2. Fundamentals of Shielding for Medical X-Ray Imaging Facilities

2.1 Basic Principles

In medical x-ray imaging applications, the radiation consists of primary and secondary radiation. *Primary radiation*, also called the useful beam, is radiation emitted directly from the x-ray tube that is used for patient imaging. A *primary barrier* is a wall, ceiling, floor or other structure that will intercept radiation emitted directly from the x-ray tube. Its function is to attenuate the useful beam to appropriate shielding design goals.

Secondary radiation consists of x rays scattered from the patient and other objects such as the imaging hardware and leakage radiation from the protective housing of the x-ray tube. A *secondary barrier* is a wall, ceiling, floor or other structure that will intercept and attenuate leakage and scattered radiations to the appropriate shielding design goal. Figure 2.1 illustrates primary, scattered, leakage and transmitted radiation in a typical radiographic room.

Primary and secondary radiation exposure to individuals depends primarily on the following factors:

- the amount of radiation produced by the source
- the *distance* between the exposed person and the source of the radiation
- the amount of *time* that an individual spends in the irradiated area
- the amount of protective *shielding* between the individual and the radiation source

The exposure rate from the source varies approximately as the inverse square of the distance from the source. To assess the distance from the source when a barrier is in place, it is usually assumed that the individual to be protected is at least 0.3 m beyond the walls bounding the source. The exposure time of an individual

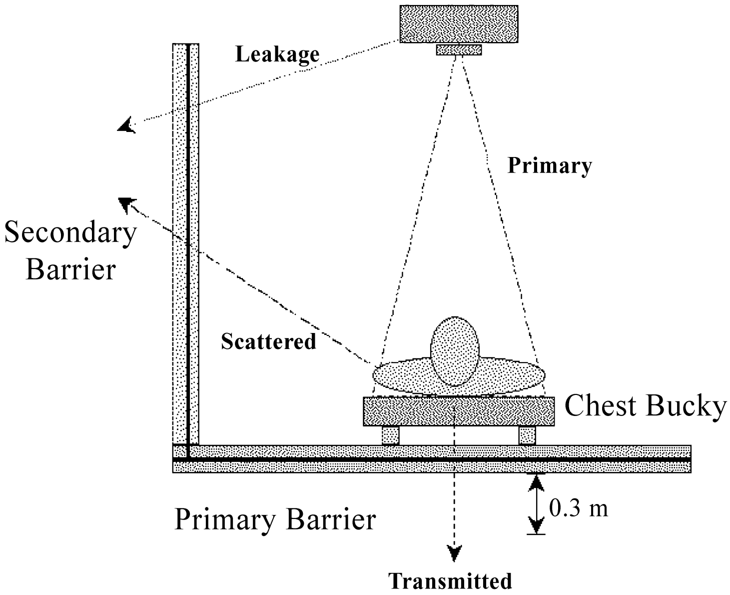

Fig. 2.1. Figure illustrating primary, scattered, leakage and transmitted radiation in a radiographic room with the patient positioned upright against the chest bucky. The minimum distance to the occupied area from a shielded wall is assumed to be 0.3 m.

involves both the time that the radiation beam is on and the fraction of the beam-on time during which a person is in the radiation field. Exposure through a barrier in any given time interval depends on the integrated tube current in that interval [workload in milliampere-minutes (mA min)], the volume of the scattering source, the leakage of radiation through the x-ray tube housing, and the energy spectrum of the x-ray source. In most applications covered by this Report, protective shielding is required.

2.2 Types of Medical X-Ray Imaging Facilities

2.2.1 *Radiographic Installations*

A general purpose radiographic system produces brief radiation exposures with applied electrical potentials on the x-ray tube (operating potential) in the range from 50 to 150 kVp (kilovolt peak) that are normally made with the x-ray beam directed down towards the patient, the radiographic table and, ultimately, the floor. However, the x-ray tube can usually be rotated, so that it is possible for the x-ray beam to be directed to other barriers. Barriers that may be directly irradiated are considered to be primary barriers. Many general purpose radiographic rooms include the capability for chest radiographs where the beam is directed to a vertical cassette assembly, often referred to as a "chest bucky" or "wall bucky." Additional shielding may be specified for installation directly behind this unit.

Provision *shall* be made for the operator to observe and communicate with the patient on the table or at the vertical cassette assembly. The operator of a radiographic unit *shall* remain in a protected area (control booth) or behind a fixed shield that will intercept the incident radiation. The control booth *should not* be used as a primary barrier. The exposure switch *shall* be positioned such that the radiographer cannot make an exposure with his or her body outside of the shielded area. This is generally accomplished if the x-ray exposure switch is at least 1 m from the edge of the control booth.

The control booth *shall* consist of a permanent structure at least 2.1 m high and *should* contain unobstructed floor space sufficient to allow safe operation of the equipment. The booth *shall* be positioned so that no unattenuated primary or unattenuated single-scattered radiation will reach the operator's position in the booth. There *shall not* be an unprotected direct line of sight from the patient or x-ray tube to the x-ray machine operator or to loaded film cassettes placed behind a control booth wall.

The control booth *shall* have a window or viewing device that allows the operator to view the patient during all x-ray exposures performed in the room. The operator must be able to view the wall bucky and x-ray table, as well as patients confined to stretchers. When an observation window is used, the window and frame *shall* provide the necessary attenuation required to reduce the air kerma to the shielding design goal. The window(s) *should* be at least 45×45 cm and centered 1.5 m above the finished floor. A typical design for a control booth is illustrated in Figure 2.2.

2.2.2 *Fluoroscopic Installations*

Fluoroscopic imaging systems are usually operated at potentials ranging from 60 to 120 kVp. A primary barrier is incorporated into the fluoroscopic image receptor. Therefore, a protective design for a room containing only a fluoroscopic unit need consider only secondary protective barriers against leakage and scattered radiations. However, the qualified expert may wish to provide fluoroscopic rooms with primary barriers so that the function of the room

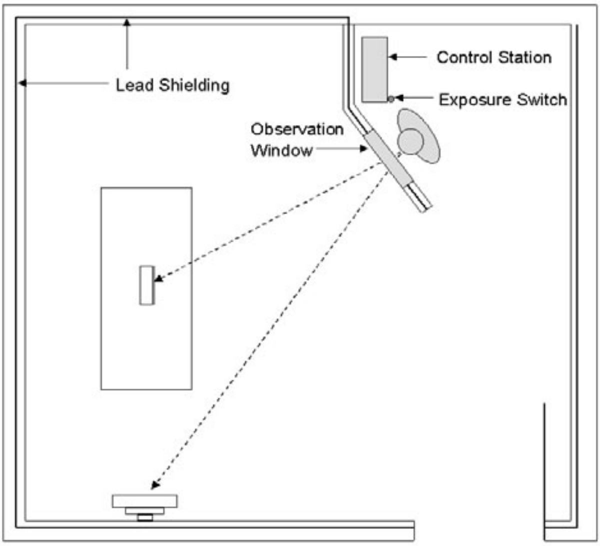

Fig. 2.2. Typical design for a control booth in a radiographic x-ray room surrounded by occupied areas. Dashed lines indicate the required radiographer's line of sight to the x-ray table and wall bucky. The exposure switch is positioned at least 1 m from the edge of the control booth, as discussed in Section 2.2.1.

can be changed at a later date without the need to add additional shielding. Most modern fluoroscopic x-ray imaging systems also include a radiographic tube. The shielding requirements for such a room are based on the combined workload of both units.

2.2.3 *Interventional Facilities*

Interventional facilities include cardiovascular imaging (cardiac catheterization) rooms, as well as peripheral angiography and neuroangiography suites. These facilities, which will be referred to as cardiac angiography and peripheral angiography,[4] may contain multiple x-ray tubes, each of which needs to be evaluated independently. Barriers *shall* be designed so that the total air kerma from all tubes does not exceed the shielding design goal. The types of studies performed in these facilities often require long fluoroscopy times, as well as cine and digital radiography. Consequently, workloads in interventional imaging rooms generally are high and tube

[4]In this Report, the data for peripheral angiography suites also apply to neuroangiography suites.

orientation may change with each of the studies performed. The shielded control area *should* be large enough to accommodate associated equipment and several persons.

2.2.4 *Dedicated Chest Installations*

In a dedicated chest radiographic room, the x-ray beam is directed to a chest image-receptor assembly on a particular wall. All other walls in the room are secondary barriers. Chest techniques generally require operating potentials >100 kVp. For the wall at which the primary beam is directed, a significant portion that is not directly behind the chest unit may be considered a secondary barrier. However, the segment of the wall directly behind and around the chest bucky is a primary barrier and may require additional shielding. The image receptor may be moved vertically to radiograph patients of various heights and areas of anatomy other than the chest. Therefore, the entire area of the wall that may be irradiated by the primary beam *shall* be shielded as a primary protective barrier.

2.2.5 *Mammographic Installations (Permanent and Mobile)*

Mammography is typically performed at low operating potentials in the range of 25 to 35 kVp. Units manufactured after September 30, 1999 are required to have their primary beams intercepted by the image receptor (FDA, 2003b). Thus permanent mammography installations may not require protection other than that provided by typical gypsum wallboard construction. Furthermore, adequate protective barriers of lead acrylic or lead glass are usually incorporated into dedicated mammographic imaging systems to protect the operator. Although the walls of a mammography facility may not require lead shielding, a qualified expert *shall* be consulted to determine whether the proposed design is satisfactory to meet the recommended shielding design goals. Doors in mammography rooms may need special consideration since wood does not attenuate x rays as efficiently as gypsum wallboard. Designers need to be aware that gypsum wallboard typically contains voids and nonuniform areas. Therefore, one should consider using a greater thickness of gypsum wallboard than required by routine calculations. However, as discussed in Section 5.5, a substantial measure of conservatism (on the safe side) is provided in the mammography energy range by the E to unit air-kerma ratio (ICRP, 1996; ICRU, 1998b).

Mobile or temporary mammographic imaging units present special problems in protection of the patient, staff and members of the public. These *shall* be evaluated by a qualified expert prior to first use.

2.2.6 *Computed Tomography Installations*

Computed tomography (CT) employs a collimated x-ray fan-beam that is intercepted by the patient and by the detector array. Consequently, only secondary radiation is incident on protective barriers. The operating potential, typically in the range of 80 to 140 kVp, as well as the workload are much higher than for general radiography or fluoroscopy. Due to the potential for a large amount of secondary radiation, floors, walls and ceilings need special consideration. Additionally, scattered and leakage radiations from CT systems are not isotropic. Although radiation levels in the direction of the gantry are much less than the radiation levels along the axis of the patient table, the model used in this Report assumes a conservatively safe isotropic scattered-radiation distribution. This is an important consideration if a replacement unit has a different orientation.

2.2.7 *Mobile Radiography and Fluoroscopy X-Ray Units*

Both mobile (or portable) radiographic and fluoroscopic imaging systems are used in the performance of examinations when the condition of the patient is such that transport to a fixed imaging system is not practical. Mobile C-arm fluoroscopic units are often used in cardiac procedures such as pacemaker implantation and in various examinations performed in the operating room, as well as other locations such as pain clinics and orthopedic suites.

Mobile radiographic equipment is used extensively for radiographic examination of the chest and occasionally for abdominal and extremity examinations. These examinations are often performed at bedside in critical care units and in patient rooms. Radiation protection issues involved in the use of mobile radiographic equipment in hospitals and clinic areas are discussed in NCRP Report No. 133, *Radiation Protection for Procedures Performed Outside the Radiology Department* (NCRP, 2000).

If the mobile x-ray equipment is used in a fixed location, or frequently in the same location, a qualified expert *shall* evaluate the need for structural shielding.

2.2.8 *Dental X-Ray Facilities*

Shielding and radiation protection requirements for dental x-ray facilities are covered in NCRP Report No. 145, *Radiation Protection in Dentistry* (NCRP, 2003).

2.2.9 *Bone Mineral Measurement Equipment*

Although bone mineral measurement equipment may not produce images, it does produce ionizing radiation and is a diagnostic modality. Factors similar to those for x-ray equipment need to be evaluated by a qualified expert. This applies to bone mineral measurement equipment in permanent or temporary (mobile) situations. Most modern bone mineral analyzers will not produce scattered radiation levels greater than an air kerma of 1 mGy y^{-1} at 1 m for the workload for a busy facility (2,500 patients per year).[5] This air-kerma level is equal to the shielding design goal for a fully-occupied uncontrolled area. Therefore, structural shielding is not required in most cases. However, it is recommended that the operator console be placed as far away as practicable to minimize exposures to the operator. See Section 5.7 for a sample calculation of scattered radiation from this type of equipment.

2.2.10 *Veterinary X-Ray Facilities*

Special consideration needs to be given to veterinary x-ray imaging facilities. Although many veterinary subjects are small, large animals are often examined. Shielding and radiation protection requirements *shall* be evaluated by a qualified expert prior to use of the facility. The radiation safety aspects of veterinary radiation facilities will be covered in a forthcoming revision of NCRP Report No. 36, *Radiation Protection in Veterinary Medicine* (NCRP, 1970; in press).

2.2.11 *Other X-Ray Imaging Systems*

New medical x-ray imaging techniques will continue to be developed in the future. All sources of ionizing radiation *shall* be evaluated by a qualified expert in order to determine the type and nature of the shielding required in the facility.

[5]Dixon, R.L. (2003). Personal communication (Wake Forest University, Winston-Salem, North Carolina).

2.3 Shielding Design Elements

2.3.1 *Interior Walls*

Local building and fire codes, as well as state health-care licensing agencies, specify requirements for wall assemblies that meet Underwriters Laboratories, Inc. standards for life safety. Unshielded walls in contemporary health-care facilities are normally constructed of metal studs and one or more layers of 5/8 inch thick drywall (gypsum wallboard) per side. The corridor side of walls may contain two layers of gypsum wallboard. Several types of shielding materials are available for walls.

2.3.1.1 *Sheet Lead*. Sheet lead has traditionally been the material of choice for shielding medical imaging x-ray room walls. Figure 2.3 shows the thicknesses of sheet lead (in millimeters and inches) and their nominal weights (in lb $foot^{-2}$) found to be commercially available from a survey of several major suppliers in the United States.[6] All of these thicknesses may not be available in every area. Figure 2.3 also presents the relative cost per sheet (on average) for each thickness compared to the cost per sheet for the 0.79 mm thickness. Note that the weight in pounds per square foot is equal to the nominal thickness in inches multiplied by 64. For example, 1/16 inch lead is equivalent to 4 lb $foot^{-2}$.

For typical shielding applications, a lead sheet is glued to a sheet of gypsum wallboard and installed lead inward with nails or screws on wooden or metal studs. X-ray images of wall segments show that insertion of the nails or screws does not result in significant radiation leaks.[7] In fact, the steel nails or screws generally attenuate radiation equally, or more effectively, than the lead displaced by the nails. Therefore, steel nails or screws used to secure lead barriers need not be covered with lead discs or supplementary lead. However, where the edges of two lead sheets meet, the continuity of shielding *shall* be ensured at the joints (Section 2.4.2)

2.3.1.2 *Gypsum Wallboard*. Gypsum wallboard (sheetrock) is commonly used for wall construction in medical facilities. As Glaze *et al*. (1979) pointed out, the gypsum in each sheet is sandwiched

[6]Archer, B.R. (2003). Personal communication (Baylor College of Medicine, Houston, Texas).

[7]Gray, J.E. and Vetter, R.J. (2002). Personal communication (Landauer, Inc., Glenwood, Illinois) and (Mayo Clinic, Rochester, Minnesota), respectively.

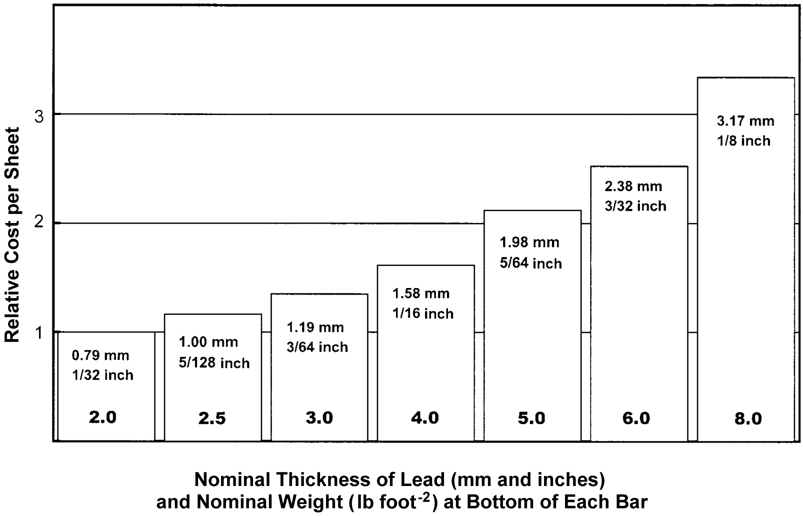

Fig. 2.3. Thicknesses of sheet lead commercially available in a recent survey of several suppliers in the United States. The height of each bar is the relative cost per sheet compared to the 0.79 mm thickness. All the thicknesses given may not be available in every area of the United States.

between a total of 1 mm of paper. A nominal 5/8 inch sheet of "Type X" gypsum wallboard has a minimum gypsum thickness of approximately 14 mm. Although gypsum wallboard provides relatively little attenuation at higher beam energies, it provides significant attenuation of the low-energy x rays used in mammography. As mentioned earlier, gypsum wallboard typically contains voids and nonuniform areas and therefore one *should* be conservatively safe when specifying this material for shielding.

2.3.1.3 *Other Materials.* Concrete block, clay brick, and tile may also be used to construct interior walls. Generally, manufacturing specifications for these products will be available and the construction standards established for their use will allow the qualified expert, in consultation with the architect, to determine their appropriateness as shielding materials. These materials may contain voids which will require special consideration during shielding design. If there are voids in the blocks or bricks that may compromise the shielding capabilities of the wall, then solid blocks or bricks may be used or the voids may be filled with grout, sand or mortar. The densities of commercial building materials can be found in Avallone and Baumeister (1996).

2.3.2 *Exterior Building Walls*

Exterior building walls of medical imaging x-ray rooms may be composed of stone, brick, stucco, concrete, wood, vinyl, synthetic stucco, or other material. The range of potential attenuating properties of these materials is very wide and the qualified expert *should* request specific exterior wall design specifications from the architect prior to determining the shielding requirements.

Wall systems are generally determined during the design development phase with the construction details established during the construction document phase. The architect *should* review the plans with the qualified expert during the design development phase of construction for shielding requirements and opportunities for structural modifications.

2.3.3 *Doors*

2.3.3.1 *Lead-Lined Doors*. The door and frame must provide at least the attenuation required to reduce the air kerma to the shielding design goal. If lead is required, the inside of the door frame *should* be lined with a single lead sheet and worked into the contour of the frame to provide an effective overlap with the adjoining barrier[8] (Figure 2.4).

2.3.3.2 *Wooden Doors*. Wooden doors exhibit limited attenuation efficiency and not all wooden doors are constructed with equal integrity. Some "drop-in-core" models exhibit large gaps between the solid core and outer frame (stiles and rails). Likewise, the "lumber core door" provides very little shielding because the core consists of staggered wooden blocks that are edge glued. This type of core demonstrates numerous voids when radiographed. Another type often classified as a wooden door is a mineral core door. The core of this door consists primarily of calcium silicate, which has attenuation properties similar to gypsum wallboard. However, the stiles and rails are constructed of wood, so the benefit of the additional core attenuation may be reduced.

There are facilities such as mammography installations where design layout, workload factors, and beam energy may allow consideration of solid wood or mineral core wood doors for shielding applications. To ensure the integrity of wooden doors one *should*

[8]Smith, B. (2004). Personal communication (Nelco Lead Company, Woburn, Massachusetts).

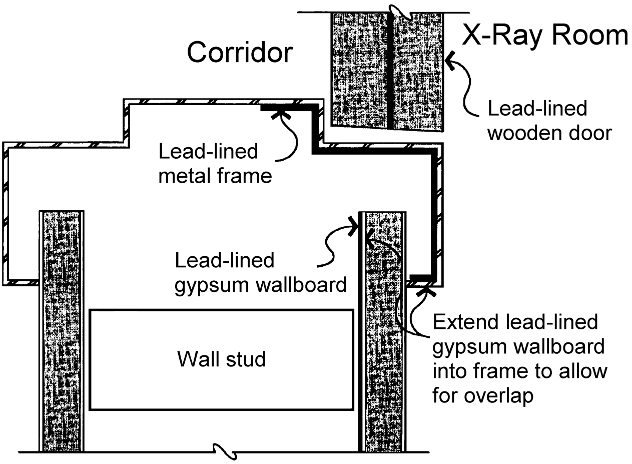

Fig. 2.4. Cross-sectional view of lead-lined door and frame illustrating the proper placement of lead shielding. When the thickness of the metal in the door frame is inadequate, the inside of the frame *should* be lined with a single lead sheet and worked into the contour of the frame to provide an effective overlap with the adjoining barrier.

specify American Woodwork Institute type PC-5 (solid wooden core) or C-45 (mineral core) for shielding applications, or equivalent. American Woodwork Institute standards (AWI, 2003) for these doors state that "the stiles and rails must be securely bonded to the core."

2.3.3.3 *Door Interlocks, Warning Lights, and Warning Signs*. Door interlocks that interrupt x-ray production are not desirable since they may disrupt patient procedures and thus result in unnecessary repeat examinations. An exception might be a control room door which represents an essential part of the control barrier protecting the operator. The qualified expert *should* consult local and state regulations with respect to interlocks, warning signs and warning lights.

2.3.4 *Windows*

There are various types of materials suitable for windows in medical x-ray imaging facilities. It is desirable that the window material be durable and maintain optical transparency over the life of the facility.

2.3.4.1 *Lead Glass*. Glass with a high lead content can be obtained in a variety of thicknesses. Lead glass is usually specified in terms of millimeter lead equivalence at a particular *kVp*.

2.3.4.2 *Plate Glass*. Ordinary plate glass may be used only where protection requirements are very low. Typically, two or more 1/4 inch (6.35 mm) thick glass sections are laminated together to form the view window. However, caution must be exercised when specifying thick, large-area plate glass windows because of weight considerations.

2.3.4.3 *Lead Acrylic*. This product is a lead-impregnated, transparent, acrylic sheet that may be obtained in various lead equivalencies, typically 0.5, 0.8, 1 and 1.5 mm lead equivalence. Lead acrylic is a relatively soft material which may scratch and can become clouded by some cleaning solvents.

2.3.5 *Floors and Ceilings*

Concrete is a basic construction material used in floor slabs. It may also be used for precast wall panels, walls, and roofs. Concrete is usually designed and specified as standard-weight or lightweight. The radiation attenuation effectiveness of a concrete barrier depends on its thickness, density and composition.

Figure 2.5 illustrates typical floor slab construction used in most health-care facilities, namely metal-deck-supported concrete and slab. The concrete equivalence of the steel decking may be estimated from the attenuation data provided in this Report. The floor slab thickness can vary from as little as 4 cm to >20 cm. For shielding purposes, the minimum concrete slab thickness *should* be incorporated in the shielding design. Optimally, the qualified expert, architect, and structural engineer *should* discuss floor systems and their potential impact on the shielding design as early as possible in the facility design process. A collaborative design could eliminate the need for the costly addition of lead shielding in the floor or ceiling.

2.3.5.1 *Standard-Weight Concrete*. Standard-weight (or normal-weight) concrete is used for most foundations and main structural elements such as columns, beams and floor slabs. The average density of standard-weight concrete is 2.4 g cm^{-3} (147 lb $foot^{-3}$). Variations in concrete density may arise from differences in density of the components, from forming or tamping techniques used in the casting or from different proportions used in the mix.

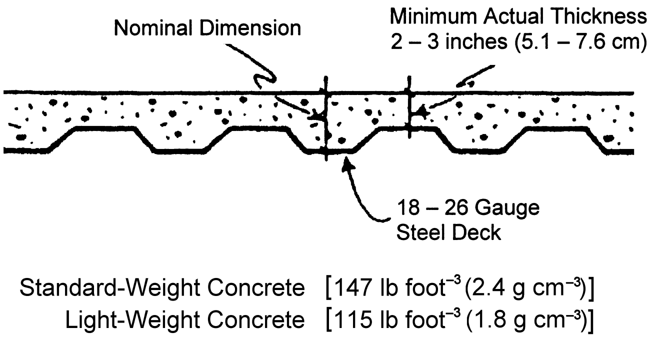

Fig. 2.5. Schematic of a typical concrete floor slab poured on a steel deck. The minimum thickness *should* be used in calculating the barrier thickness.

2.3.5.2 *Light-Weight Concrete.* Light-weight concrete is often specified in floor slabs as a weight saving and fire protection measure. The air space pores reduce heat conduction, often allowing it to be classified as a primary fire barrier. Typically, light-weight concrete will have a density of 1.8 g cm^{-3} (115 lb $foot^{-3}$) or about three-quarters that for standard-weight concrete, depending on the aggregate used. "Honeycombing," the creation of voids in the concrete, will affect its shielding properties. If the total design thickness of concrete is required to meet the shielding design goal, then testing for voids and a plan for corrective measures may be needed.

2.3.5.3 *Floor Slab Construction.* A typical concrete floor slab is a variable structure as shown in Figure 2.5, having been poured on a steel deck. Note that the minimum thickness of the concrete is less than the nominal dimension which is usually quoted. The minimum thickness *should* be used in calculating the barrier equivalence.

2.3.6 *Floor-to-Floor Heights*

Floor-to-floor height is the vertical distance from the top of one floor to the top of the next floor. The floor-to-floor height should provide adequate ceiling height for the use and servicing of imaging equipment. Although floor-to-floor height will range from 3 to 5 m, protective shielding need normally extend only to a height of 2.1 m above the floor, unless additional shielding is required in the ceiling directly above the x-ray room (over and above the inherent shielding of the ceiling slab). In this latter case, it may be necessary to extend the wall lead up to the ceiling shielding material. Darkroom walls may also require shielding that extends to the ceiling to protect film stored on shelves above the standard 2.1 m height.

2.3.7 *Interstitial Space*

Typical interstitial space is 1.5 to 2.4 m in height and contains structural support for maintenance or room for construction personnel to work above the ceiling. The floor of the interstitial space is much thinner than a typical concrete slab, it may be a steel deck without a concrete topping, a steel deck with a gypsum topping, or a steel deck with a light-weight concrete deck. Interstitial space makes it possible for a person to work above or below an x-ray unit while the unit is in operation. The occupancy factor for this space is normally extremely low since access is usually restricted, but this *should* be determined on a case-by-case basis.

2.4 Shielding Design Considerations

2.4.1 *Penetrations in Protective Barriers*

Air conditioning ducts, electrical conduit, plumbing, and other infrastructure will penetrate shielded walls, floors and ceilings. The shielding of the x-ray room *shall* be constructed such that the protection is not impaired by these openings or by service boxes, etc., embedded in barriers. This can be accomplished by backing or baffling these penetrations with supplementary lead shielding. The supplementary thickness *shall* at least have shielding equivalent to the displaced material. The method used to replace the displaced shielding *should* be reviewed by the qualified expert to establish that the shielding of the completed installation will be adequate.

Whenever possible, openings *should* be located in a secondary barrier where the required shielding is less. Other options designed by the qualified expert, such as shielding the other side of the wall that is opposite the penetrated area, may also be effective. Openings in medical x-ray imaging rooms above 2.1 m from the finished floor do not normally require backing since the shielding in these rooms is generally not required above this height.

Field changes in duct and conduit runs are common during construction and corrections made after the room is completed can be expensive. If changes in wall or floor penetrations will impair shielding by the removal of part of it, construction documents *should* note the need to alert the architect, engineer, and qualified expert to ensure the integrity of these barriers.

2.4.2 *Joints*

The joints between lead sheets *should* be constructed so that their surfaces are in contact and with an overlap of not <1 cm (lead shielding can be purchased with the lead sheet extending beyond the edge of the drywall to allow for adequate overlap). When brick or masonry construction is used as a barrier, the mortar *should* be evaluated, as well as the brick. Joints between different kinds of protective material, such as lead and concrete, *should* be constructed so that the overall protection of the barrier is not impaired. However, small gaps between the lead shielding and the floor will not be detrimental in most cases.

2.5 Construction Standards

Generally, institutional construction is of a high quality and meets the most rigid standards in life safety design. However, construction does not take place in a controlled environment. Site conditions, weather, construction schedules, available materials, and qualifications of construction personnel may ultimately affect the integrity of the completed project. Shielding designs that require excessive precision in order to provide the required shielding may not be obtainable in the field. The qualified expert *should* work closely with the architect and the contractor in areas that require close attention to detail to ensure the appropriate shielding.

2.6 Dimensions and Tolerances

Design and construction professionals often discuss the dimension of system components in "nominal" terms or dimensions. For example, a "two-by-four" piece of wood is actually 1 1/2 × 3 1/2 inches (3.8 × 8.9 cm), a "four-inch" brick is actually 3 5/8 inches thick (9.2 cm), and a nominal 20 cm thick concrete slab may actually be only 15 cm at its thinnest point. Likewise, construction tolerances allow for variations in design dimensions.

The qualified expert *should* request actual material dimensions and material tolerances for the materials and systems used to create the shielding. The qualified expert needs to be aware that some dimensions may be to the center line of a wall, column, beam or slab. The nominal thicknesses, tolerances, and minimum allowed thickness of various shielding materials are shown in Table 2.1.

TABLE 2.1—*The nominal thicknesses and tolerances of various shielding materials used in walls, doors and windows (adapted from Archer et al., 1994).*

Material	Traditional Designation	Nominal Thickness	Thickness Tolerance	Material Thickness
Sheet lead (ASTM, 2003a)	lb foot^{-2}	≤2.54 mm >2.54 mm	–0.13 mm, +0.20 mm ±5% of specified thickness	—
Steel (SDI, 2003)	16 gauge 18 gauge 20 gauge	0.057 inch 0.045 inch 0.034 inch	–0.004 inch –0.003 inch –0.002 inch	1.4 mm[a] 1.1 mm[a] 0.86 mm[a]
Plate glass (ASTM, 2001)	1/4 inch	0.23 inch (0.58 cm)	0.22 to 0.24 inch (0.56 to 0.62 cm)	5.6 mm[b]
Gypsum wallboard (ASTM, 2003b)	5/8 inch	5/8 inch (1.59 cm)	±1/64 inch (±0.04 cm)	14 mm[c]
Wooden doors (AWI, 2003)	1 3/4 inch	1 3/4 inch (4.45 cm)	±1/16 inch (±0.16 cm)	43 mm[d]

[a]This value represents the thickness of a single sheet of steel of the indicated gauge. For shielding applications, two sheets of steel of a given gauge are used in steel doors (*e.g.*, for 16 gauge, the steel thickness in the door would be 2.8 mm).

[b]This value represents a "single pane" of 1/4 inch plate glass.

[c]This value represents the gypsum thickness in a single sheet of 5/8 inch "Type X" gypsum wallboard.

[d]This value represents the thickness of a single, solid-core wooden door.