X-Ray Shielding
X-Ray Uses in Image Guided Surgery

- X-ray II is the standard detector for current projection radiography system
X-Ray Uses for Radiation Therapy

• X-ray II is the standard detector for current projection radiography system
X-Ray Sources

Protective casing

Anode assembly

Filament circuit

Cathode assembly

Ground

High voltage

Stator

X-rays

Primary radiation

Leakage radiation

• Motor, Why?

• Rotating target

• Electron beam? How are electrons generated?

• Filament

Figure 5.4
Schematic diagram of an x-ray tube.
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.
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.
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.
X-Ray Sources

Protective casing

Anode assembly

Stator

Filament circuit

Cathode assembly

X-rays

Primary radiation

leakage radiation

- Motor, Why?
- Rotating target
- Filament
- Electron beam? How are electrons generated?

Figure 5.4
Schematic diagram of an x-ray tube.
Considerations for X-ray Shielding Design

**Table 10.1. Occupancy Factors**

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

ICRP 60 Limits for X-ray exposure:

- 100mSv (100,000rems) over 5 years
- Maximum dose in any single year <50mSv (50,000mrems)
Typical X-ray Shielding Setup

- Primary (for x-ray beam passing through the patient) and secondary (for leakage and scattered photons) shielding:

\[
\text{Area-of-interest (AOI), Maximum permissible dose rate: } P \text{ (rem/week)}
\]

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

Consider that

- The maximum allowed dose rate (or exposure rate) at the AOI is $P$,
- A shielded source is tuned to deliver a weekly dose exactly equal to $P$, with a given workload of $W$ (mA·min/wk),
- The AOI is occupied only for a fraction ($T$) of time,
- The source, when operating, has a use factor of $U$ (the fraction of time that the source is pointing towards the AOI).

**Question:** What is the thickness of primary barrier needed to ensure the dose rate (or exposure rate) at the AOI to stay below the limit $P$?
Design of the Primary Barrier

Consider the primary barrier moved to here

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 distance of 1 m away by running at 1 mA for 1 min is given by

\[
K = \frac{d^2 \cdot P}{W \cdot T \cdot U} \quad \Rightarrow \text{normalized shielded source output factor}
\]

Question: how much shielding is needed for the source to deliver a given dose (or exposure) \(K\) per \((mA \cdot min)\) at 1 m away?
If we consider X-ray sources of different kVp values running with 1 unit workload of 1 mA·min/week, these curve give the thicknesses of shielding needed for the sources to deliver an exposure of K (R) at 1m.

Note that 1 Roentgen (R) = 2.58 × 10⁻⁴ (C/kg)
Determining the Requirement for Primary Shielding

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 $\frac{1}{3}$ 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 \( U = 1/2 \) and the occupancy factor (Table 15.3) is \( T = 1/4 \). Equation (15.13) gives

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

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.
Chapter 7: External Radiation Protection

Secondary Protection Barrier against Scattered Radiation

Max. dose(exposure) rate, P

AOI

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, \( \text{cm}^2 \); and
- \( t \) = exposure time.
Secondary Protection Barrier against Scattered Radiation

The extend 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$^a$

<table>
<thead>
<tr>
<th>Source</th>
<th>Scattering Angle (from Central Ray)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>X-rays</td>
<td></td>
</tr>
<tr>
<td>50 kV$^b$</td>
<td>0.0005</td>
</tr>
<tr>
<td>70 kV$^b$</td>
<td>0.00065</td>
</tr>
<tr>
<td>100 kV$^b$</td>
<td>0.0015</td>
</tr>
<tr>
<td>125 kV$^b$</td>
<td>0.0018</td>
</tr>
<tr>
<td>150 kV$^b$</td>
<td>0.0020</td>
</tr>
<tr>
<td>200 kV$^b$</td>
<td>0.0024</td>
</tr>
<tr>
<td>250 kV$^b$</td>
<td>0.0025</td>
</tr>
<tr>
<td>300 kV$^b$</td>
<td>0.0026</td>
</tr>
<tr>
<td>4 MV$^c$</td>
<td>—</td>
</tr>
<tr>
<td>6 MV$^d$</td>
<td>0.007</td>
</tr>
<tr>
<td>Gamma rays</td>
<td></td>
</tr>
<tr>
<td>$^{137}$Cs$^e$</td>
<td>0.0065</td>
</tr>
<tr>
<td>$^{60}$Co$^f$</td>
<td>0.0060</td>
</tr>
</tbody>
</table>

---

$^a$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.


$^d$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.
Chapter 7: External Radiation Protection

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 \(K\)

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

to Point \(Q\), which is the normalized shielded output factor ...

Exposure rate at point \(Q\):

\[
\dot{X}_Q = \dot{X}_u \cdot d_{sec}^2 \cdot a \cdot \frac{P \left(\frac{R}{\omega \cdot k}\right) \cdot d_{sec}^2 \cdot d_{sca}^2 \cdot 400 \text{(cm}^2\text{)}}{a \cdot F \text{(cm}^2\text{)}}.
\]

Exposure rate at point \(U\):

\[
\dot{X}_u = \frac{P \left(\frac{R}{\omega \cdot k}\right) \cdot d_{sec}^2 \cdot 400 \text{(cm}^2\text{)}}{a \cdot F \text{(cm}^2\text{)}},
\]

where \(F \text{ (cm)}\) is the actual target area of the object

Assuming the exposure rate at the AOI is

\[
\dot{X}_s = P \left(\frac{R}{\omega \cdot k}\right)
\]
Secondary Protection Barrier against Scattered Radiation

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

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

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

- $P$: Workload – the amount of usage of the x-ray tube (mA·min/wk)
- $a$: ratio between incident exposure and scattered exposure measured at 1 m from the object, whose scattering area is assumed to be 400 cm$^2$
- $WT$: Occupancy of the AOI
- $d_{sca}$: Distance from the source to the scatterer
- $d_{sec}$: Distance from the scatterer to the AOI
- $F$: Actual size of the scatterer/object
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

\[
K = \frac{P \times (d_{sca})^2 \times (d_{sec})^2 \times 400}{a \times W \times T \times F \times f} \text{ rem/mA} \cdot \text{min}
\]

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

<table>
<thead>
<tr>
<th>kV</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 or less</td>
<td>1</td>
</tr>
<tr>
<td>1000</td>
<td>20</td>
</tr>
<tr>
<td>2000</td>
<td>300</td>
</tr>
<tr>
<td>3000</td>
<td>700</td>
</tr>
</tbody>
</table>
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)

FIGURE 15.3. Attenuation in lead of X rays produced with (peak) potential differences from 50 kVp to 200 kVp. (National Bureau of Standards Handbook 76, 1961, Washington, 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

\[
\hat{D}_L \left( \frac{\text{rem}}{\text{wk}} \right) = \frac{0.1 \left( \frac{\text{rem}}{\text{h}} \right)}{d^2} \times \frac{t \left( \frac{\text{min}}{\text{wk}} \right)}{60 \left( \frac{\text{min}}{\text{h}} \right)}
\]

Distance between AOI and the source

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

Assuming working for t mins per week, $t = \frac{W}{I}$

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

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

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

\[
B_{LX} = \frac{P}{D_L} = \frac{P \cdot d^2 \cdot 600 \cdot I}{W \cdot T}
\]

Dose limit at the AOI

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.

\[
\text{workload}
\]

**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

Considering

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

The maximum dose that is allowed at a unit distance delivered by the shielded source running at the standard operating condition (mA·1min, \( U = 1 \), \( T = 1 \)) is given by

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

Then we convert the maximum allowed dose \( K_{\text{dose}} \) to the maximum allowed exposure \( K_{\text{exposure}} \), 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

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

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

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 \( K_{\text{exposure}} \) is 21.5 cm.

\[ \text{FIGURE 10.13. Attenuation in concrete of X-rays produced by potentials of 50 to 300 kVp, 400 kV constant potential. The measurements were made with a 90° angle between the electron beam and the axis of the X-ray beam. The curves for 50 to 300 kV are for a pulsed waveform. The filtrations were 1 mm Al for 50 kV, 1.5 mm Al for 70 kV, 2 mm Al for 100 kV, and 3 mm Al for 125, 150, 200, 250, and 300 kV. The 400-kV curve was interpolated from data obtained with a constant potential generator and inherent filtration of approximately 3 mm Cu. (From NCRP Report No. 49, Structural Shielding Design and Evaluation for Medical Use of X-Rays and Gamma Rays of Energies up to 10 MeV, 1976. Full-size reproductions of the figures giving barrier requirements are available from the NCRP as an adjunct to the report. By permission.)} \]
Step 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)
- 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 purpose, this source is typically running for 302 mins per week.

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

\[
B_{Lx} = \frac{0.02 \text{ (mSv/wk)}}{\frac{(1 \text{ (mSv/h)})}{d^2} \frac{(0.1 \text{ (mSv/h)})}{60 \text{ (min/wk)}}} = \frac{0.02 \text{ (mSv/wk)}}{\frac{(0.1 \text{ (mSv/h)})}{(2.5 \text{ m})^2} \frac{(302 \text{ (min/wk)})}{60 \text{ (min/wk)}}} = 0.0248
\]

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

\[
0.0248 = \frac{1}{2n'} \text{ and } n=5.33
\]

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

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

\[
K_u = \frac{P}{a \cdot W \cdot T} \cdot d_{sca}^2 \cdot d_{sec}^2 \cdot \frac{400 \text{ cm}^2}{F \text{ cm}^2} = 1.4 \times 10^{-3} \text{ rem/(mA \cdot min)} \text{ at 1m} \\
= 1.4 \times 10^{-5} \text{ Sv/(mA \cdot min)} \text{ at 1m}
\]
Step 3: Design of the second barrier (ceiling) against scattered radiation

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

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

Then we convert the maximum allowed dose \( K_{\text{dose}} \) to the maximum allowed exposure \( K_{\text{exposure}} \), 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 = 34 Gy
- 1 X Unit = 3881 Roentgen

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

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