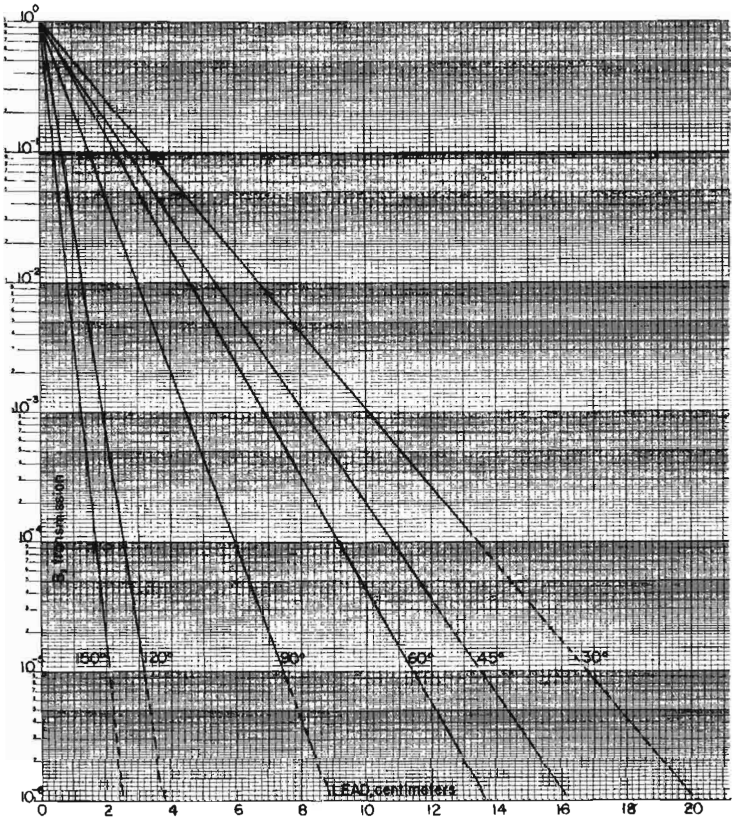

Fig. 14 Transmission through lead of cobalt-60 radiation scattered from a cylindrical unit density phantom, 20 cm diameter field at 1 m from source (Mooney and Braestrup [25]).

[Data courtesy of the authors.]

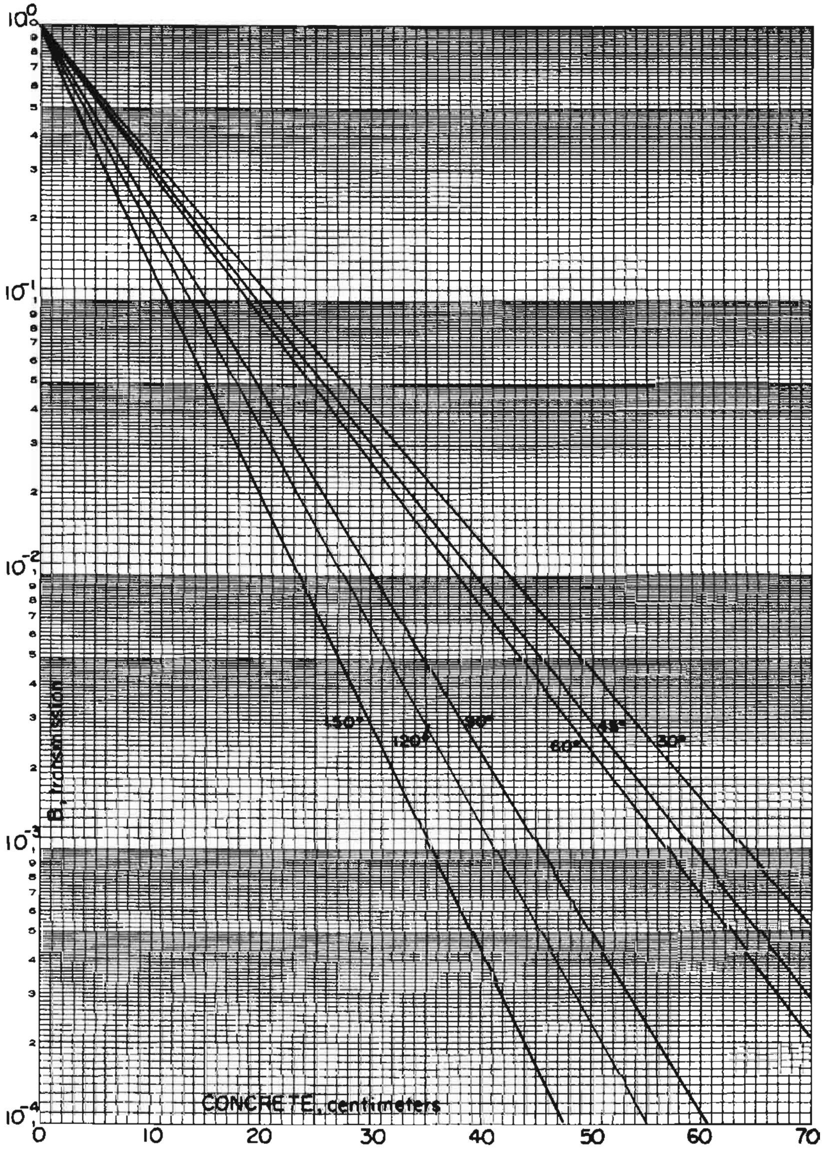

Fig. 15 Transmission through concrete, density 2.35 g cm^{-3} (147 lb ft^{-3}), of cobalt-60 radiation scattered from a cylindrical unit density phantom, 20 cm diameter field, at 1 m from source (Mooney and Braestrup [25]).
[Data courtesy of the authors.]

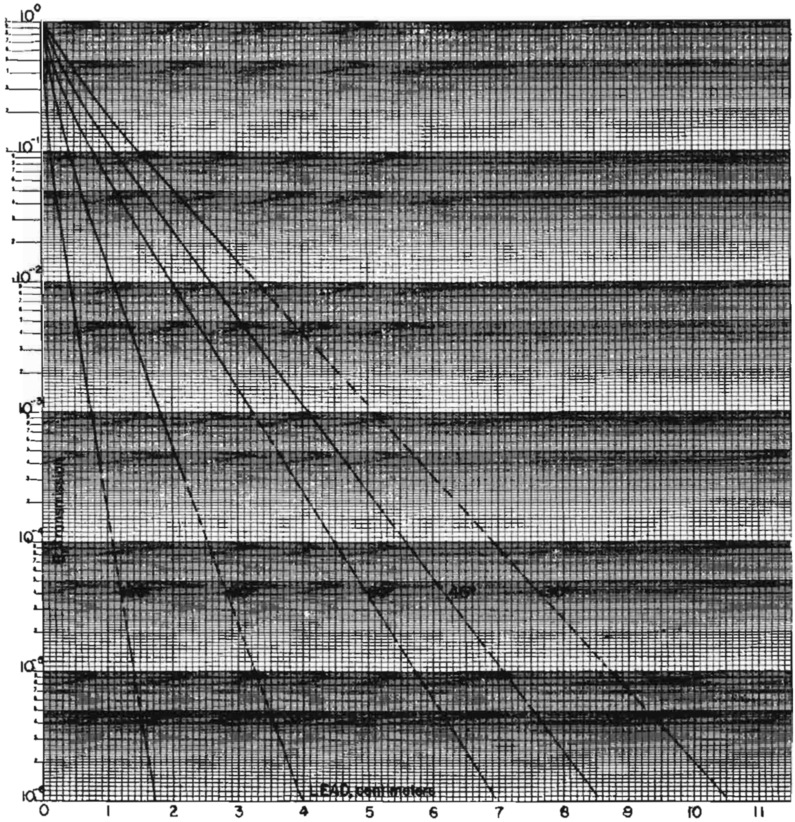

Fig. 16 Transmission through lead of cesium-137 scattered radiation. (Interpolated from Frantz and Wyckoff [26]).
[Data courtesy of the authors and Radiology.]

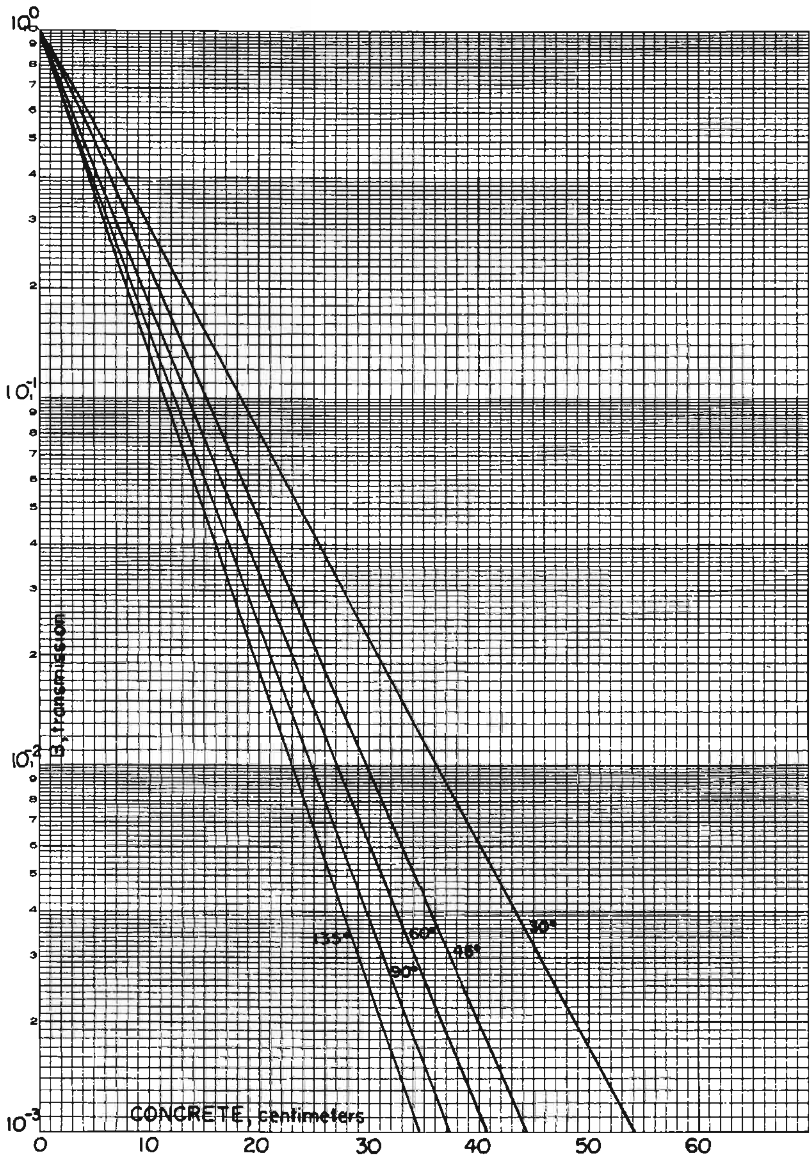

Fig. 17 Transmission through concrete, density 2.35 g cm^{-3} (147 lb ft^{-3}), of cesium-137 scattered radiation (interpolated from Frantz and Wyckoff [26]). [Data courtesy of the authors and Radiology.]

APPENDIX E

Architectural and Equipment Information to be Supplied To the Qualified Expert for Use in Shielding Design

A. Architectural

1. Drawings of radiation rooms and adjacent area; scale preferred $^1/_4$ inch = 1 foot, or larger, including position of radiation source, doors and windows.
2. Information about occupancy below, above and adjacent to radiation rooms.
3. Type of proposed, or existing, construction of floors, ceilings and walls.
4. For megavoltage therapy installations, including cobalt, vertical sections and plot plans.

B. Equipment

1. Below 150 kV.
   a. Purpose: therapy, radiography, fluoroscopy, special procedures, cystoscopy, etc.
   b. kV and expected weekly workload, if known.
2. 150 kV and above, including gamma beam apparatus.
   a. kV, or type of gamma source.
   b. mA or R per minute at 1 meter.
   c. Weekly workload, if known, expressed in mA min, or R at 1 meter.
   d. Restrictions in beam orientations without and with beam interceptor, if any.
   e. Use factor for walls and ceiling, if known.
   f. Leakage radiation of source housing with beam "ON."
   g. Attenuation by beam interceptor, if any.
3. Possible future increases in workload and radiation energy and modification in beam orientation.

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

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The NCRP

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1. Collect, analyze, develop, and disseminate in the public interest information and recommendations about (a) protection against radiation and (b) radiation measurements, quantities, and units, particularly those concerned with radiation protection;
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;
3. Develop basic concepts about radiation quantities, units, and measurements, about the application of these concepts, and about radiation protection;
4. Cooperate with the International Commission on Radiological Protection, the International Commission on Radiation Units and Measurements, and other national and international organizations, governmental and private, concerned with radiation quantities, units, and measurements and with radiation protection.

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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
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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)
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32	*Radiation Protection in Educational Institutions* (1966)
35	*Dental X-Ray Protection* (1970)
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Volume V.	NCRP Reports Nos. 42, 44, 46
Volume VI.	NCRP Reports Nos. 47, 49, 50, 51
Volume VII.	NCRP Reports Nos. 52, 53, 54, 55, 57
Volume VIII.	NCRP Report No. 58
Volume IX.	NCRP Reports Nos. 59, 60, 61, 62, 63
Volume X.	NCRP Reports Nos. 64, 65, 66, 67
Volume XI.	NCRP Reports Nos. 68, 69, 70, 71, 72
Volume XII.	NCRP Reports Nos. 73, 74, 75, 76
Volume XIII.	NCRP Reports Nos. 77, 78, 79, 80
Volume XIV.	NCRP Reports Nos. 81, 82, 83, 84, 85
Volume XV.	NCRP Reports Nos. 86, 87, 88, 89
Volume XVI.	NCRP Reports Nos. 90, 91, 92, 93
Volume XVII.	NCRP Reports Nos. 94, 95, 96, 97
Volume XVIII.	NCRP Reports Nos. 98, 99, 100
Volume XIX.	NCRP Reports Nos. 101, 102, 103, 104
Volume XX.	NCRP Reports Nos. 105, 106, 107, 108
Volume XXI.	NCRP Reports Nos. 109, 110, 111
Volume XXII.	NCRP Reports Nos. 112, 113, 114
Volume XXIII.	NCRP Reports Nos. 115, 116, 117, 118

(Titles of the individual reports contained in each volume are given above.)

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)

Proceedings of the Annual Meeting

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]

11 *How to be Quantitative about Radiation Risk Estimates* by Seymour Jablon (1988) [Available also in *New Dosimetry at Hiroshima and Nagasaki and its Implications for Risk Estimates*, see above]

12 *How Safe is Safe Enough?* by Bo Lindell (1988) [Available also in *Radon*, see above]

13 *Radiobiology and Radiation Protection: The Past Century and Prospects for the Future* by Arthur C. Upton (1989) [Available also in *Radiation Protection Today*, see above]

14 *Radiation Protection and the Internal Emitter Saga* by J. Newell Stannard (1990) [Available also in *Health and Ecological Implications of Radioactively Contaminated Environments*, see above]

15 *When is a Dose Not a Dose?* by Victor P. Bond (1992) [Available also in *Genes, Cancer and Radiation Protection*, see above]

16 *Dose and Risk in Diagnostic Radiology: How Big? How Little?* by Edward W. Webster (1992)[Available also in *Radiation Protection in Medicine*, see above]

17 *Science, Radiation Protection and the NCRP* by Warren K. Sinclair (1993)

Symposium Proceedings

The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack, Proceedings of a Symposium held April 27-29, 1981 (1982)

NCRP Statements

No.	Title
1	"Blood Counts, Statement of the National Committee on Radiation Protection," Radiology **63**, 428 (1954)
2	"Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol., Radium Ther. and Nucl. Med. **84**, 152 (1960) and Radiology **75**, 122 (1960)
3	*X-Ray Protection Standards for Home Television Receivers, Interim Statement of the National Council on Radiation Protection and Measurements* (1968)
4	*Specification of Units of Natural Uranium and Natural Thorium, Statement of the National Council on Radiation Protection and Measurements*, (1973)

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]

13 *Protection Against Radiations from Radium, Cobalt-60 and Cesium-137* (1954) [Superseded by NCRP Report No. 24]
14 *Protection Against Betatron-Synchrotron Radiations Up to 100 Million Electron Volts* (1954) [Superseded by NCRP Report No. 51]
15 *Safe Handling of Cadavers Containing Radioactive Isotopes* (1953) [Superseded by NCRP Report No. 21]
16 *Radioactive-Waste Disposal in the Ocean* (1954) [Out of Print]
17 *Permissible Dose from External Sources of Ionizing Radiation* (1954) including *Maximum Permissible Exposures to Man, Addendum to National Bureau of Standards Handbook 59* (1958) [Superseded by NCRP Report No. 39]
18 *X-Ray Protection* (1955) [Superseded by NCRP Report No. 26]
19 *Regulation of Radiation Exposure by Legislative Means* (1955) [Out of Print]
20 *Protection Against Neutron Radiation Up to 30 Million Electron Volts* (1957) [Superseded by NCRP Report No. 38]
21 *Safe Handling of Bodies Containing Radioactive Isotopes* (1958) [Superseded by NCRP Report No. 37]
24 *Protection Against Radiations from Sealed Gamma Sources* (1960) [Superseded by NCRP Reports No. 33, 34 and 40]
26 *Medical X-Ray Protection Up to Three Million Volts* (1961) [Superseded by NCRP Reports No. 33, 34, 35 and 36]
28 *A Manual of Radioactivity Procedures* (1961) [Superseded by NCRP Report No. 58]
29 *Exposure to Radiation in an Emergency* (1962) [Superseded by NCRP Report No. 42]
31 *Shielding for High-Energy Electron Accelerator Installations* (1964) [Superseded by NCRP Report No. 51]
33 *Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV—Equipment Design and Use* (1968) [Superseded by NCRP Report No. 102]
34 *Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Structural Shielding Design and Evaluation Handbook* (1970) [Superseded by NCRP Report No. 49]
39 *Basic Radiation Protection Criteria* (1971) [Superseded by NCRP Report No. 91]
43 *Review of the Current State of Radiation Protection Philosophy* (1975) [Superseded by NCRP Report No. 91]
45 *Natural Background Radiation in the United States* (1975) [Superseded by NCRP Report No. 94]
48 *Radiation Protection for Medical and Allied Health Personnel* (1976) [Superseded by NCRP Report No. 105]

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]

NCRP Proceedings

No.	Title
2	*Quantitative Risk in Standards Setting*, Proceedings of the Sixteenth Annual Meeting held on April 2-3, 1980 [Out of Print]

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