X-Ray Shielding

X-Ray Uses in Image Guided Surgery

X-Ray Uses for Radiation Therapy

A Typical X-Ray Sources

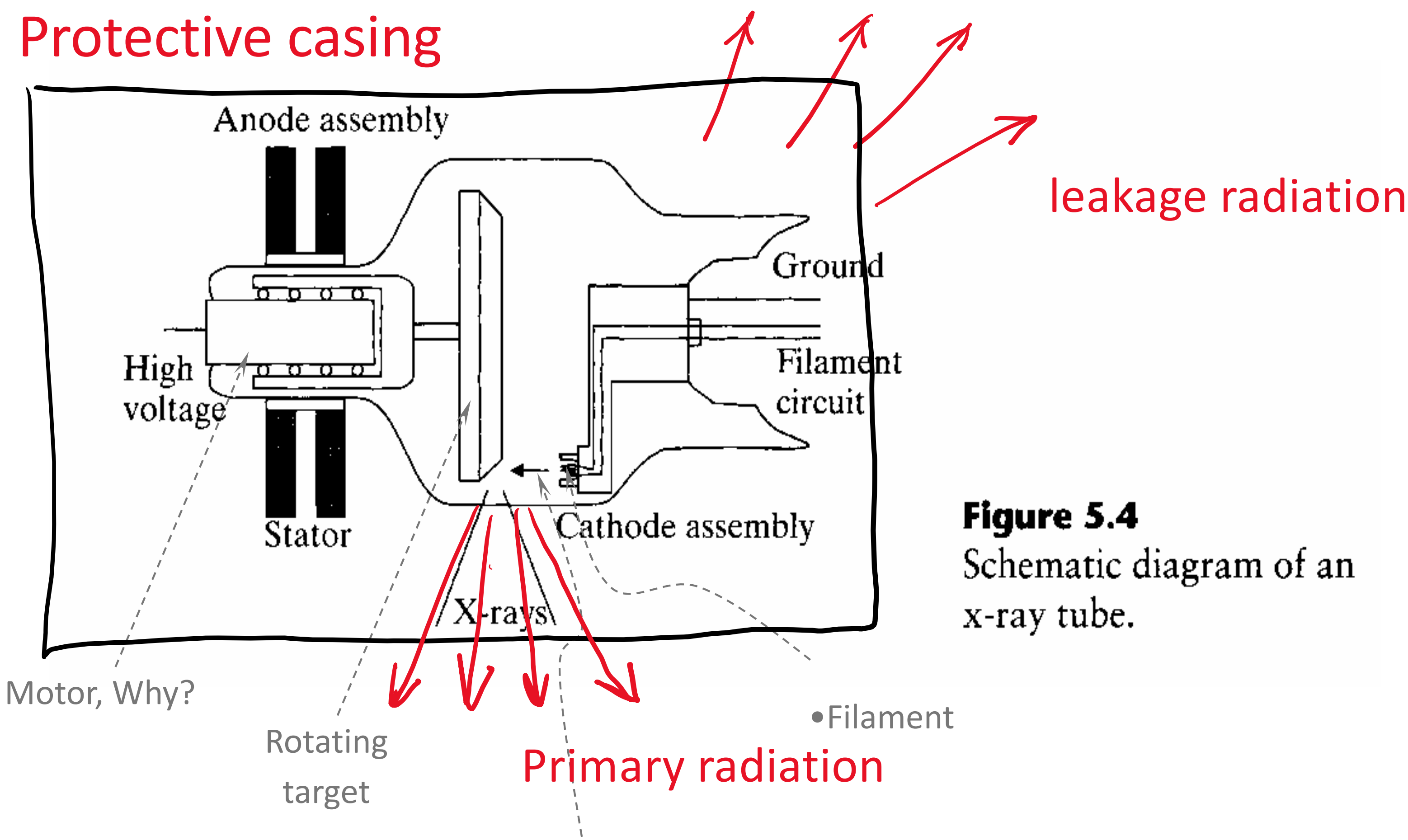


Figure 5.4
Schematic diagram of an x-ray tube.

Shielding for protection against X-rays is considered under two categories: source shielding and structural shielding. Source shielding is usually supplied by the manufacturer of the X-ray equipment as a lead shield in which the X-ray tube is housed. The safety standards recommended by the National Council on Radiation Protection specify the following types of protective tube housings for medical X-ray installations*:

1. *Diagnostic type*: One so built that the leakage radiation air kerma at a distance of 1 m from the target cannot exceed 1 mGy (100 mrads) in 1 h when the tube is operated at its maximum continuous rated current and high voltage.
2. *Therapeutic type*:
   a. For X-rays generated at voltages of 5 to 50 kV. The tube housing is built so that the maximum leakage kerma rate at any point 5 cm from the tube housing does not exceed 1 mGy (100 mrads) in 1 h when the tube is operated at its maximum rated beam current and high voltage.
   b. For X-rays generated at voltages greater than 50 kV but less than 500 kV. A tube housing built so that the leakage kerma rate at a distance of 1 m from the target does not exceed 1 cGy (1 rad) in 1 h. Furthermore, the leakage kerma rate at a distance of 5 cm from the tube housing does not exceed 30 cGy/h (30 rads/h).
   c. For X-ray generated at peak voltages of 500 kV or more. A tube housing built so that (1) the leakage radiation rate in a region outside of the maximum-sized useful beam but within a 2-m radius circular plane centered on the beam's central axis at the normal treatment distance does not exceed 0.2% of the treated tissue dose rate and (2) except for this region, the absorbed dose rate at 1 m from the electron path between the source and the target does not exceed 0.5% of the treatment dose rate on the central axis of the beam at the normal treatment distance.

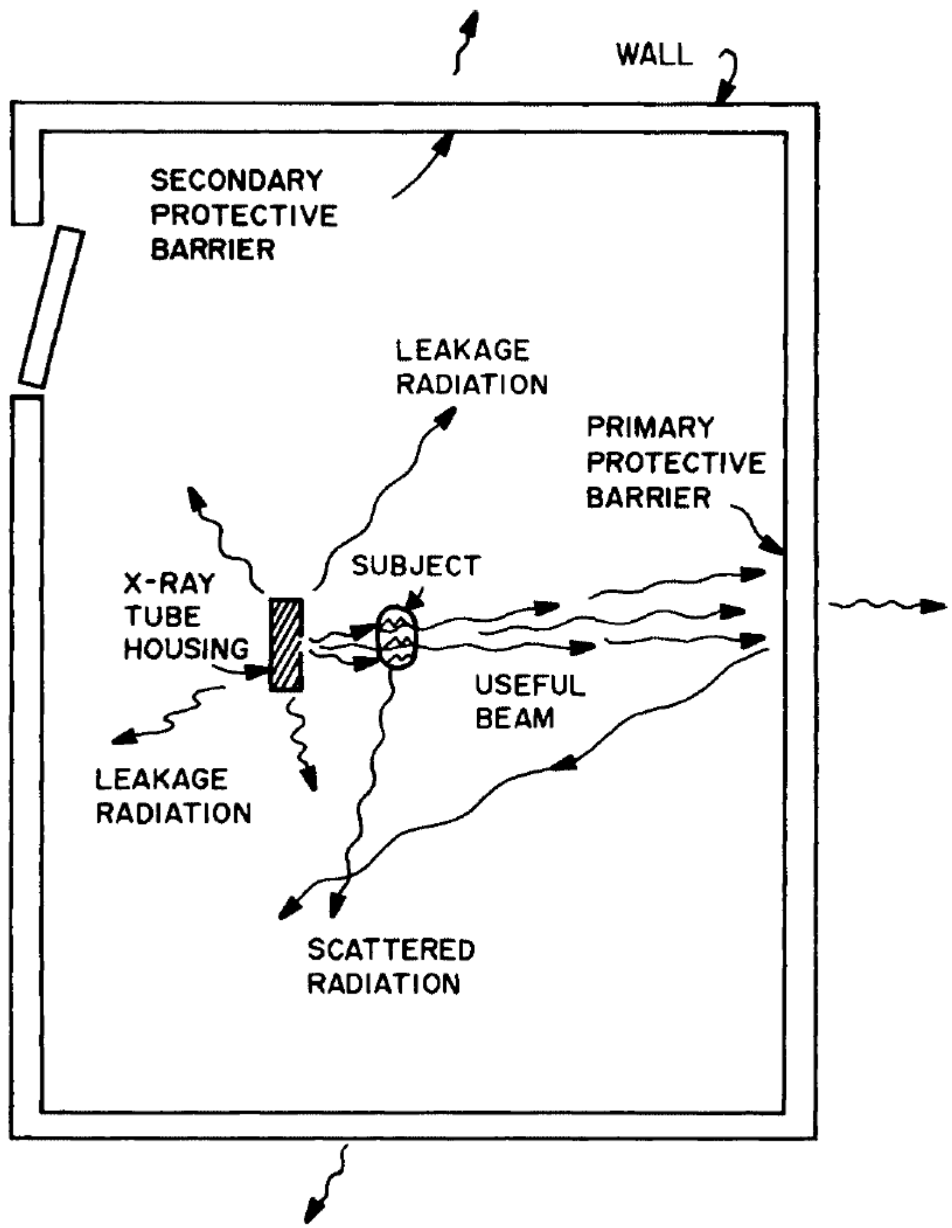


Fig. 15.8 Schematic plan view of X-ray room showing the different radiation components considered in the design of structural shielding to provide primary and secondary protective barriers.

Key Characteristics of X-ray Source Operation

☞ Requirements for structural shielding is determined by considering

1. The maximum kilovoltage at which the X-ray tube is operated.
2. The maximum milliamperes of beam current.
3. The workload (*W*), which is a measure, in suitable units, of the amount of use of an X-ray machine. For X-ray shielding design, workload is usually expressed in units of milliampere-minutes per week.
4. The use factor (*U*), which is the fraction of the workload during which the useful beam is pointed in the direction under consideration.
5. The occupancy factor (*T*), which is the factor by which the workload should be multiplied to correct for the degree or type of occupancy of the area in question. When adequate occupancy data are not available, the values for *T* given in Table 10.1 may be used as a guide in planning shielding.

A Typical X-Ray Generator

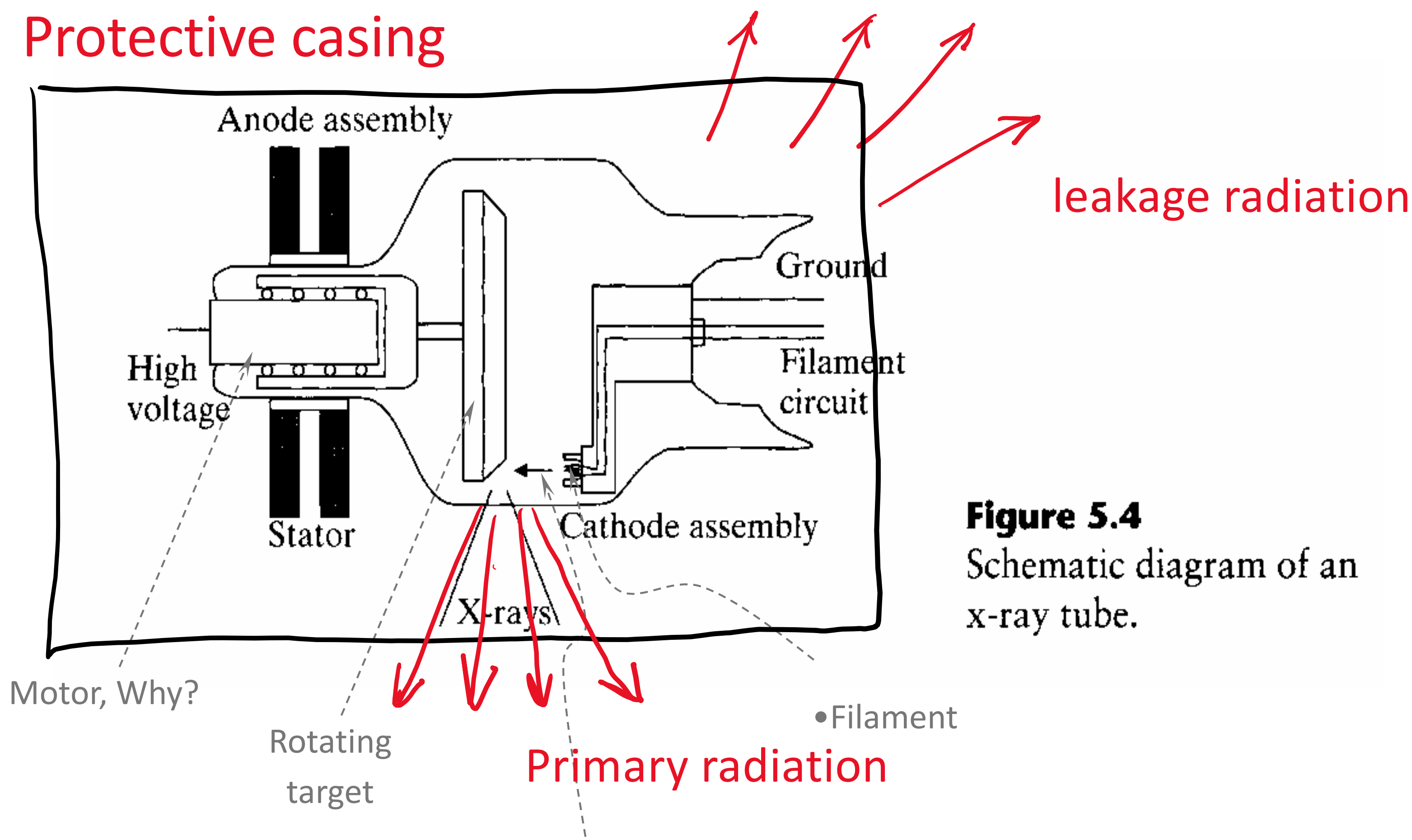


Figure 5.4
Schematic diagram of an x-ray tube.

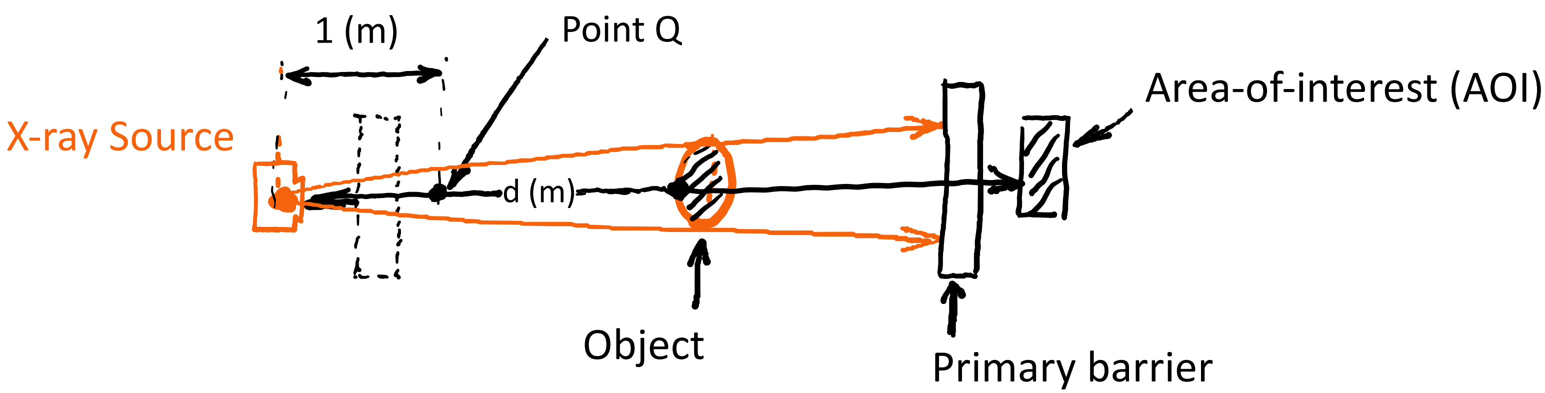
Considerations for X-ray Shielding Design

TABLE 10.1. Occupancy Factors

Full occupancy $T = 1$	Control space, wards, workrooms, darkrooms, corridors large enough to hold desks, waiting rooms, rest rooms used by occupationally exposed personnel, children's play areas, living quarters, occupied space in adjacent buildings
Partial occupancy $T = 1/4$	Corridors too narrow for desks, utility rooms, rest rooms not used routinely by occupationally exposed personnel, elevators run by operators, and uncontrolled parking lots
Occasional occupancy $T = 1/16$	Stairways, automatic elevators, outside areas used only for pedestrians or vehicular traffic, closets too small for future workrooms, toilets not used routinely by occupationally exposed personnel

- ICRP 60 Limits for X-ray exposure:
  - 100mSv (100,000rems) over 5 years.
  - Maximum dose in any single year <50mSv (50,000mrems).

Design of the Primary Protection Barrier

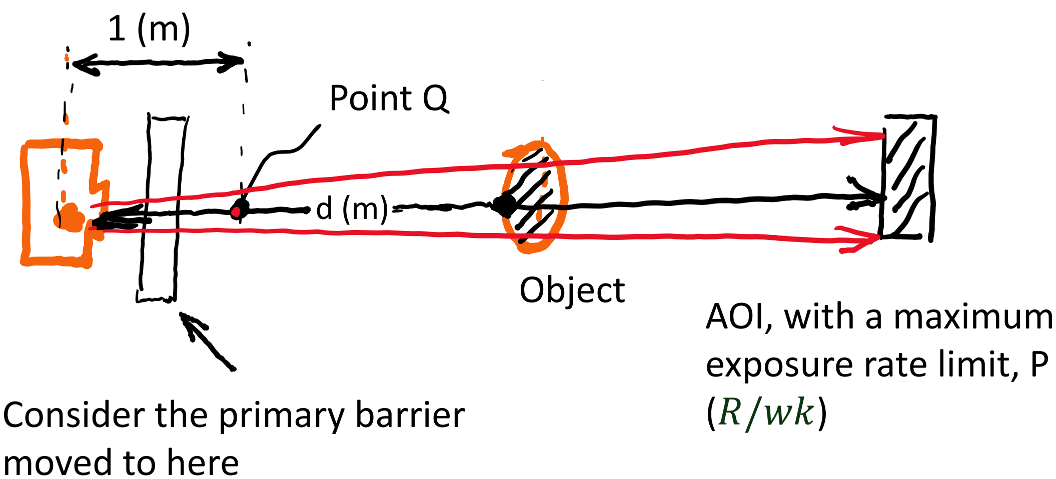


Consider that

- ✓ The maximum allowed exposure rate at the AOI is P (R/wk),
- ✓ The source is operated at a given workload, W (mA·min/wk),
- ✓ The AOI is occupied only for a fraction (T) of time,
- ✓ The use factor of the source is U (the fraction of time when the source is pointing towards the AOI).

Question: What is the thickness of the primary barrier needed to ensure the exposure rate at the AOI stays below the limit P?

Design of the Primary Barrier (A Slightly Different Geometry)



Consider that

- ✓ The maximum allowed exposure rate at the AOI is P (R/wk),
- ✓ The source is operated at a given workload, W (mA·min/wk),
- ✓ The AOI is occupied only for a fraction (T) of time,
- ✓ The use factor of the source is U (the fraction of time when the source is pointing towards the AOI).

Consider that the setup above delivers an exposure rate of *P* (R/wk) at the AOI …

Question: If the source (with the shielding in place) is only running at a unit workload of 1 $mA \cdot min/wk$, what would be the exposure rate at Point Q of 1 m away from the source?

$$K\ (R \cdot mA^{-1} \cdot min^{-1}\ at\ 1m)\ = \frac{d^2 \cdot P(R/wk)}{W(mA \cdot min/wk) \cdot T \cdot U}$$

➔ normalized shielded source output factor

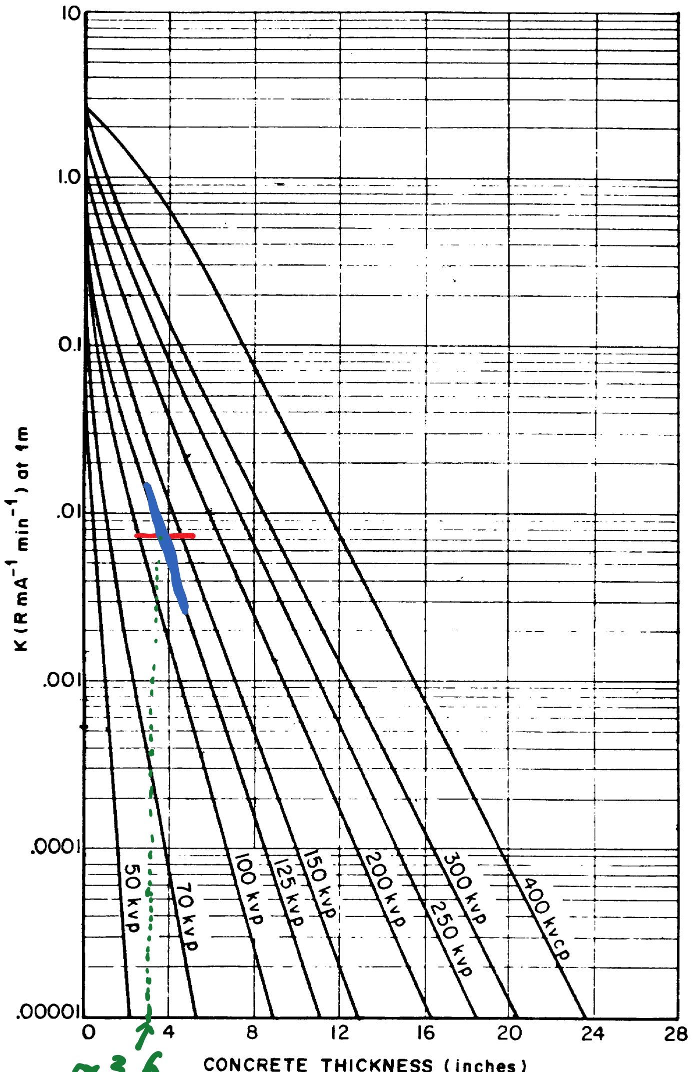
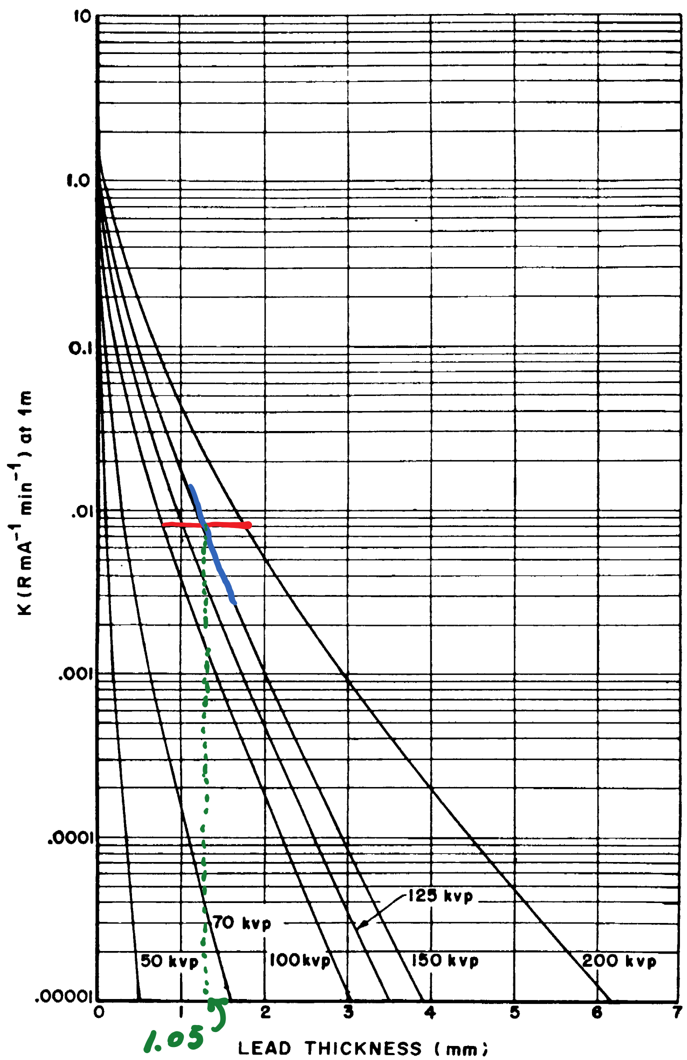


FIGURE 15.6. Attenuation in concrete of X rays produced with (peak) potential differences from 50 kVp to 400 kVp. (*National Bureau of Standards Handbook 76*, 1961, Washington, DC)



IGURE 15.3. Attenuation in lead of X rays produced with (peak) potential differences rom 50 kVp to 200 kVp. (*National Bureau of Standards Handbook 76*, 1961, Washngton, DC)

1 Roentgen (R) = 2.58 × 10−4 (C/kg)

Determining the Requirement for Primary Shielding

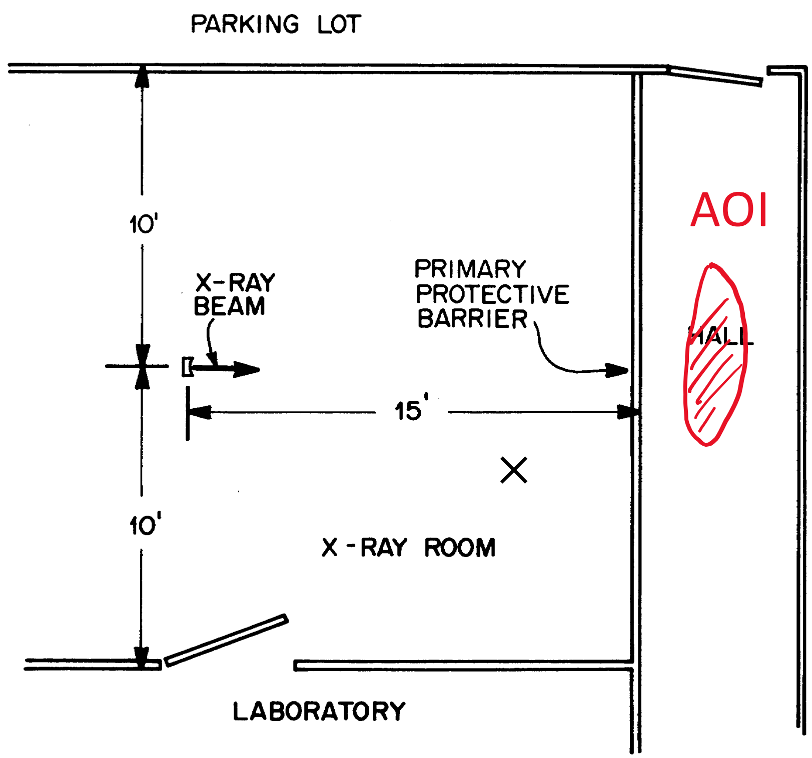


FIGURE 15.8. Schematic top view of an X-ray facility.

The exposure limit for the AOI is *P=0.01 R/wk*

Workload: *W*=220*mA*×1.5*min/wk*

Use factor: *U*=1/3

Occupancy factor: *T*=1/4

Example

A diagnostic X-ray machine is operated at 125 kVp and 220 mA for an average of 90 s wk^{-1}. Calculate the primary protective barrier thickness if lead or concrete alone were to be used to protect an uncontrolled hallway 15 ft from the tube target (Fig. 15.8). The useful beam is directed horizontally toward the barrier ⅓ of the time and vertically into the ground the rest of the time.

Determine the Requirement for Primary Shielding

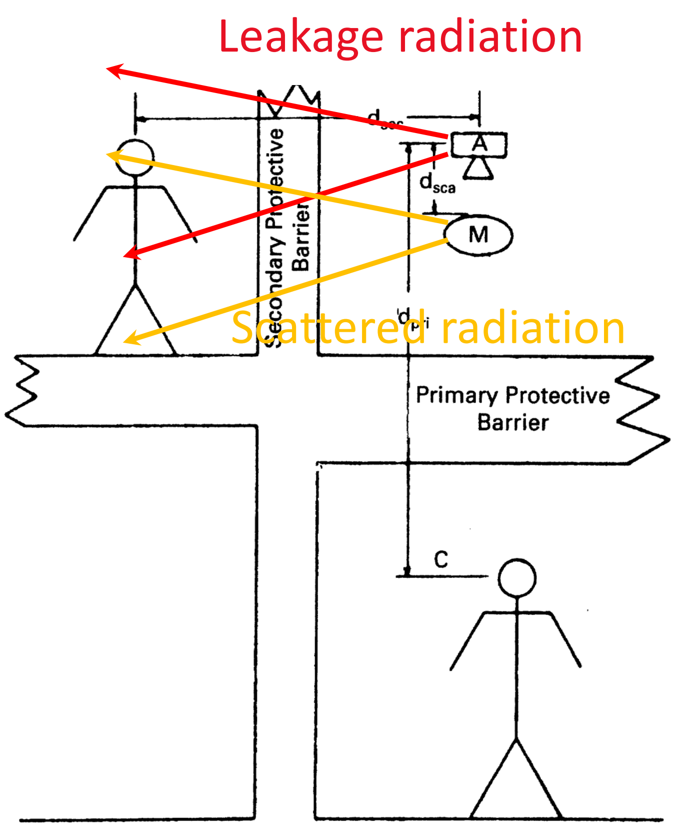
Solution

For the uncontrolled hall, $P = 0.01$ R wk^{-1}. The distance to the hall in meters is $d = 15/3.28$, and the workload is $W = 220$ mA $\times$ 1.5 min wk^{-1} = 330 mA min wk^{-1}. The use of factor is $U = ⅓$ and the occupancy factor (Table 15.3) is $T = ¼$. Equation (15.13) gives

$$K = \frac{d^2P}{WUT} = \frac{0.01 \times (15/3.28)^2}{330 \times 1/3 \times 1/4} = 7.61 \times 10^{-3} \text{ R mA}^{-1} \text{ min}^{-1} \text{ at 1 m.}$$

From Fig. 15.3 we find, for 125 kVp, that the required thickness of lead is about 1.05 mm; from Fig. 15.6, that of concrete is about 3.6 in.

Design of the Secondary Protection Barrier



- Used against the scattered photons and the leakage radiation dose.
- Depends on
  - Scattering angle – assumed to be anisotropic.
  - The energy of the primary photons – a simple energy dependency is assumed to simplify the derivation.
  - Scattering area – assuming a perfect scattering plane.
  - Type of the X-ray tube – in particular in the calculation of the dose rate from leakage radiation.
- Required shielding need to be determined separately for each of these components.

Secondary Protection Barrier against Scattered Radiation

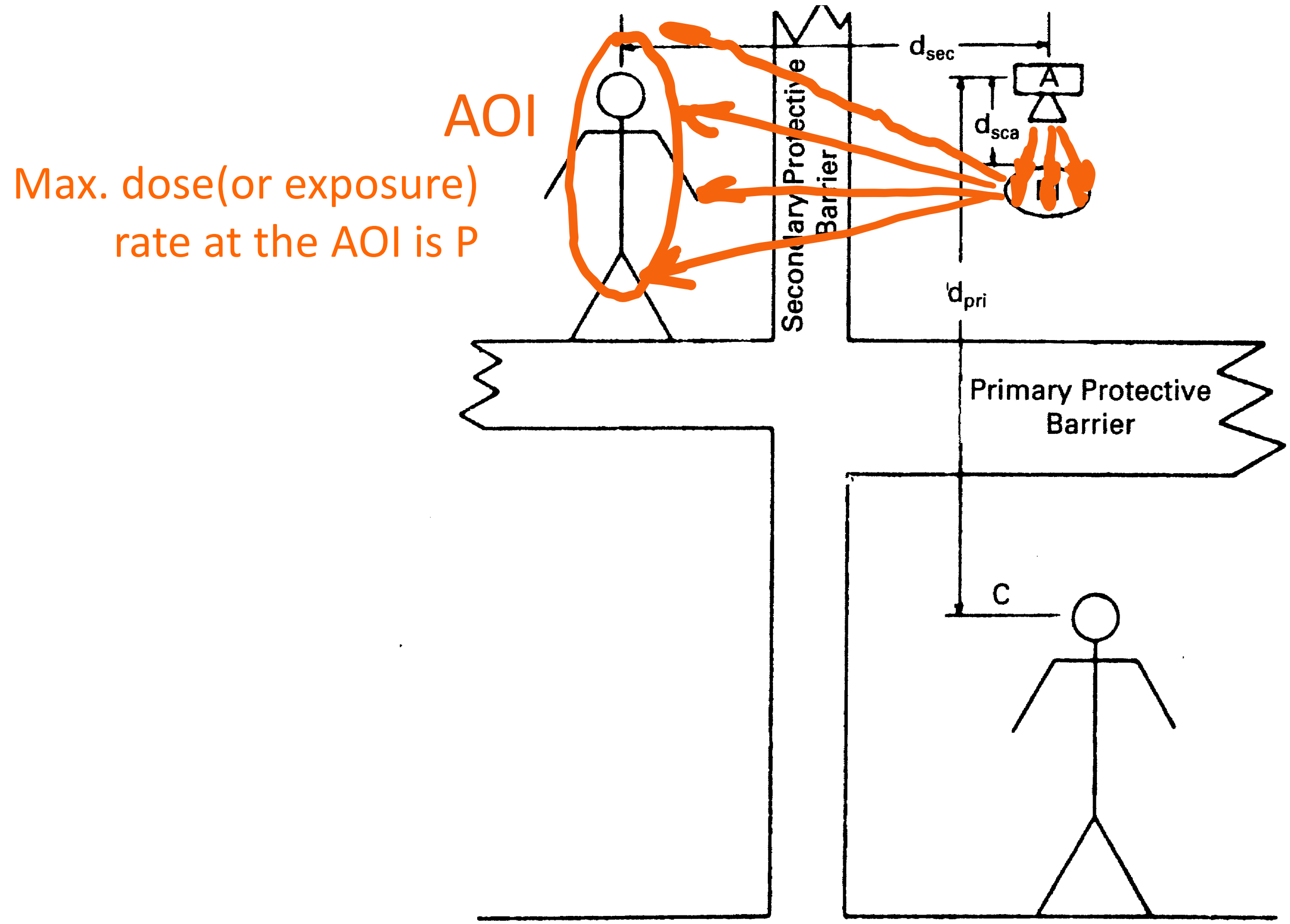
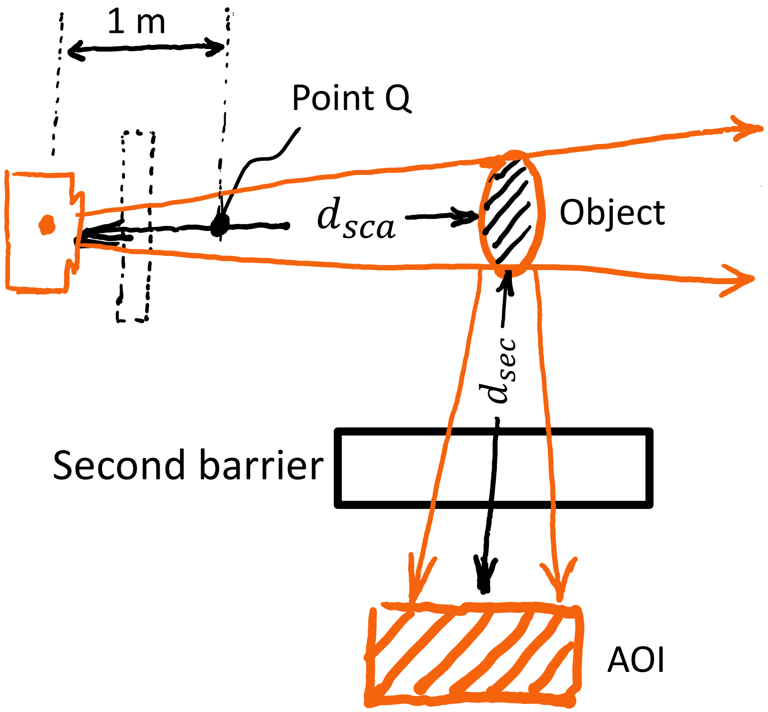
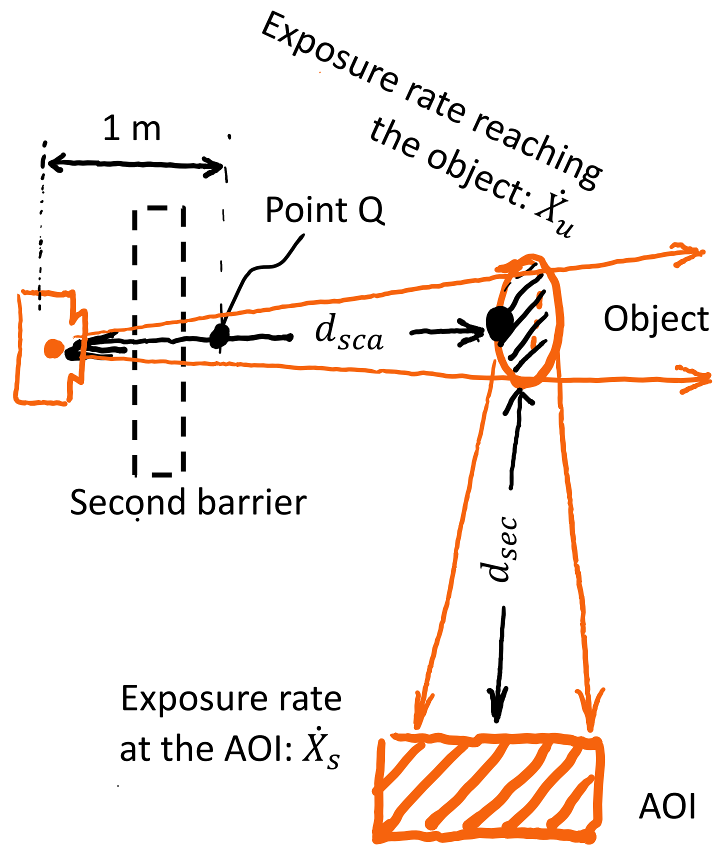


FIGURE 10.11. Elevation view of radiation room and its surroundings with indication of distances of interest for radiation shielding calculations. A is the radiation source, M represents the patient, and C and E are positions that may be occupied by personnel. (From NCRP Report No. 49: *Structural Shielding Design and Evaluation for Medical Use of X-rays and Gamma Rays of Energies up to 10 MeV*, 1976. By permission.)

Secondary Protection Barrier against Scattered Radiation





$$\dot{X}_S = \frac{a \times \dot{X}_u}{(d_{sec})^2} \cdot \frac{F}{400}$$

where a = ratio of scattered to incident radiation, Table 10.3;
$\dot{X}_u$ = exposure rate incident on scatterer;
d_{sec} = distance from scatterer to point of interest;
F = scattering field size, cm^2; and
t = exposure time.

Secondary Protection Barrier against Scattered Radiation

- The amount of **scattered radiation** may be determined based on
  - primary beam energy,
  - scattering angle and
  - scattering area.
- If the exposure rate incident on the object is $\dot{X}_u$, then the exposure rate from scattered radiation **without shielding** may be given by

$$\dot{X}_S = \frac{a \times \dot{X}_u}{(d_{sec})^2} \cdot \frac{F}{400}$$

where a = ratio of scattered to incident radiation, Table 10.3;
$\dot{X}_u$ = exposure rate incident on scatterer;
d_{sec} = distance from scatterer to point of interest;
F = scattering field size, cm^2; and

TABLE 10.3. 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 1 m from phantom when field area is 400 cm^2 at the phantom surface; incident exposure measured at center of field 1 m from the source but without phantom.
[b]From Trout and Kelley (*Radiology* 104:161, 1972. By permission). 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 (*Br J Radiol* 34:389, 1961. By permission.), cylindrical phantom.
[d]From Karzmark and Capone (*Br J Radiol* 41:222 1968. By permission.), cylindrical phantom.
[e]Interpolated from Frantz and Wyckoff (*Radiology* 73:263 1959. By permission). 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. By permission.), modified for F = 400 cm^2.
Source: From NCRP 49. By permission.

Secondary Protection Barrier against Scattered Radiation

In designing secondary protective barriers, we make the following simplifying and conservative assumptions:

1. The energy of the scattered radiation, when the X-rays are generated at 500 kV or less, is equal to the energy of the useful beam.
2. Primary X-ray beams generated at voltages greater than 500 kV are degraded in energy to that of a 500-kV beam after being scattered, and the exposure rate at 1 m from the scatterer is 0.1% of that in the useful beam at the point of scattering.

Secondary Protection Barrier against Scattered Radiation

If the shielded source (shown below) running with given (U, W, T) delivers an exposure rate P at the AOI, then the same shielded source running at 1 $(mA \cdot min)$ should deliver an exposure rate K,

$$K = \frac{\dot{X}_Q}{W \cdot U \cdot T} = \frac{P(R/wk) \cdot d_{sec}^2 \cdot d_{sca}^2}{a \cdot W(mA \cdot min/wk) \cdot T} \cdot \frac{400(cm^2)}{F(cm^2)},$$

to Point Q ...

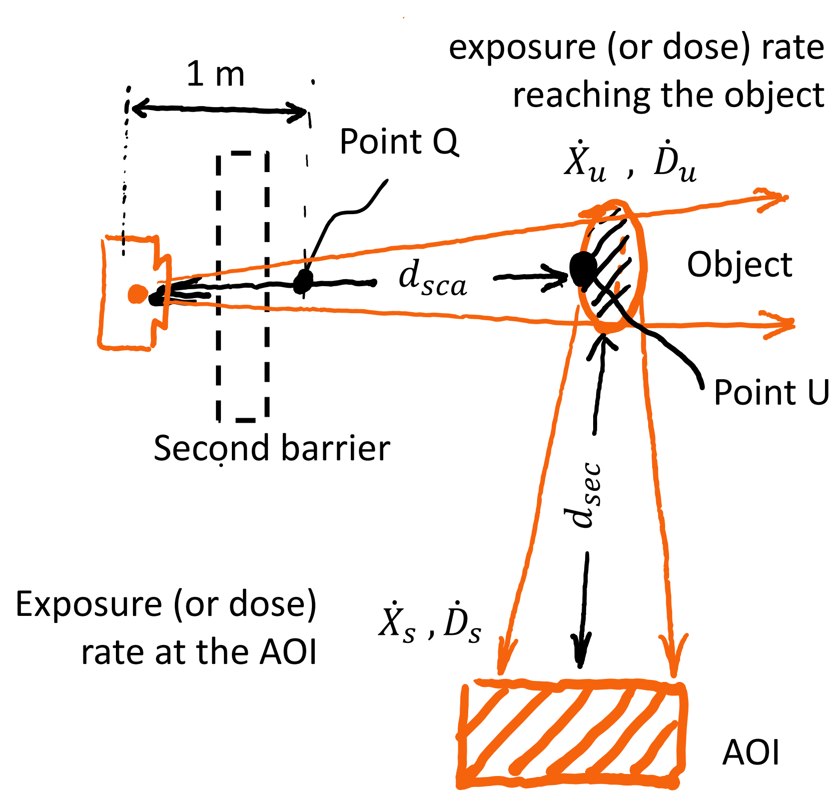
Exposure rate at point Q :

$$\dot{X}_Q = \dot{X}_u \cdot d_{sca}^2 = \frac{P(R/wk) \cdot d_{sec}^2 \cdot d_{sca}^2}{a} \cdot \frac{400(cm^2)}{F(cm^2)}$$

Exposure rate at point U:

$$\dot{X}_u = \frac{P(R/wk) \cdot d_{sec}^2}{a} \cdot \frac{400(cm^2)}{F(cm^2)},$$

where F (cm) is the actual target area of the object



Assuming the exposure rate at the AOI is

$$\dot{X}_s = P(R/wk)$$

Secondary Protection Barrier against Scattered Radiation

Since $It = WT$, and since $U = 1$ for scattered radiation, then,

Normalized shielded source output factor: the dose or exposure that the shielded source running at 1mA for 1 minute should deliver to a reference point at 1 m away

Dist. from the source to the scatterer

Dist. from the scatterer to the AOI

$$K = \frac{P}{aWT} \times (d_{sca})^2 \times (d_{sec})^2 \times \frac{400}{F}.$$

a: ratio between incident exposure and scattered exposure measured at 1 m from the object/scatterer, whose scattering area is assumed to be 400 cm^2

Actual size of the scatterer/object

The occupancy of the AOI

Workload – the amount of usage of the x-ray tube (mA·min/wk)

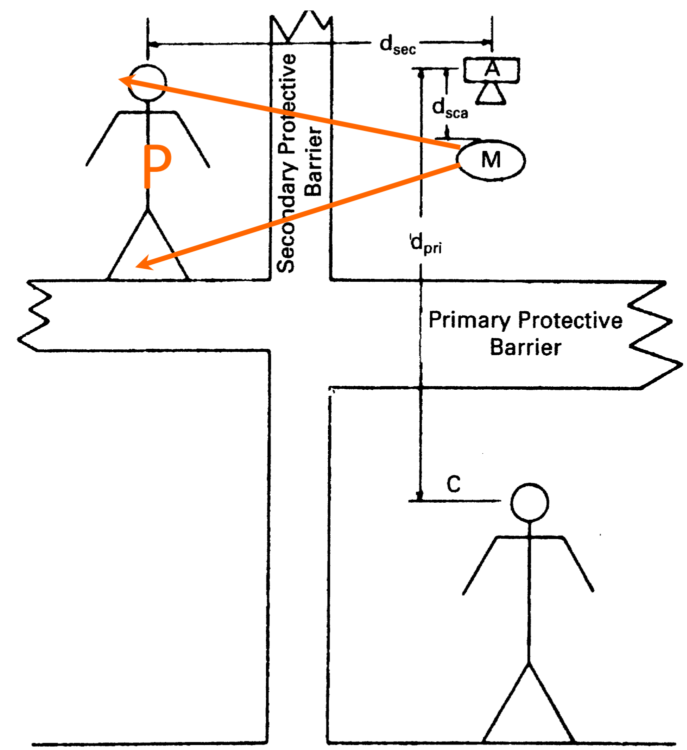
Secondary Protection Barrier for Scattered Radiation

☞ The exposure rate that the same source would deliver at 1 m away (within the primary beam) by running at 1 mA for 1 min is given by

$$K = \frac{P \times (d_{sca})^2 \times (d_{sec})^2 \times 400}{a \times W \times T \times F \times f} \quad (R \cdot mA^{-1} \cdot min^{-1} \; at \; 1m)$$

Correction factor, whose value increases with the increasing HV of the tube.

kV	f
500 or less	1
1000	20
2000	300
3000	700



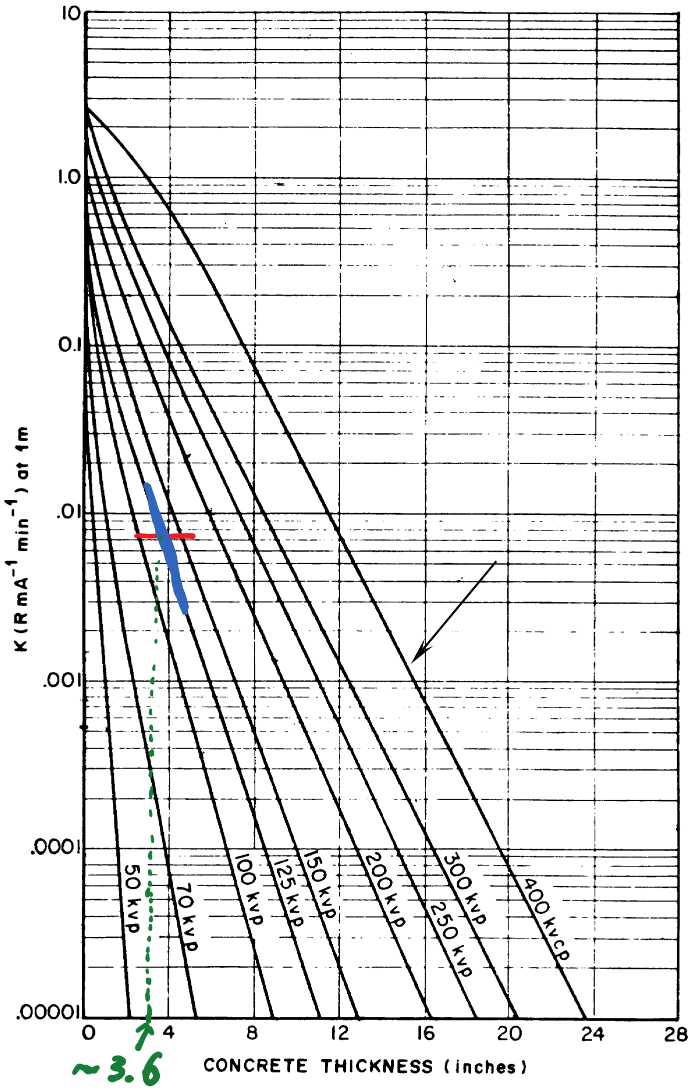
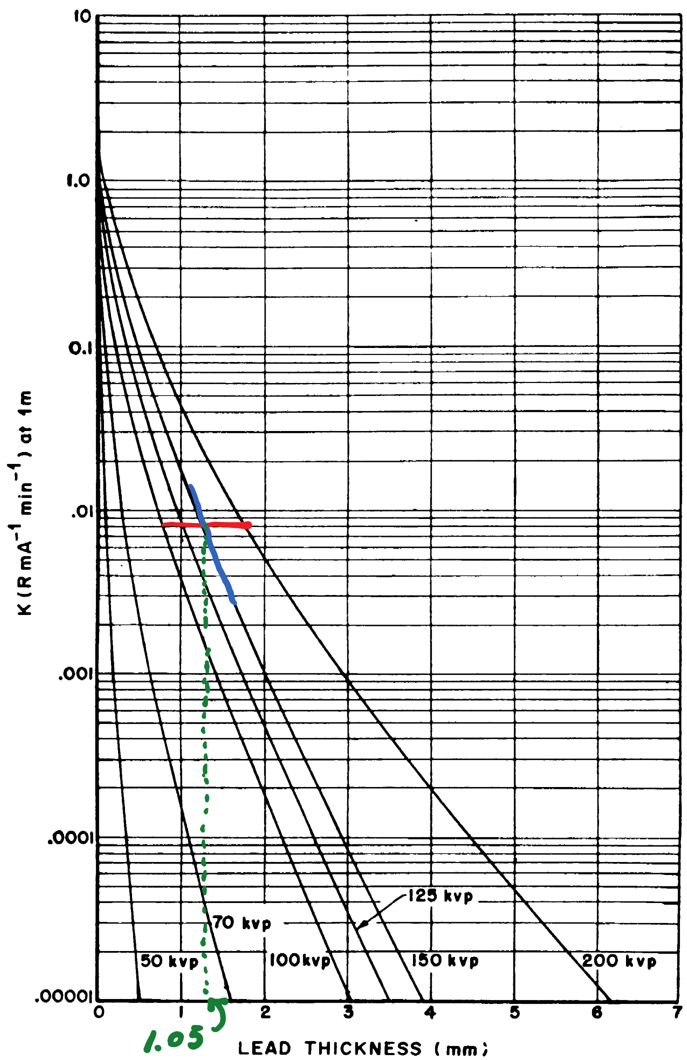


FIGURE 15.6. Attenuation in concrete of X rays produced with (peak) potential differences from 50 kVp to 400 kVp. (*National Bureau of Standards Handbook 76*, 1961, Washington, DC)



IGURE 15.3. Attenuation in lead of X rays produced with (peak) potential differences rom 50 kVp to 200 kVp. (*National Bureau of Standards Handbook 76*, 1961, Washngton, DC)

Secondary Protection Barrier for Leakage Radiation

- Considerations on the dose by leakage radiation
  - For diagnostic x-ray tubes, the maximum leakage dose rate is 1 mSv (0.1 rem) per h at 1 m (quality standard for x-ray tube manufacturers).
  - If the source is running for t mins per week, the maximum leakage dose rate delivered to an area at a distance *d* meter away is

ICRP dose limit imposed on all commercial X-ray generators (Rem/h at 1 m)

Assuming working for t mins per week, t=W/I

Dose rate: Rem/wk

$$\dot{D}_L\left(\frac{rem}{wk}\right) = \frac{0.1\left(\frac{rem}{h}\right)}{d^2} \times \frac{t\left(\frac{min}{wk}\right)}{60\left(\frac{min}{h}\right)}$$

Distance between the AOI and the source

- Consider the occupancy factor (T) of the area-of-interest and the workload of the x-ray source (W), the maximum dose rate delivered by the leakage radiation is

$$\dot{D}_L\left(\frac{rem}{wk}\right) = \frac{0.1\left(\frac{rem}{h}\right)}{d^2} \times \frac{W\left(\frac{mA \cdot min}{wk}\right) \cdot T}{60\left(\frac{min}{h}\right) \cdot I(mA)}$$

I: Tube current (mA)

Secondary Protection Barrier for Leakage Radiation

☞ If the maximum dose rate (P) allowed at a distance d (m) from the target, the shielding factor, $B_{Lx,}$ of the barrier for leakage radiation may be determined by

Dose limit at the AOI

$$B_{LX} = \frac{P}{\dot{D}_L} = \frac{P \cdot d^2 \cdot 600 \cdot I}{\mathrm{W} \cdot T}$$

Dose at the AOI without shielding

Design of An X-ray Shielding Structure

Example 10.9

The room shown in Fig. 10.17 will be used for diagnostic radiology. From the floor to the ceiling is 9 ft 7 in. (292 cm). The room above is another office that is not controlled by the radiologist. The X-ray room is on the ground floor of the building; there is no occupied space below. The floor and ceiling are made of concrete 5 in. (12.7 cm) thick; wall A is made of concrete 4 in. (10.2 cm) thick. Walls B, C, and D are made of hollow tile and thin plaster, as shown in section A-A. The maximum machine ratings are 125 kVp and 200 mA. As a fluoroscope, the machine will be operated 5 h a week at 3.5 mA, and for radiography the machine will be operated at 200 mA for 2 min in a week. The average target to skin distance if 0.5 m. Compute the required shielding for the ceiling and for wall B.

workload

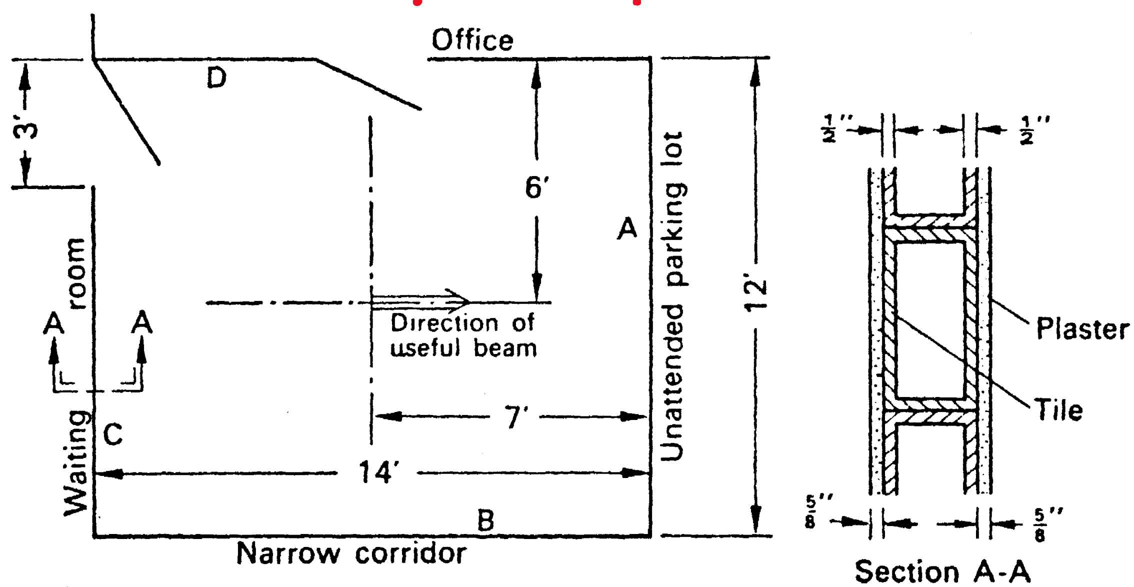


FIGURE 10.17. Layout of diagnostic X-ray room of Example 10.9.

Design of An X-ray Shielding Structure

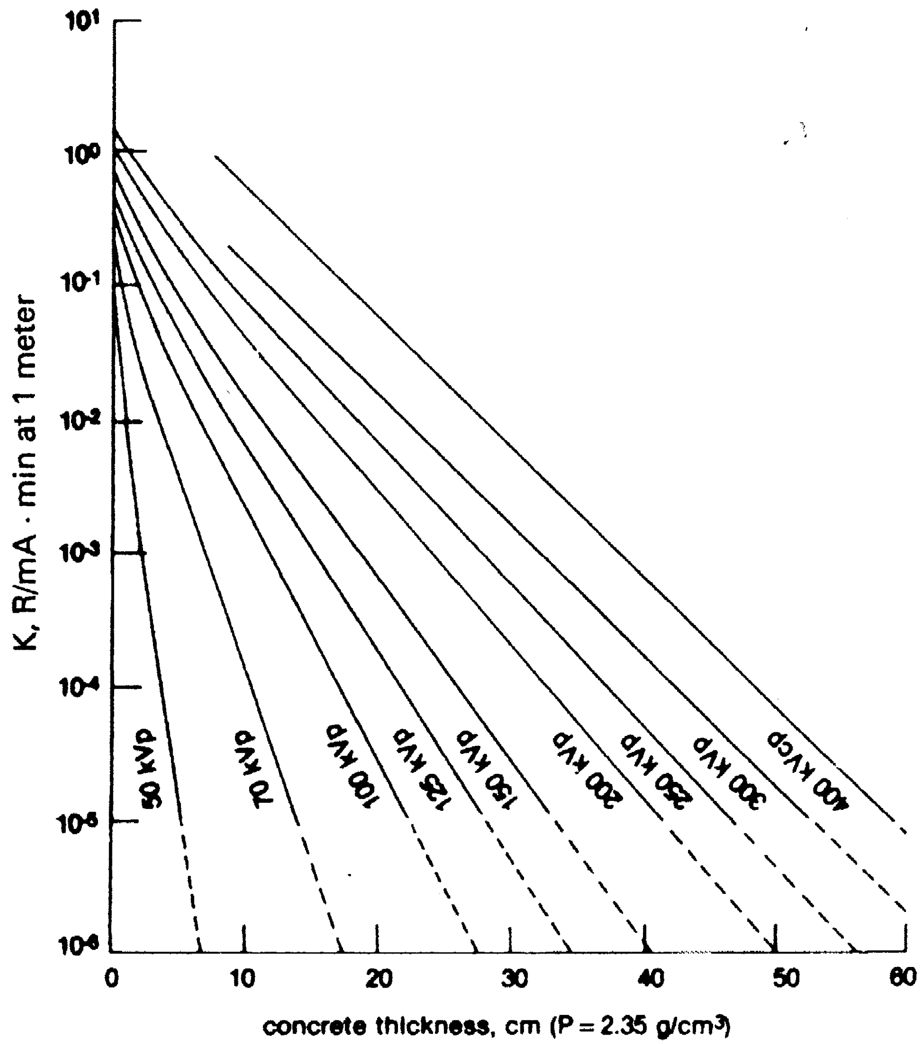


FIGURE 10.13. Attenuation in concrete of X-rays produced by potentials of 50 to 300 kVp; 400 kV constant potential. The measurements were made with a 90° angle between the electron beam and the axis of the X-ray beam. The curves for 50 to 300 kV are for a pulsed waveform. The filtrations were 1 mm Al for 50 kV, 1.5 mm Al for 70 kV, 2 mm Al for 100 kV, and 3 mm Al for 125, 150, 200, 250, and 300 kV. The 400-kV curve was interpolated from data obtained with a constant potential generator and inherent filtration of approximately 3 mm Cu. (From NCRP Report No. 49, *Structural Shielding Design and Evaluation for Medical Use of X-Rays and Gamma Rays of Energies up to 10 MeV*, 1976. Full-size reproductions of the figures giving barrier requirements are available from the NCRP as an adjunct to the report. By permission.)

Step 1: Design of the primary barrier

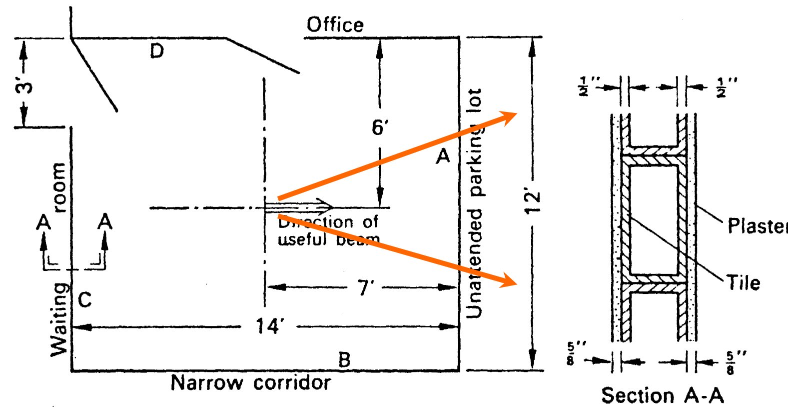


FIGURE 10.17. Layout of diagnostic X-ray room of Example 10.9.

Considering

- Directly irradiating Wall A at a distance **d**=7 feet,
- Workload: **W**=2 (mins/week) × 200 (mA),
- Use factor: **U**=1,
- Occupancy factor: **T**=1/4,
- Maximum allowed weekly dose to an uncontrolled area: **P**=0.02 mSv/wk.

Consider a shielded X-ray source that is running with given (W, U, T) and delivers a dose rate (or exposure) rate P at the AOI. If we move the shielding in front of the same source, then the **dose (or exposure) that this shielded source would deliver to point Q at a distance of 1 m away by running the source with 1 mA tube current for 1 min** is given by

$$K_{dose} = \frac{d^2 \cdot P}{W \cdot U \cdot T} = 9.07 \times 10^{-4} mSv/(mA \cdot min) \ \text{at } 1m$$

Then we convert the maximum allowed dose K_{dose} to the maximum allowed exposure $K_{exposure}$, so we could use existing data to derive the shielding requirement.

For this purpose, we consider

- The quality factor or photons is 1, and
- 1 X Unit = 34Gy
- 1 X Unit = 3881 Roentgen

$$K_{exposure} = K_{dose}(Sv)/34 \times 3881$$
$$= 1.03 \times 10^{-4} R/(mA \cdot min) \text{ at } 1\, m$$

Step 1: Design of the primary barrier (continued)

The maximum exposure that is allowed at a unit distance and delivered by the source running at the "standard" operating condition (W=1, U=1, T=1)

$$\mathbf{K_{exposure} = K_{dose}/34 \times 3881 = 1.03 \times 10^{-4}\,R/(mA \cdot min)\ at\ 1\ m}$$

Given the source is 125 kVp, we can use the figure on the right to find the thickness of the concrete slab needed to achieve the maximum allowed exposure limit $K_{exposure}$ is 21.5 cm.

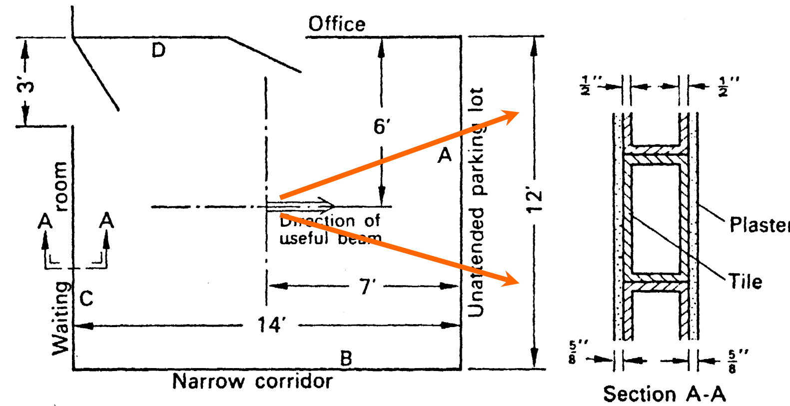


FIGURE 10.17. Layout of diagnostic X-ray room of Example 10.9.

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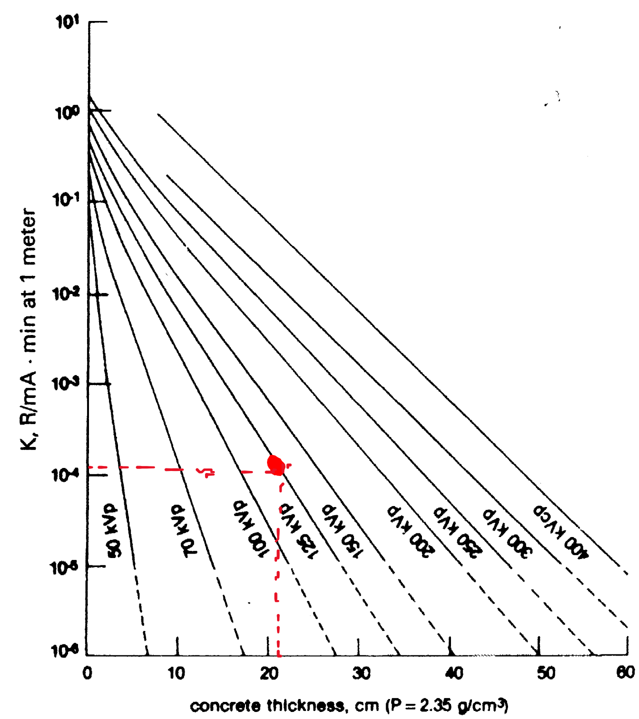


Step 2: Design of the second barrier (ceiling) against leakage radiation

Considering

- The source is installed **1.5 m** from the ceiling,
- The AOI is 3 feet above the ceiling, and about 8 feet from the source, **d=8 feet=2.5m**.
- The maximum dose allowed for an uncontrolled area is **P=0.002 Rem/week** (0.02 mSv/week)
- Assuming the source is **generating 0.1 Rem/h (1 mSv/h) dose at 1 m through leakage radiation by running for 60 mins per week** (the ICRP limit on commercial diagnostic X-ray source).
- For diagnosis purposes, this source is typically running for **t=302 mins/wk**.

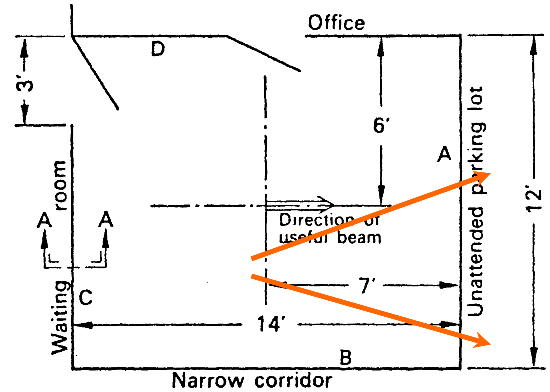


FIGURE 10.17. Layout of diagnostic X-ray room of Example 10.9.

Then , the attenuation factor required to bring the radiation dose at the AOI to below **the 0.02 mSv/wk limit** is given by

$$\dot{D}_L\left(\frac{rem}{wk}\right) = \frac{0.1\left(\frac{rem}{h}\right)}{d^2} \times \frac{t(\frac{min}{wk})}{60(\frac{min}{h})}$$

$$B_{Lx} = \frac{0.02(\mathrm{m}Sv/\mathrm{wk})}{\frac{1\,(mSv/h)}{d^2}\cdot\frac{t(\mathrm{min/wk})}{60\,(\mathrm{min/wk})}} = \frac{0.02(\mathrm{m}Sv/\mathrm{wk})}{\frac{0.1\,(mSv/h)}{(2.5\,m)^2}\cdot\frac{302\,(\mathrm{min/wk})}{60\,(\mathrm{min/wk})}} = 0.0248$$

It would take a concrete shielding of (n × half-value layer) to achieve the desired shielding effect, where n is given by

$$0.0248 = \frac{1}{2^n}, \text{ and n=5.33}$$

Finally, considering the half-value layer for concrete for X-rays from the 125 kVp source is 2 cm, then the total thickness of concrete to protect the AOI from leakage radiation is about 10 cm.

Step 3: Design of the second barrier (ceiling) against scattered radiation

Considering

- Workload: **W=2 (mins/week) × 200 (mA)=1200 (mA ·min/week)**,
- Use factor: **U=1**,
- Occupancy factor: **T=1**,
- **d_{sca}=0.5 m** (distance between the source and the patient),
- **d_{sec}=2.5 m** (distance between the patent and the area of interest, AOI),
- **a=0.0015** from Table 10.17, Ratio of scattered to incident radiation
- Target area of the patient to the incident X-rays, **F=400 cm^2**,
- Maximum allowed weekly dose to an uncontrolled area: **P=0.02 mSv/wk**,

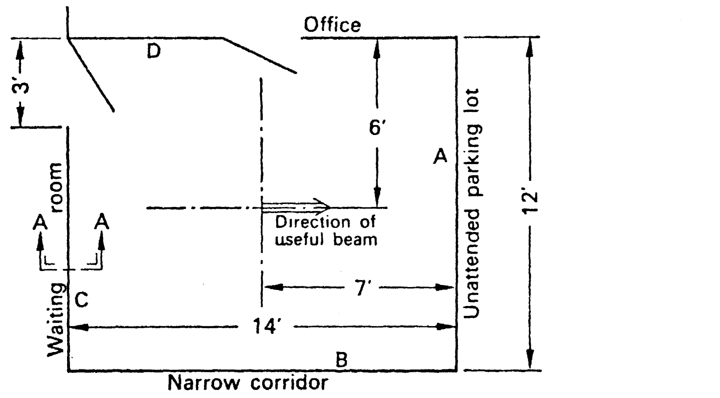


FIGURE 10.17. Layout of diagnostic X-ray room of Example 10.9.

The maximum dose that is allowed at a unit distance delivered by the source running at 1 mA for 1 min is given by

$$K = \frac{P}{a \cdot W \cdot T} \cdot d_{sca}^2 \cdot d_{sec}^2 \cdot \frac{400\ \mathrm{cm}^2}{F\ \mathrm{cm}^2}$$
$$= 1.4 \times 10^{-3} rem/(mA \cdot \min)\ at\ 1m$$
$$= 1.4 \times 10^{-5} Sv/(mA \cdot \min)\ at\ 1m$$

TABLE 10.3. 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 1 m from phantom when field area is 400 cm^2 at the phantom surface; incident exposure measured at center of field 1 m from the source but without phantom.
[b]From Trout and Kelley (*Radiology* 104:161, 1972. By permission). 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 (*Br J Radiol* 34:389, 1961. By permission.), cylindrical phantom.
[d]From Karzmark and Capone (*Br J Radiol* 41:222 1968. By permission.), cylindrical phantom.
[e]Interpolated from Frantz and Wyckoff (*Radiology* 73:263 1959. By permission). 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. By permission.), modified for *F* = 400 cm^2.
Source: From NCRP 49. By permission.

Secondary Protection Barrier against Scattered Radiation

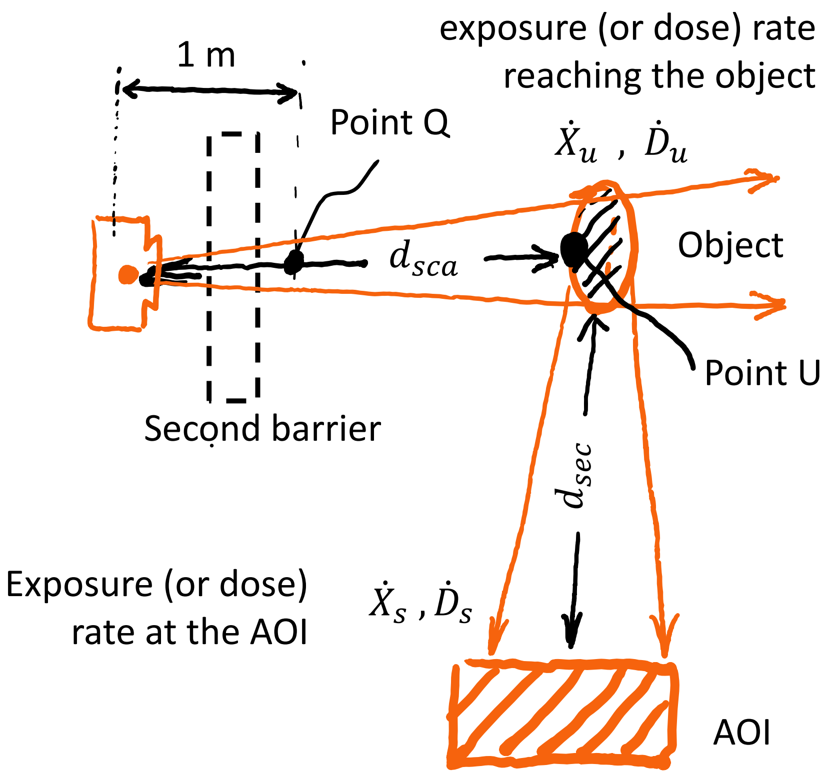
If the shielded source (shown below) running with given (U, W, T) delivers an exposure rate P at the AOI, then the same shielded source running at 1 mA for 1 min should deliver an exposure K,

$$K = \frac{\dot{X}_Q}{W \cdot U \cdot T} = \frac{P(R/wk) \cdot d_{sec}^2 \cdot d_{sca}^2}{a \cdot W(mA \cdot min/wk) \cdot T} \cdot \frac{400(cm^2)}{F(cm^2)},$$

to Point Q, which is the normalized shielded output factor …

Exposure rate at point Q :

$$\dot{X}_Q = \dot{X}_u \cdot d_{sca}^2 = \frac{P(R/wk) \cdot d_{sec}^2 \cdot d_{sca}^2}{a} \cdot \frac{400(cm^2)}{F(cm^2)}$$



Exposure rate at point U:

$$\dot{X}_u = \frac{P(R/wk) \cdot d_{sec}^2}{a} \cdot \frac{400(cm^2)}{F(cm^2)},$$

where F (cm) is the actual target area of the object

Assuming the exposure rate at the AOI is

$$\dot{X}_s = P(R/wk)$$

Step 3: Design of the second barrier (ceiling) against scattered radiation (continued)

The maximum dose that is allowed at a unit distance delivered by the source running at 1 mA for 1 min is given by

$$K = \frac{P}{a \cdot W \cdot T} \cdot d_{sca}^2 \cdot d_{sec}^2 \cdot \frac{400 \text{ cm}^2}{F \text{ cm}^2}$$
$$= 1.4 \times 10^{-3} rem/(mA \cdot \text{min}) \ at \ 1m$$
$$= 1.4 \times 10^{-5} Sv/(mA \cdot \text{min}) \ at \ 1m$$

Then we convert the maximum allowed dose K_{dose} to the maximum allowed exposure $K_{exposure}$, so we could use existing data to derive the shielding requirement.

For this purpose, we consider

- The quality factor or photons is 1, and
- 1 X Unit = 34Gy
- 1 X Unit = 3881 Roentgen

$$\mathbf{K_{exposure}} = \mathbf{K_{dose}}(Sv)/34 \times 3881$$
$$= 1.4 \times 10^{-5}\, Sv/(\text{mA} \cdot \text{min})/34 * 3881 =$$
$$1.6 \times 10^{-3}\, R/(\text{mA} \cdot \text{min}) \text{ at } 1 \text{ m}$$

Using the figure on the right, we find that the thickness of concrete needed to bring the exposure down to the maximum allowed value $\mathbf{K_{exposure}}$ is 14 cm.

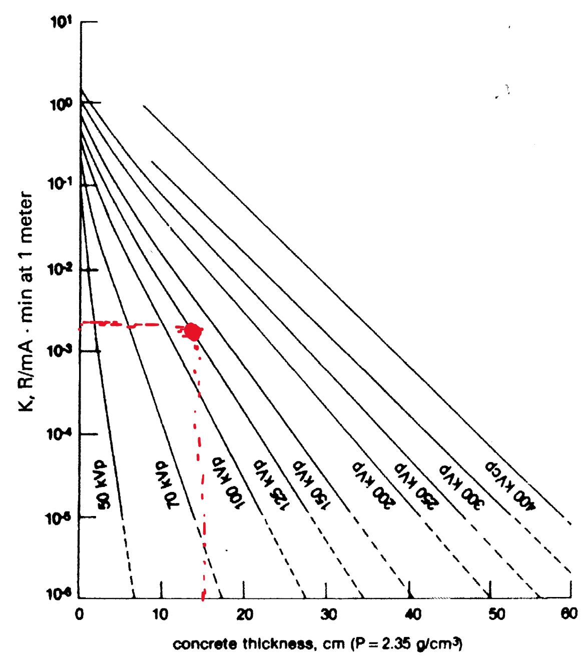


FIGURE 10.13. Attenuation in concrete of X-rays produced by potentials of 50 to 300 kVp; 400 kV constant potential. The measurements were made with a 90° angle between the electron beam and the axis of the X-ray beam. The curves for 50 to 300 kV are for a pulsed waveform. The filtrations were 1 mm Al for 50 kV, 1.5 mm Al for 70 kV, 2 mm Al for 100 kV, and 3 mm Al for 125, 150, 200, 250, and 300 kV. The 400-kV curve was interpolated from data obtained with a constant potential generator and inherent filtration of approximately 3 mm Cu. (From NCRP Report No. 49, *Structural Shielding Design and Evaluation for Medical Use of X-Rays and Gamma Rays of Energies up to 10 MeV*, 1976. Full-size reproductions of the figures giving barrier requirements are available from the NCRP as an adjunct to the report. By permission.)