

Shielding Radiation

Alphas, Betas, Gammas and Neutrons

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General

General

- Shielding calculations done “by hand” are often ballpark approximations
- The most accurate shielding calculations are performed by computers
- Shields are often “over-designed” so that they can handle more intense sources of radiation that might be used in the future
- The photon shielding calculations in this handout only apply to monoenergetic photons (e.g., gamma rays). Shielding x-rays, which have a continuous range of energies, is a specialized topic not considered here

General

The required shield thickness depends on three things:

1. Radiation Energy. The greater the energy of the radiation (e.g., beta particles, gamma rays, neutrons) the thicker the shield must be.
2. The shield material. For photons (x-rays, gamma rays) the lower the atomic number of the shield, the thicker it must be. For neutrons, the general rule is that the lower the hydrogen content, the thicker the shield must be.
3. Radiation intensity. The higher the radiation intensity, and the more it must be reduced, the thicker the shield.

Shielding Alpha Emitters

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Shielding Alpha Emitters

- For external alpha emitting sources, the alpha particles themselves are not a radiation hazard. However, we must consider the possibility that other types of radiation might be present. *This possibility must always be considered when shielding any type of radiation!*
- While we might assume that an alpha emitter doesn't emit gamma rays, it might actually do so. Pu-239 for example emits a large number of gamma rays. Nevertheless, we often consider Pu-239 a "pure alpha" emitter because the gamma intensity is low .

Shielding Alpha Emitters

- Alpha emitters might also emit conversion electrons and low energy x-rays.
- Furthermore, alpha sources often contain trace quantities of impurities some of which might emit beta particles.
- These kinds of issues are primarily a concern when large quantities of alpha emitters are handled, e.g., in glove box facilities where curie and megacurie quantities might be encountered.

Shielding Beta Particles

Shielding Beta Particles

General

- The dose from an external source of beta particles is primarily to the skin. The penetrating power of betas is low - approximately a few mm in tissue.
- Beta particles, like alpha particles, can be completely stopped by a shield. It rarely requires more than 5- 10 mm of material to do so.
- The material the shield is made of is not very important in terms of its ability to stop the beta particles.

Shielding Beta Particles

Beta Particle Range

- Beta ranges are often expressed as a “density thickness” which has units of g/cm². These ranges can be converted to centimeters as follows:

$$Range(cm) = \frac{Range(g/cm^2)}{Density(g/cm^3)}$$

- The easy way to estimate the range (in mg/cm²) of beta particles is to obtain it from the graph on page 162 of the PTP Radiological Health Handbook. The energy specified on the graph is the maximum beta energy.

Shielding Beta Particles

Beta Particle Range

Several equations approximate the range of betas, i.e., the thickness of the shield required to stop all the betas.

- The equation below (Feather's Rule) applies to betas with a maximum energy above 0.6 MeV:

$$\text{Range (g/cm}^2\text{)} = 0.542 E - 0.133$$

E is the maximum β energy (MeV)

- The following equation applies to betas with a maximum energy below 0.8 MeV:

$$\text{Range (g/cm}^2\text{)} = 0.407 E^{1.38}$$

Shielding Beta Particles

Bremsstrahlung

- While it is easy to completely stop beta particles, the very act of doing so produces bremsstrahlung, a more penetrating type of radiation. Shielding bremsstrahlung can be more of a problem than shielding gammas.
- A good shielding material for betas minimizes bremsstrahlung i.e., low Z material such as plastic.
- Like beta particles, bremsstrahlung photons have a range of energies up to a maximum. The maximum energy of the bremsstrahlung photons is the same as the maximum energy of the betas. When shielding bremsstrahlung, we can take the very conservative approach that all the bremsstrahlung photons have this maximum energy.

Shielding Beta Particles

Example calculation

A 1 Ci P-32 source (50 mls aqueous) is in a polyethylene bottle (0.93 g/cm³). The effective atomic numbers of the solution and vial wall are assumed to be 7.5.

- a. How thick should the vial be?
- b. What is the exposure rate at 1 meter due to bremsstrahlung?

Shielding Beta Particles

Example calculation

a. How thick should the vial be?

The maximum beta energy for P-32 is 1.71 MeV. From the curve (p 162) in the PTP Radiological Health Handbook, the maximum range of the P-32 betas is 800 mg/cm² (0.8 g/cm²).

Essentially the same result is obtained using the equation:

$$\begin{aligned}\text{Range (g/cm}^2\text{)} &= 0.542 E - 0.133 \\ &= 0.542 \times 1.71 - 0.133 \\ &= 0.79 \text{ g/cm}^2\end{aligned}$$

As such, the vial should be at least 0.86 cm thick (0.8 g/cm² divided by 0.93 g/cm³).

Shielding Beta Particles

Example calculation

- b. What is the exposure rate at 1 meter due to bremsstrahlung?

The fraction of the beta energy released in the form of bremsstrahlung from interactions in the solution (and to a lesser extent in the vial wall) is calculated as follows:

$$\begin{aligned} f &\approx \frac{E_{\beta} Z}{3000} \\ &\approx \frac{1.71 \times 7.5}{3000} \\ &\approx 0.0043 \end{aligned}$$

Shielding Beta Particles

Example calculation

- b. What is the exposure rate at 1 meter due to bremsstrahlung? - continued

The beta energy emission rate from the 1 Ci P-32 source is:

$$= 3.7 \times 10^{10} \text{ dps} \times 0.7 \text{ MeV per decay}$$

$$= 2.59 \times 10^{10} \text{ MeV/s}$$

The bremsstrahlung energy emission rate is therefore:

$$= 0.0043 \times 2.59 \times 10^{10} \text{ MeV/s}$$

$$= 1.11 \times 10^8 \text{ MeV/s}$$

Shielding Beta Particles

Example calculation

- b. What is the exposure rate at 1 meter due to bremsstrahlung? - continued

The energy fluence rate (ψ) through a 1 cm² area at 1 meter is:

$$\begin{aligned}\text{Energy Fluence Rate } (\psi) &= \frac{\text{Energy Emission Rate}}{4\pi d^2} \\ &= \frac{1.11 \times 10^8 \text{ MeV/s}}{4\pi (100 \text{ cm})^2} \\ &= 883 \text{ MeV cm}^{-2} \text{ s}^{-1}\end{aligned}$$

Shielding Beta Particles

Example calculation

- b. What is the exposure rate at 1 meter due to bremsstrahlung? - continued

The dose rate to air is the energy fluence rate (MeV, cm⁻², s⁻¹) times the mass energy absorption coefficient for air (cm²/g).

$$\text{Absorbed dose rate} = \psi \times u_{\text{en}}/\rho$$

Mass energy absorption coefficients apply to single photon energies but bremsstrahlung photons have a range of energies. A conservative assumption is that they all have an energy of 1.71 MeV (the maximum energy for P-32).

The mass energy absorption coefficient for 1.71 MeV photons in air is approximately 0.025 cm²/g.

Shielding Beta Particles

Example calculation

b. What is the exposure rate at 1 meter due to bremsstrahlung? - continued

$$\begin{aligned}\text{Absorbed dose rate} &= \psi \times u/\rho \\ &= 883 \text{ (MeV cm}^{-2} \text{ s}^{-1}) \times 0.025 \text{ cm}^2/\text{g} \\ &= 22.1 \text{ MeV g}^{-1} \text{ s}^{-1} \\ &= 22.1 \times 10^6 \text{ eV g}^{-1} \text{ s}^{-1}\end{aligned}$$

Since one ion pair is produced for every 34 eV absorbed by the air, the ion pair production rate is:

$$\begin{aligned}&= 22.1 \times 10^6 \text{ (eV, g}^{-1}, \text{ s}^{-1}) / 34 \text{ (eV/ion pair)} \\ &= 0.65 \times 10^6 \text{ ion pairs per gram per second}\end{aligned}$$

Shielding Beta Particles

Example calculation

- b. What is the exposure rate at 1 meter due to bremsstrahlung? - continued

Since the charge produced in air for one member of each ion pair is 1.6×10^{-19} C, the rate of charge production is :

$$\begin{aligned} &= 0.65 \times 10^6 \text{ (ion pairs g}^{-1} \text{ s}^{-1}) \times 1.6 \times 10^{-19} \text{ C} \\ &= 1.23 \times 10^{-13} \text{ C g}^{-1} \text{ s}^{-1} \\ &= 1.23 \times 10^{-10} \text{ C kg}^{-1} \text{ s}^{-1} \\ &= 4.44 \times 10^{-7} \text{ C kg}^{-1} \text{ hr}^{-1} \end{aligned}$$

Shielding Beta Particles

Example calculation

- b. What is the exposure rate at 1 meter due to bremsstrahlung? - continued

Finally, the answer:

Since 2.58×10^{-4} C/kg equals 1 roentgen, the exposure rate in R/hr is

$$= 4.44 \times 10^{-7} \text{ (C kg}^{-1} \text{ hr}^{-1}) / 2.58 \times 10^{-4} \text{ (C/kg)}$$

$$= 1.72 \times 10^{-3} \text{ R/hr}$$

Shielding Positrons

Shielding Positrons

- In general, positron energies (and the bremsstrahlung they produce) tend to be higher than beta energies. Even so, the positrons themselves are easy to stop. It requires at most a cm or so of plastic.

The most important positron emitter, F-18, emits positrons that are of fairly low energy: maximum 633.5 keV, average 249.8 keV.

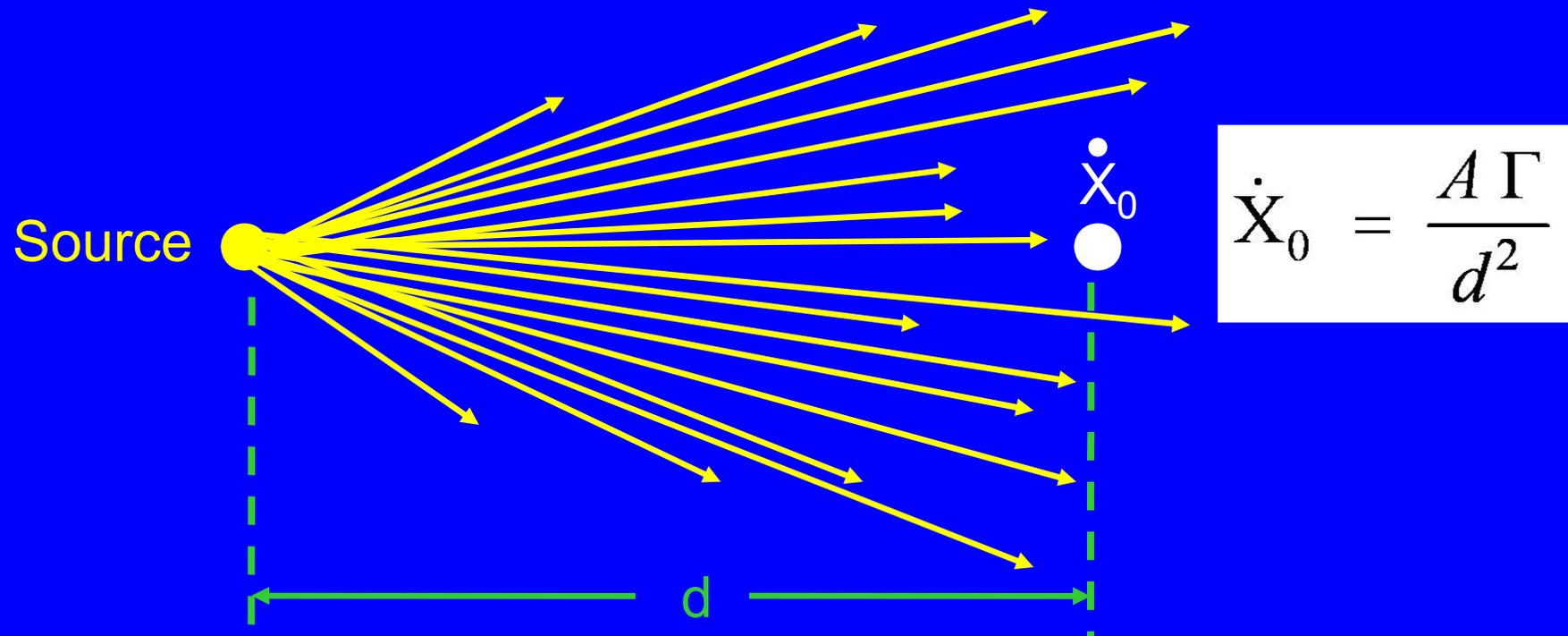
- What we don't want to forget is that each emitted positron will produce two 511 keV annihilation photons that must be shielded. These annihilation photons are not always mentioned in tables of decay data.

Shielding Gamma Rays

Shielding Gamma Rays

General

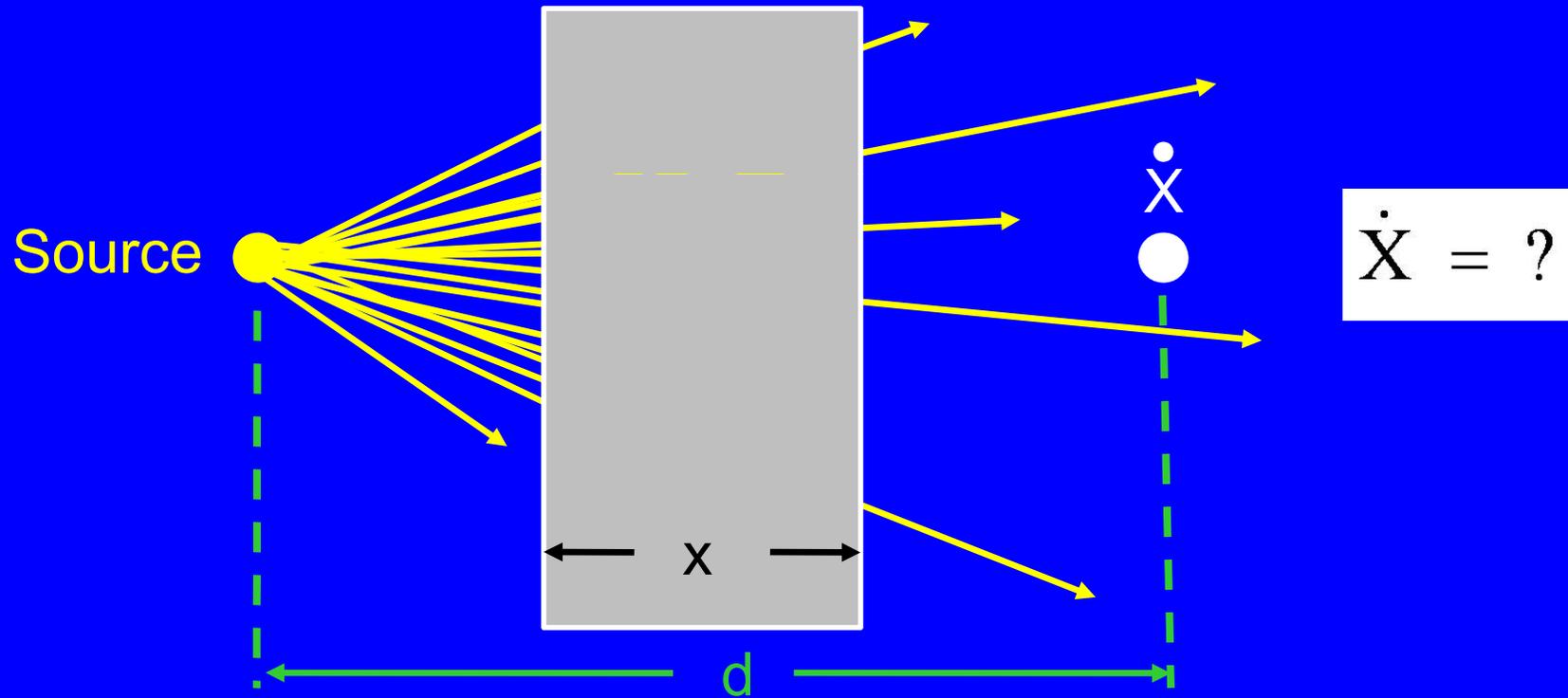
\dot{X}_0 is the exposure rate in the absence of shielding.



Shielding Gamma Rays

General

We want an equation that gives the exposure rate (\dot{X}) when shielding of a given thickness (x) is present.



Shielding Gamma Rays

Basic Equation

The following basic equation assumes a narrow beam of radiation penetrating a thin shield (a situation referred to as "good geometry").

$$\dot{X} = \dot{X}_0 e^{-u x}$$

X is the exposure rate with the shield in place (e.g., R/hr)

X_0 is the exposure rate without the shield (e.g., R/hr)

x is the thickness of the shield (e.g., cm)

u is the linear attenuation coefficient (e.g., cm^{-1}).

The linear attenuation coefficient (u) is the probability of any type of interaction (PE, CS, PP) per unit path length.

Shielding Gamma Rays

Basic Equation

Listings of the linear attenuation coefficient (μ) are hard to find. However, listings of a related quantity, the mass attenuation coefficient (μ/ρ), are easy to find.

The “classic” listing of mass attenuation coefficients is that of Hubbell. Hubbell’s tables can be found in the PTP Radiological Health Handbook beginning on page 90.

The mass attenuation coefficient (μ/ρ) is the probability of an interaction (PE, CS, PP) per unit density thickness. Its units are cm^2/g . In other words, μ/ρ is the probability of interactions per g/cm^2 travelled by the photon.

Shielding Gamma Rays

Basic Equation

The value of the mass attenuation coefficient depends on the shielding material and the energy of the photons.

Nevertheless, mass attenuation coefficients for different materials are very similar. For example, the following table lists some mass attenuation coefficients for 1 MeV photons.

Shield Material	u/ρ (cm ² /g)
water	0.0707
concrete	0.0637
air	0.0636
iron	0.0599

The mass attenuation coefficient is the linear attenuation divided by the density of the material.

Shielding Gamma Rays

Basic Equation

When using the mass attenuation coefficient instead of the linear attenuation coefficient, the basic shielding equation is:

$$\dot{X} = \dot{X}_0 e^{-\frac{\mu}{\rho} \rho x}$$

μ/ρ is the mass attenuation coefficient (cm^2/g)

ρ is the density of the shielding material (g/cm^3)

Note, the units in the exponent must cancel out:

$$\text{cm}^2/\text{g} \times \text{g}/\text{cm}^3 \times \text{cm}$$

Shielding Gamma Rays

Basic Equation – First example calculation

The exposure rate at a particular point is 100 R/hr due to 1332 keV gamma rays from Co-60. What would be the resulting exposure rate if a 1 cm lead shield were employed between the source and the point?

Warning!

In this example, we will use the basic equation which assumes we have “good” geometry, i.e., a narrow beam and thin shield. As we will see later, in the “real world” we rarely have good geometry and this equation would result in an underestimate of the exposure rate.

Shielding Gamma Rays

Basic Equation – First example calculation

u/ρ is approximately $0.057 \text{ cm}^2/\text{g}$ (I eyeballed this)

ρ_{actual} is assumed to be the same as the theoretical density,
 11.35 g/cm^3

$$\begin{aligned}\dot{X} &= \dot{X}_0 e^{-\frac{u}{\rho} \rho x} \\ &= 100(R/hr) \times e^{-0.057 \times 11.35 \times 1} \\ &= 52 R/hr\end{aligned}$$

Shielding Gamma Rays

Basic Equation – Second example calculation

The exposure rate at a particular point is 100 R/hr due to 662 keV gamma rays from Cs-137. What would be the resulting exposure rate if a 1 cm lead shield were employed?

μ/ρ is approximately 0.11 cm²/g (I eyeballed this)

$$\begin{aligned}\dot{X} &= \dot{X}_0 e^{-\frac{\mu}{\rho} \rho x} \\ &= 100(R/hr) \times e^{-0.11 \times 11.35 \times 1} \\ &= 29 R/hr\end{aligned}$$

Shielding Gamma Rays

Relaxation Length

The relaxation length is the thickness of a shielding material that will reduce the intensity of the radiation to $1/e$ (37%) of its original intensity.

$$\text{Relaxation length (cm)} = 1/u$$

u is the linear attenuation coefficient (cm^{-1})

Shielding Gamma Rays

Calculating the required shielding thickness

The preceding equation can be rewritten as follows so as to calculate the shielding thickness (x) necessary to achieve the desired reduction in the exposure rate:

$$\begin{aligned}x &= -\frac{1}{u} \ln \left(\frac{\dot{X}}{\dot{X}_0} \right) \\ &= -\frac{\ln \left(\frac{\dot{X}}{\dot{X}_0} \right)}{\left(\frac{u}{\rho} \right) \rho}\end{aligned}$$

Shielding Gamma Rays

Calculating the required shielding thickness - Example

What thickness of a lead shield would be required to reduce the exposure rate due to Cs-137 from 100 R/hr to 1 R/hr?

$$\begin{aligned}x &= -\frac{\ln\left(\frac{\dot{X}}{\dot{X}_0}\right)}{\left(\frac{u}{\rho}\right)\rho} \\ &= -\frac{\ln\left(\frac{1}{100}\right)}{(0.11)11.3} \\ &= 3.7 \text{ cm}\end{aligned}$$

Shielding Gamma Rays

Shielding multiple gamma ray energies

Since the mass attenuation coefficient (μ/ρ) depends on the energy of the photons, the preceding shielding calculations only work if the exposure rate is due to a single gamma ray energy.

This works fine for Cs-137 which has a single gamma ray.

How do we handle the situation where the exposure rate is due to more than one gamma ray energy, e.g., the two gamma rays of Co-60 at 1173 keV and 1332 keV?

Shielding Gamma Rays

Shielding multiple gamma ray energies

We could take a conservative approach and do the calculation only using the highest of the gamma ray energies. This overestimates the exposure rate and the required shielding.

This approach might be reasonable for something like Co-60 where the two gamma rays are of similar energy and contribute nearly equally to the exposure rate.

On the other hand, this approach could be a disaster for the situation where the highest gamma ray energy contributes only a little to the exposure rate (e.g., a high activity Am-241 source combined with a low activity Cs-137 source.)

Shielding Gamma Rays

Shielding multiple gamma ray energies

The correct approach is to determine the exposure rate for each gamma ray energy. Then we determine the attenuation of each gamma ray energy as an independent calculation.

Here is an example problem of how this can be done.

The exposure rate at a particular point is 100 R/hr due to the 1173 and 1332 keV Co-60 gamma rays. What would be the resulting exposure rate if a 1 cm lead shield were employed between the source and the point? Once again, we assume “good” geometry, i.e., a narrow beam and thin shield.

Shielding Gamma Rays

Shielding multiple gamma ray energies - Example

The 100 R/hr is the sum of the 1173 keV gamma ray (X_{1173}) and 1332 keV gamma ray (X_{1332}) exposure rates.

$$\dot{X}_{\text{Co-60}} = \dot{X}_{1173} + \dot{X}_{1332} = 100 \text{ R/hr}$$

X_{1173} and X_{1332} can be determined from their specific gamma ray constants: Γ_{1173} and Γ_{1332}

The specific gamma ray constant for Co-60 ($1.3 \text{ R m}^2 \text{ hr}^{-1} \text{ Ci}^{-1}$) is the sum of the specific gamma ray constants for the 1173 and 1332 keV gamma rays:

$$\Gamma_{\text{Co-60}} = \Gamma_{1173} + \Gamma_{1332}$$

Shielding Gamma Rays

Shielding multiple gamma ray energies - Example

The specific gamma ray constant for a given gamma ray energy can be calculated with the equation:

$$\Gamma = 19.53 E I \frac{\mu_{en}}{\rho}$$

Γ is the specific gamma ray constant in R hr⁻¹ m² Ci⁻¹

E is the gamma ray energy in MeV,

I is the gamma ray intensity (abundance)

μ_{en}/ρ is the mass energy absorption coefficient

Shielding Gamma Rays

Shielding multiple gamma ray energies - Example

The specific gamma ray constants for the two gammas are:

$$\begin{aligned}\Gamma_{1173} &= 19.53 E I \frac{\mu_{en}}{\rho} \\ &= 19.53 \times 1.173 \times 1.0 \times 0.027 \\ &= 0.618 R hr^{-1}m^2 Ci^{-1}\end{aligned}$$

$$\begin{aligned}\Gamma_{1332} &= 19.53 E I \frac{\mu_{en}}{\rho} \\ &= 19.53 \times 1.332 \times 1.0 \times 0.0263 \\ &= 0.684 R hr^{-1}m^2 Ci^{-1}\end{aligned}$$

Shielding Gamma Rays

Shielding multiple gamma ray energies - Example

$$\begin{aligned}\dot{X}_{1173} &= \dot{X}_{Co-60} \left(\frac{\Gamma_{1173}}{\Gamma_{Co-60}} \right) \\ &= 100 \left(\frac{0.618}{1.3} \right) \\ &= 47 \text{ R/hr}\end{aligned}$$

$$\begin{aligned}\dot{X}_{1332} &= \dot{X}_{Co-60} \left(\frac{\Gamma_{1332}}{\Gamma_{Co-60}} \right) \\ &= 100 \left(\frac{0.684}{1.3} \right) \\ &= 53 \text{ R/hr}\end{aligned}$$

Shielding Gamma Rays

Shielding multiple gamma ray energies - Example

First we calculate the effect of 1 cm of lead on the 47 R/hr due to the 1173 keV photons. The mass attenuation coefficient is estimated to be 0.0625 cm²/g

$$\begin{aligned}\dot{X}_{1173} &= \dot{X}_0 e^{-\frac{\mu}{\rho} \rho x} \\ &= 47(R/hr) \times e^{-0.0625 \times 11.35 \times 1} \\ &= 23 R/hr\end{aligned}$$

Shielding Gamma Rays

Shielding multiple gamma ray energies - Example

Second we calculate the effect of 1 cm of lead on the 53 R/hr due to the 1332 keV photons. The mass attenuation coefficient is estimated to be 0.057 cm²/g

$$\begin{aligned}\dot{X}_{1332} &= \dot{X}_0 e^{-\frac{\mu}{\rho} \rho x} \\ &= 53(R/hr) \times e^{-0.057 \times 11.35 \times 1} \\ &= 28 R/hr\end{aligned}$$

Shielding Gamma Rays

Shielding multiple gamma ray energies - Example

Finally we add the exposure rates for the 1173 and 1332 keV gamma rays:

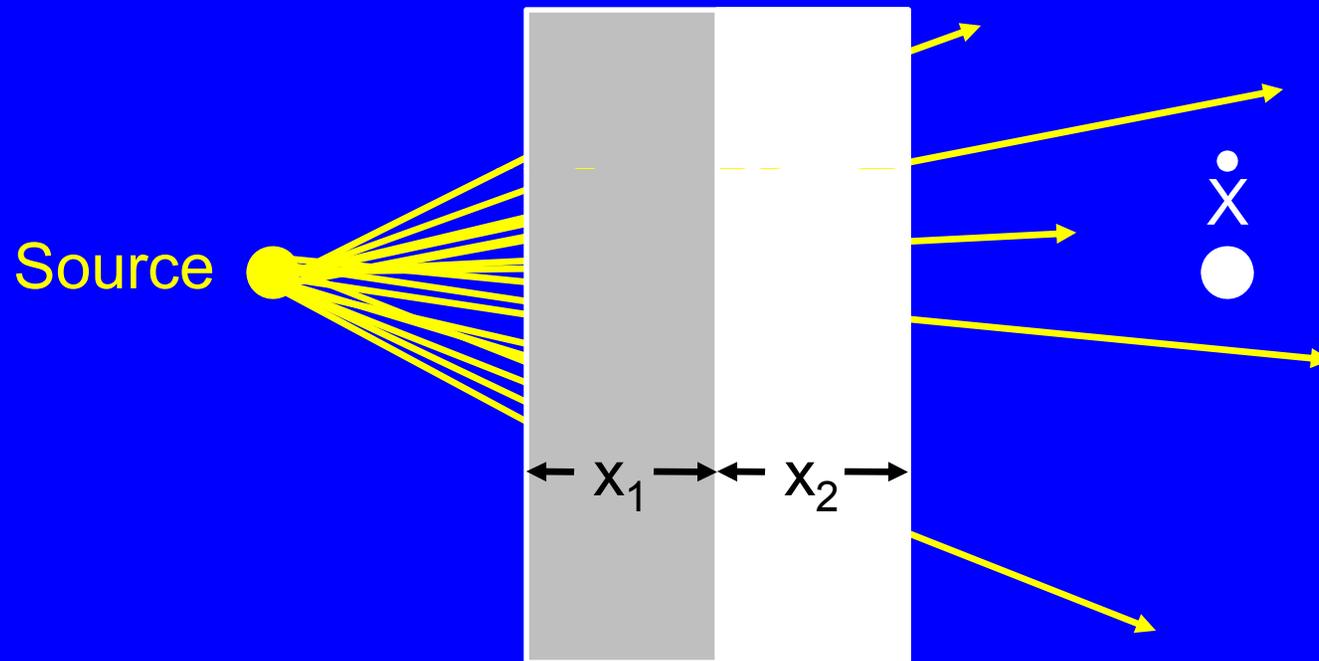
$$\begin{aligned}\dot{X}_{\text{Co-60}} &= \dot{X}_{1173} + \dot{X}_{1332} \\ &= 23 + 28 \\ &= 51 \text{ R/hr}\end{aligned}$$

As expected, the exposure rate (51 R/hr) is not much different from what we calculated when we assumed the exposure rate was only due to the 1332 keV gamma ray (52 R/hr).

Shielding Gamma Rays

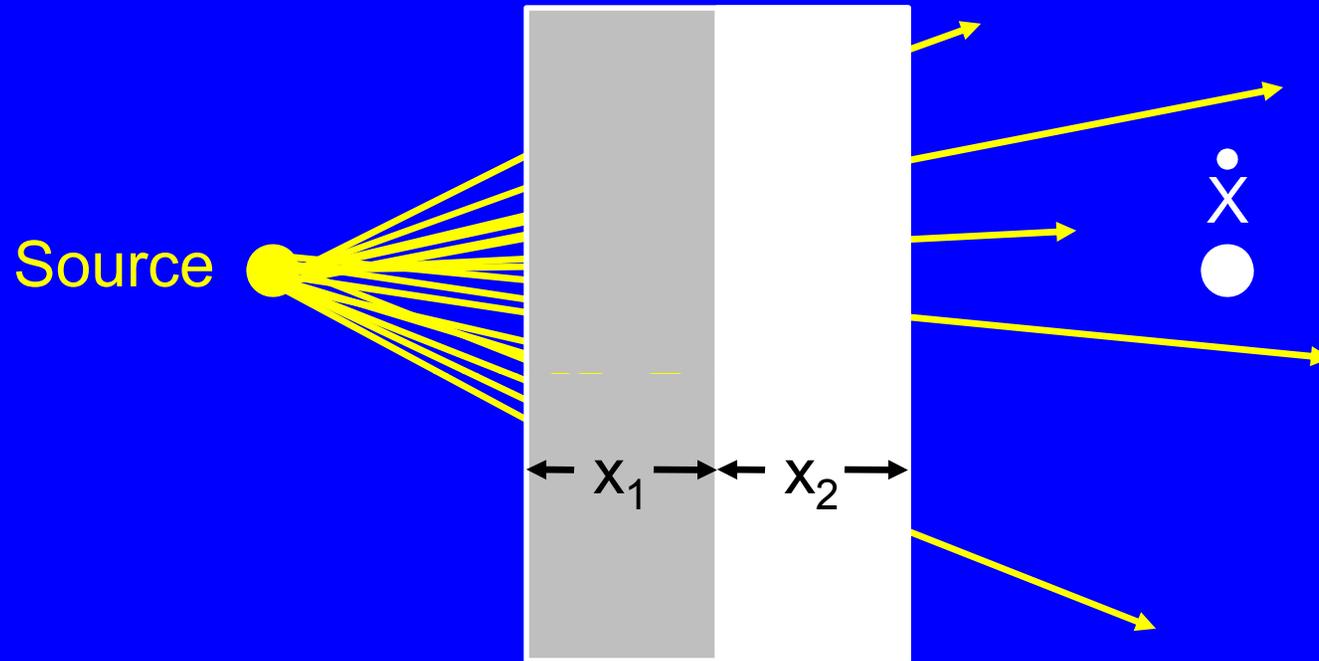
Layered (compound) Shielding

It is often the case that the shielding material consists of several layers



Shielding Gamma Rays

Layered (compound) Shielding



$$\dot{X} = \dot{X}_0 e^{-\left(\frac{u_1}{\rho_1} \rho_1 x_1 + \frac{u_2}{\rho_2} \rho_2 x_2\right)}$$

Shielding Gamma Rays

Layered (compound) Shielding – Example

The exposure rate at a particular point is 100 R/hr due to 662 keV gamma rays. Estimate the resulting exposure rate if a shield consisting of 1 cm of lead and 2 cm of iron were employed between the source and the point? Assume “good” geometry, i.e., a narrow beam and thin shield.

μ/ρ is approximately 0.11 cm²/g for lead

μ/ρ is approximately 0.075 cm²/g for iron

ρ for the lead is assumed to be the same as its theoretical density of 11.35 g/cm³

ρ for the iron is assumed to be the same as its theoretical density of 7.86 g/cm³

Shielding Gamma Rays

Layered (compound) Shielding – Example

$$\begin{aligned}\dot{X} &= \dot{X}_0 e^{-\left(\frac{u_1}{\rho_1} \rho_1 x_1 + \frac{u_2}{\rho_2} \rho_2 x_2\right)} \\ &= 100 \text{ (R/hr)} e^{-(0.11 \times 11.35 x_1 + 0.075 \times 7.86 x_2)} \\ &= 100 \text{ (R/hr)} e^{-2.43} \\ &= 8.8 \text{ R/hr}\end{aligned}$$

Shielding Gamma Rays

Half Value Layers

Instead of using attenuation coefficients to perform shielding calculations, we can use half (or tenth) value layers. A half value layer is the thickness of material that reduces the radiation intensity by one-half.

$$HVL = \frac{0.693}{\mu} = \frac{0.693}{(\mu/\rho)\rho}$$

The following equation using HVL's looks very similar to the radioactive decay equation:

$$\dot{X} = \dot{X}_0 e^{-\frac{0.693}{HVL} x}$$

Shielding Gamma Rays

Half Value Layers

A mathematically equivalent form of this equation is:

$$\dot{X} = \dot{X}_0 (0.5)^{(\# \text{ of HVLs})}$$

Half value and tenth value layers for some materials can be found in PTP's Radiological Health Handbook on page 79.

Don't be surprised if you see slightly different values in the literature for the half value layers of different nuclides, e.g., 0.6 cm or 0.65 cm for Cs-137 in lead.

Shielding Gamma Rays

Half Value Layers

The following table gives an idea as to the approximate half value layer thicknesses for several shielding materials.

Energy (MeV)	Approximate Half Value Layers in cm (TVL in parentheses)					
	Uranium	Tungsten	Lead	Iron	Concrete	Water
0.5			0.51	1.0	3.30	7.62
1.0			0.76	1.52	4.57	9.91
1.5			1.27	1.78	5.84	12.19
2.0			1.52	2.03	6.60	13.97
Ir-192	0.28	0.33	0.48	1.27	4.5	
Cs-137			0.65 (2.16)	1.6 (5.3)	4.8 (15.7)	
Co-60	0.69	0.79	1.2 (4.0)	2.1 (6.9)	6.2 (20.6)	
Ra-226			1.66 (5.5)	2.2 (7.4)	6.9 (23.4)	

Shielding Gamma Rays

Half Value Layers - Example

The exposure rate is 100 R/hr due to a Cs-137 source. What would the exposure rate be if the source were shielded with 2 cm of lead?

$$\begin{aligned}\dot{X} &= \dot{X}_0 e^{-\frac{0.693}{HVL} x} \\ &= 100 (R/hr) e^{-\left(\frac{0.693}{0.65}\right) 2} \\ &= 100 (R/hr) \times 0.119 \\ &= 12 R/hr\end{aligned}$$

Shielding Gamma Rays

Tenth Value Layers

In a similar manner, a tenth value layer (TVL) is defined as that thickness which will reduce the radiation intensity to one-tenth of its original value. The equations for using TVL's are as follows:

$$TVL = \frac{2.3}{\mu} = \frac{2.3}{(\mu/\rho)\rho}$$

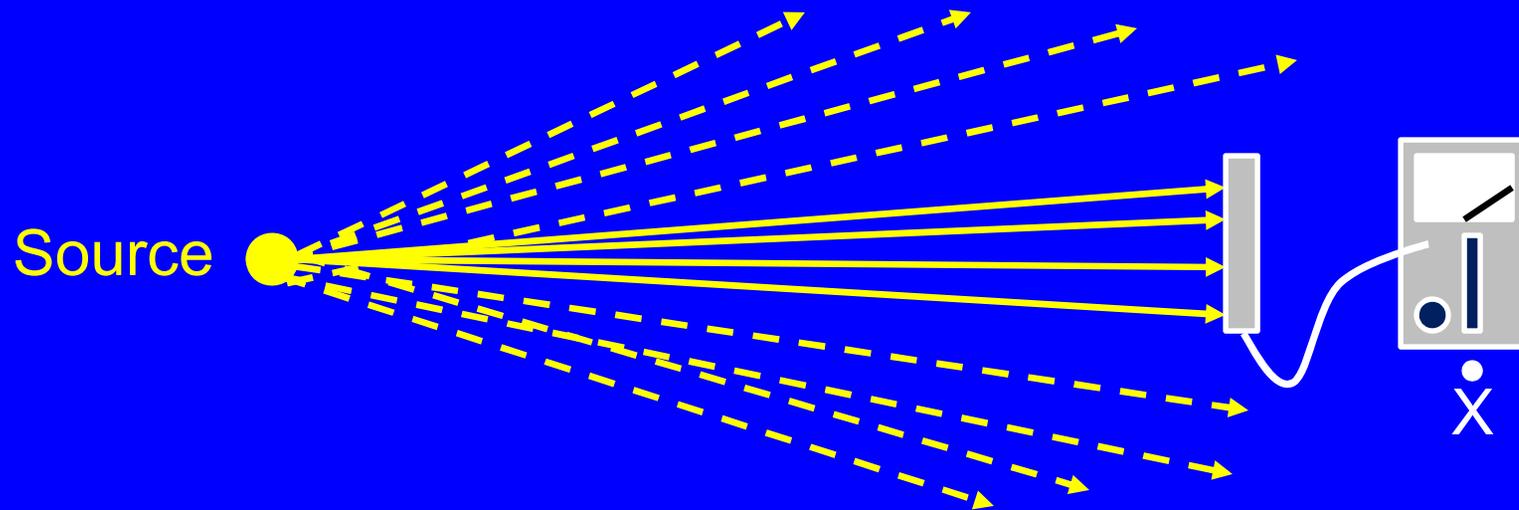
$$\begin{aligned}\dot{X} &= \dot{X}_0 e^{-\frac{2.30}{TVL} x} \\ &= \dot{X}_0 (0.1)^{(\# \text{ of TVLs})}\end{aligned}$$

Shielding Gamma Rays

$$\dot{X} = \frac{A \Gamma}{d^2}$$

Buildup

When the exposure rate at a given distance from a point source is calculated using the standard equation, we assume scattered radiation doesn't contribute to the exposure rate. Only those gamma rays originally directed to the point of interest contribute.

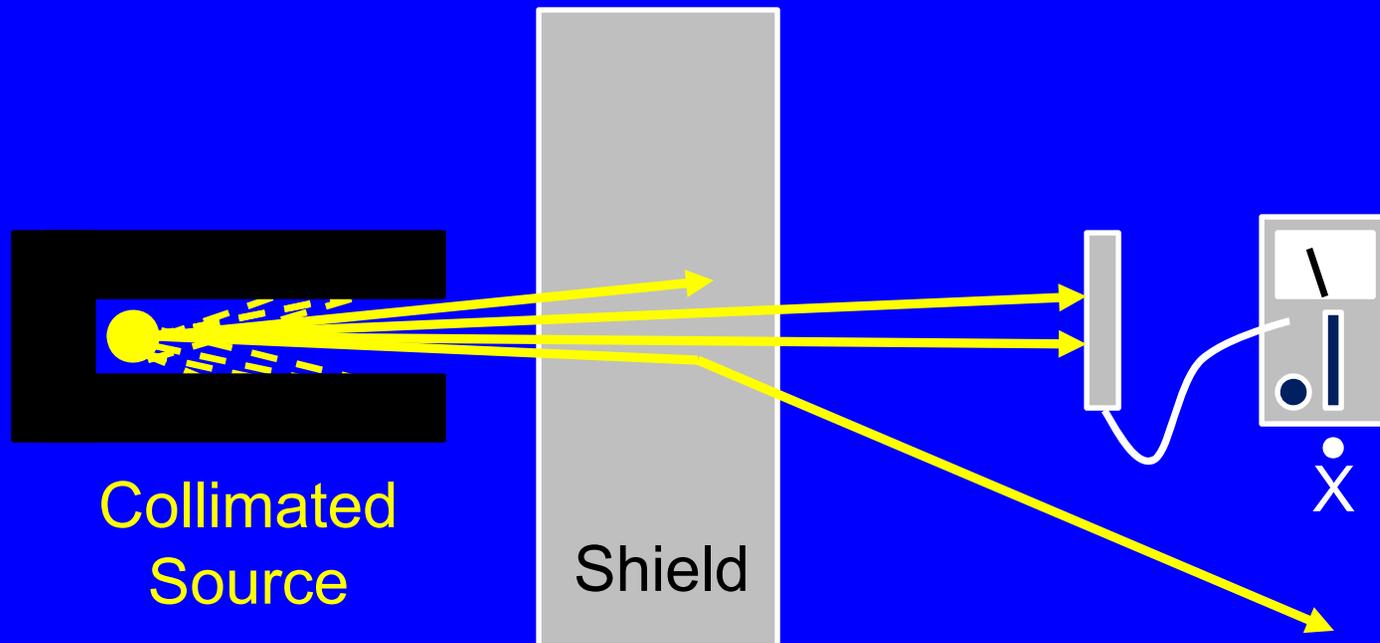


Shielding Gamma Rays

$$\dot{X} = \dot{X}_0 e^{-\frac{\mu}{\rho} \rho x}$$

Buildup

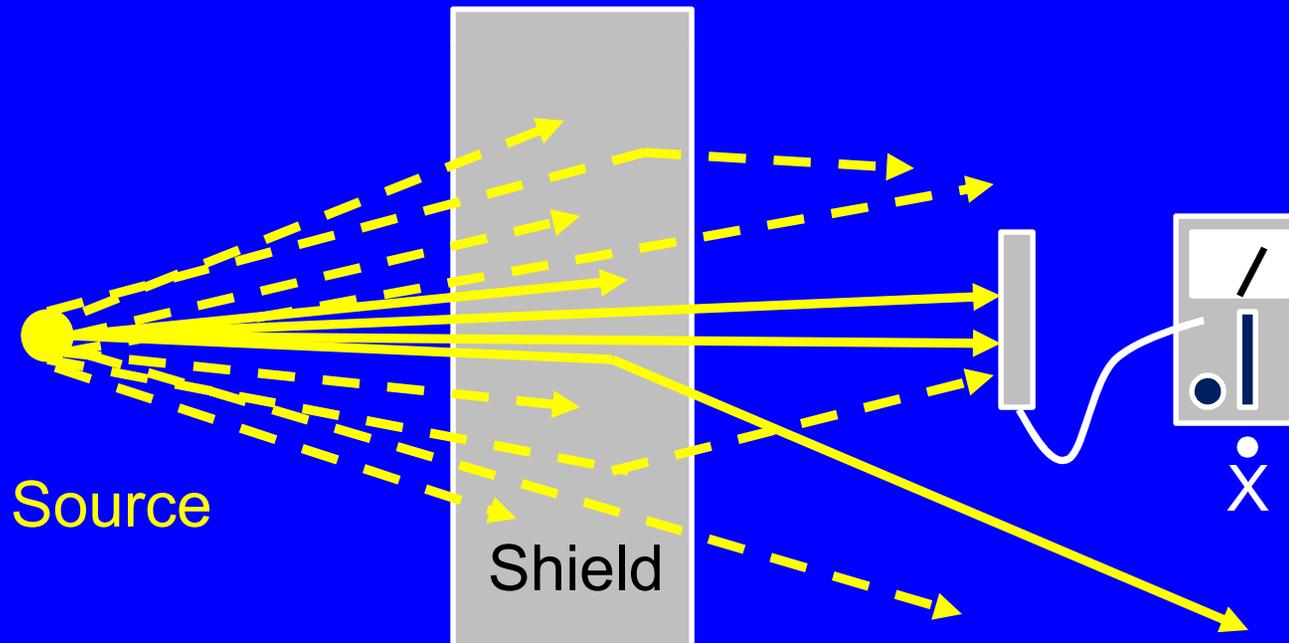
Similarly, the shielding equations considered so far assume no contribution from radiation scattered by the shield towards the point of interest. This is the so-called “good geometry” only possible with a narrow (collimated beam) and a thin shield.



Shielding Gamma Rays

Buildup

For a broad beam or thick shield situation like that below, radiation scattered in the shield contributes to the exposure rate. This is the real world (“bad geometry”). Scattering of radiation towards the point of interest is referred to as buildup.

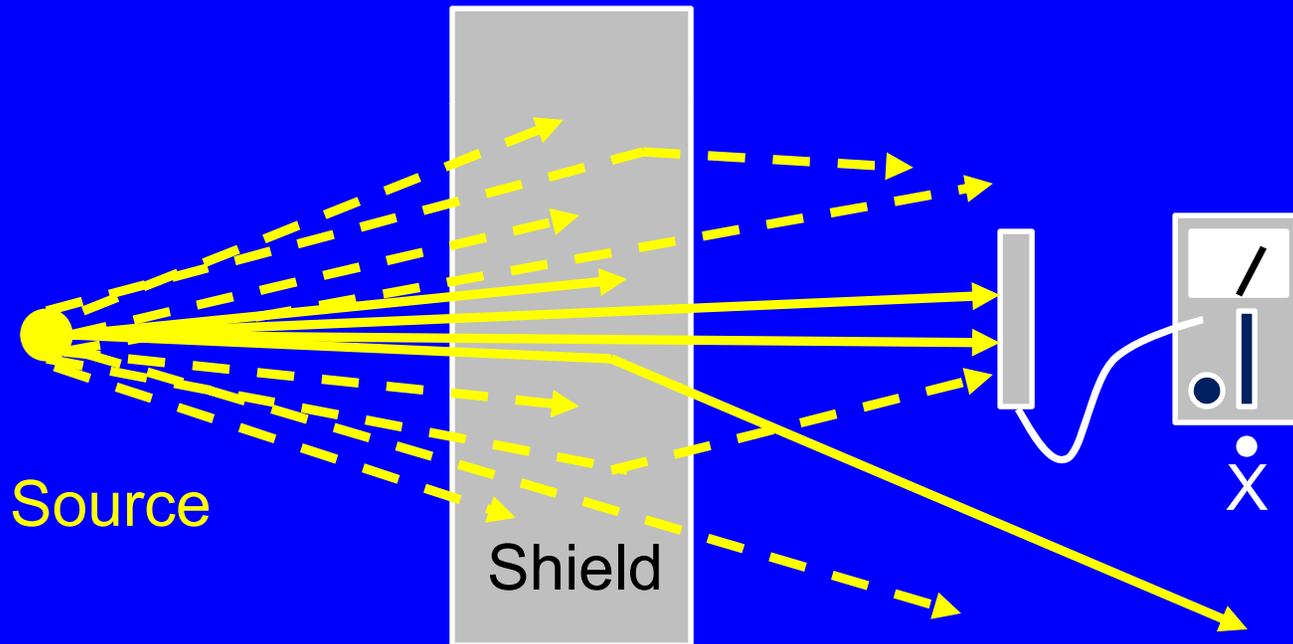


Shielding Gamma Rays

Buildup

To account for buildup, we can incorporate a “fudge factor” known as the buildup factor into our equations.

$$\dot{X} = B \dot{X}_0 e^{-\frac{\mu}{\rho} \rho x}$$



Shielding Gamma Rays

Buildup Factor

The buildup factor is a unitless number greater than 1.

$$\dot{X} = B \dot{X}_0 e^{-\frac{\mu}{\rho} \rho x}$$

The value we assign to the buildup factor depends on three things:

- Shield material
- Energy of the photons
- Value of the equation's exponent $(\mu/\rho) \rho x$ (i.e., μx)

Buildup factors can be found on page 88 of PTP's Radiological Health Handbook.

Shielding Gamma Rays

Buildup Factor

The equation's exponent, the product ux , is sometimes referred to as the number of mean free paths.

The mean free path (mfp) is the average distance a photon travels before an interaction takes place. It is the reciprocal of the linear attenuation coefficient (u).

$$\text{mfp} = \frac{1}{\mu}$$

$$\text{number of mean free paths} = \frac{x}{\text{mfp}} = ux = \frac{u}{\rho} \rho x$$

Shielding Gamma Rays

Buildup Factor - Example

The exposure rate at a particular point is 100 R/hr due to 1332 keV gamma rays. What would be the resulting exposure rate if a 1 cm lead shield were employed between the source and the point? Assume “poor” geometry, i.e., a broad beam and thick shield.

u/ρ is approximately 0.057 cm²/g

ρ_{actual} is assumed to be 11.35 g/cm³

B is estimated to be 1.2, based on an energy of 1332, and a value of 0.647 for u_x (number of mean free paths)

Shielding Gamma Rays

Buildup Factor - Example

$$\begin{aligned}\dot{X} &= B \dot{X}_0 e^{-\frac{\mu}{\rho} \rho x} \\ &= 100 (R/hr) \times 1.2 \times e^{-0.057 \times 11.35 \times 1} \\ &= 100 (R/hr) \times 1.2 \times e^{-0.647} \\ &= 63 R/hr\end{aligned}$$

Shielding Gamma Rays

Determining the Required Shield Thickness with Buildup

The following equation gives the shield thickness (x) necessary to reduce the exposure rate from X_0 to X :

$$x = -\frac{1}{u} \ln\left(\frac{\dot{X}}{\dot{X}_0 B}\right) = -\frac{\ln\left(\frac{\dot{X}}{\dot{X}_0 B}\right)}{\left(\frac{u}{\rho}\right)\rho}$$

A problem with this equation is that the buildup factor (B) depends on the thickness of the shield (x), which is exactly what we are trying to determine.

In other words, we can't determine B before we know x . ⁶⁹

Shielding Gamma Rays

Determining the Required Shield Thickness with Buildup

First approach - iteration

We could estimate B by guessing what x is likely to be.

Then we could plug B and x into the following equation, and see how close we get to the required exposure rate X.

$$\dot{X} = B \dot{X}_0 e^{-\frac{\mu}{\rho} \rho x}$$

If X is too high, increase the shield thickness and redo the calculation. Keep doing this until we find the shield thickness that achieves the desired exposure rate. This approach is referred to as iteration. An unsavory sledgehammer approach to be sure, but it works.

Shielding Gamma Rays

Determining the Required Shield Thickness with Buildup

Second approach – energy absorption coefficient

We could eliminate the buildup factor in our equations by substituting the mass energy absorption coefficient (μ_{en}/ρ) for the mass attenuation coefficient (μ/ρ). Then we use the following equation for x:

$$x = -\frac{\ln\left(\frac{\dot{X}}{\dot{X}_0}\right)}{\left(\frac{\mu_{en}}{\rho}\right)\rho}$$

Although not technically correct, this approach is simple .⁷¹

Shielding Gamma Rays

Determining the Required Shield Thickness with Buildup

Third approach- computers

Swallow our pride and use a computer.

Computer calculations can produce very accurate results for complicated shield and source geometries.

Computer modeling typically uses the Discrete Ordinates Technique (DOT for short) or the Monte Carlo Technique.

The DOT is a numerical integration technique used to derive solutions of the Boltzmann Transport equation in certain simplified cases.

Shielding Gamma Rays

Determining the Required Shield Thickness with Buildup

Third approach - computers

The Monte Carlo method uses extensive data tables and a random number generator to mathematically "track" thousands of simulated emissions of radiation through a shield.

Perhaps the best known shielding code is Microshield ®

Shielding Gamma Rays

Determining the Required Shield Thickness with Buildup

Fourth approach – transmission curves

One way to determining the required shielding thickness (or reduction in exposure rate due to a given shield thickness) is to use a transmission curve that accounts for buildup.

Transmission curves are plots of transmission (X/X_0) versus shield thickness for various radionuclides. Examples curves are on page 82 of PTP's Radiological Health Handbook.

Alas, transmission graphs are only available for a limited number of radionuclides and shield materials and therefore have somewhat limited applicability.

Shielding Gamma Rays

Determining the Required Shield Thickness with Buildup

Fourth approach – transmission curves example

What thickness of lead shielding is required to reduce the exposure rate due to Co-60 from 100 R/hr to 22 mR/hr?

$$\begin{aligned} \text{Transmission factor} &= \frac{\dot{X}}{\dot{X}_0} \\ &= \frac{22 \text{ mR/hr}}{100,000 \text{ mR}} \\ &= 2.2 \times 10^{-4} \end{aligned}$$

Shielding Gamma Rays

Determining the Required Shield Thickness with Buildup

Fourth approach – transmission curves example

From the curve on page 83 of PTP's Radiological Health Handbook, approximately 15 cm of lead correspond to a transmission factor of 2.2×10^{-4}

Shielding Neutrons

Neutron Shielding

The Three Steps

Shielding neutrons involves three steps:

1. Slow the neutrons
2. Absorb the neutrons
3. Absorb the gamma rays

Neutron Shielding

1. Slow the neutrons

- Neutrons are slowed to thermal energies with hydrogenous material: water, paraffin, plastic.
- Water can evaporate or leak, paraffin is flammable and plastic is expensive.
- To slow down very fast neutrons, iron or lead might be used in front of the hydrogenous material.

Neutron Shielding

2. Absorb the neutrons

- Hydrogenous materials are also very effective at absorbing neutrons - the cross section for neutron capture by H-1 is 0.33 barns.
- Unfortunately, a difficult to shield 2.2 MeV gamma ray is emitted when H-1 absorbs a neutron.
- Boron might be incorporated into the shield because it has a large cross section for neutron absorption and only emits a low energy capture gamma ray.
- To slow down very fast neutrons, iron or lead might be used in front of the hydrogenous material.

Neutron Shielding

3. Absorb the gamma rays

- Gamma rays are produced in the neutron shield by neutron (radiative) capture, inelastic scattering, and the decay of activation products.

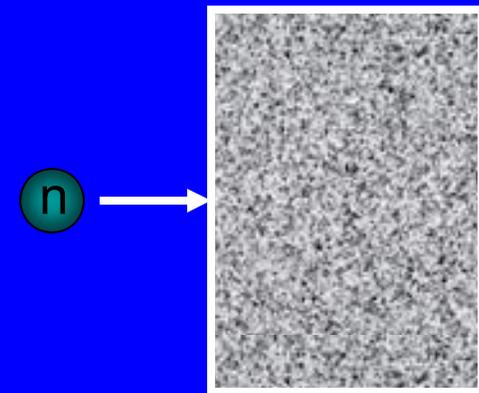
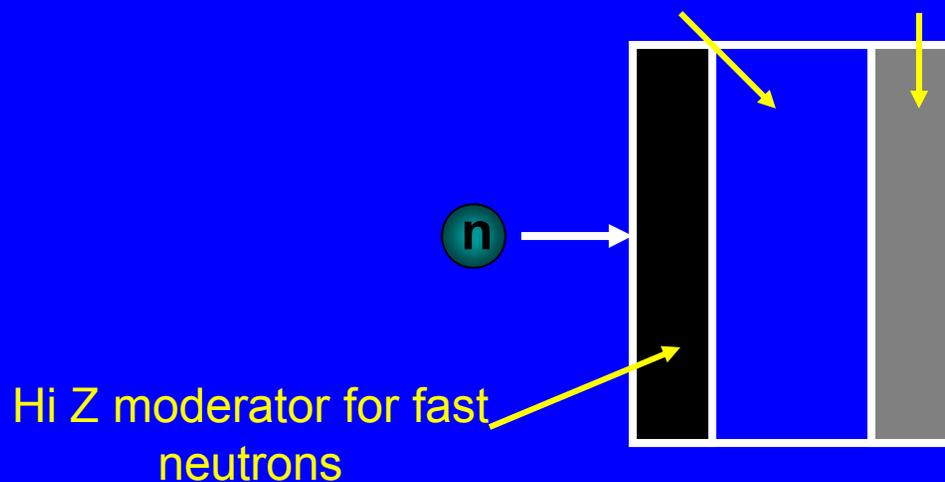
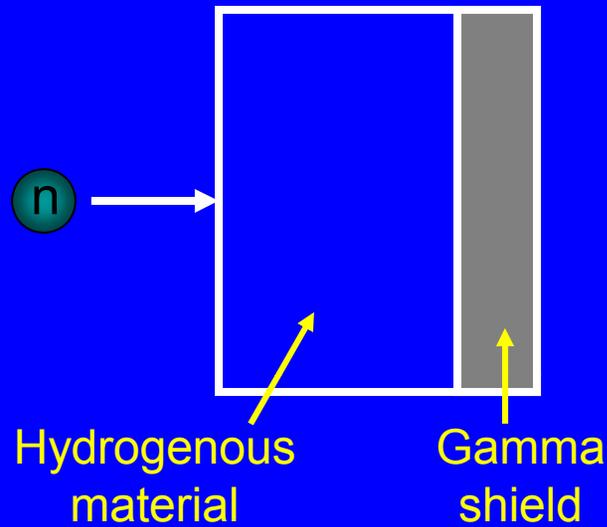
Neutron Shielding

Multipurpose Materials for Neutron Shields

- Concrete, especially with barium mixed in, can slow and absorb the neutrons, and shield the gamma rays.
- Plastic with boron is also a good multipurpose shielding material.

Neutron Shielding

Possible Neutron Shield Options



Combination material e.g., borated plastic or concrete with barium

Neutron Shielding

Neutron Shielding Calculations – fast neutrons

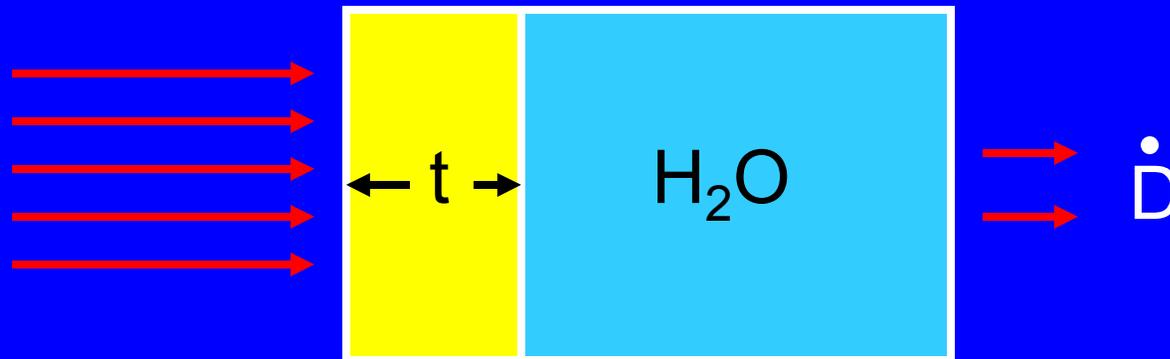
Neutron shielding calculations are best done by computers. Nevertheless, in some limited situations, it is possible to employ a simplistic exponential equation similar to that used for monoenergetic photons.

The following equation (Schaeffer 1973) describes the effect of a given shielding material (e.g., steel) on fast neutron dose rate. It only works if there is at least 50 cm of water (or equivalent hydrogenous material) behind the shield.

Neutron Shielding

Neutron Shielding Calculations – fast neutrons

$$\dot{D} = \dot{D}_0 e^{-\Sigma_R t}$$



- \dot{D} is the dose rate with shield
- \dot{D}_0 is the dose rate without shield
- t is the shield thickness (e.g., cm)
- Σ_R is the neutron removal cross section (e.g., cm^{-1})

Neutron Shielding

Neutron Shielding Calculations

– alpha-beryllium sources

The following equation (modified from one in from NBS Handbook 63) describes the effect of shield thickness on the neutron dose rate associated with a radioactive neutron source (e.g., AmBe).

$$\dot{D} = B \dot{D}_0 e^{-\Sigma_R t}$$

B is a buildup factor usually assumed to be 5

Neutron Shielding

Neutron Shielding Calculations

The following values for removal cross sections are from NBS Handbook 63.

Material	Removal Cross Section Σ_R (cm ⁻¹)
water	0.103
iron	0.1576
ordinary concrete	0.0942
barytes concrete	0.0945
graphite	0.0785

For what it is worth, the removal cross section is approximately 2/3 to 3/4 of the total cross section.

Neutron Shielding

Neutron Shielding Calculations

In neutron shielding calculations, we might also use the mass attenuation coefficient symbolized Σ_R/ρ

According to Schaeffer (1973), the mass attenuation coefficient (Σ_R/ρ) for fast neutrons can be approximated with your choice of one of the following:

$$\begin{aligned}\Sigma_R/\rho &= 0.19 Z^{-0.743} \text{ cm}^2/\text{g} \quad (Z \leq 8) \\ &= 0.125 Z^{-0.565} \text{ cm}^2/\text{g} \quad (Z > 8)\end{aligned}$$

$$\Sigma_R/\rho = 0.206 A^{-1/3} Z^{-0.294} \sim 0.206 (A Z)^{-1/3}$$

$$\Sigma_R/\rho = 0.21 A^{-0.58}$$

Neutron Shielding

Neutron Shielding Calculations

When the neutron mass attenuation coefficient (Σ_R/ρ) is employed instead of the neutron removal cross section, the previous equation becomes:

$$\dot{D} = B \dot{D}_0 e^{-(\Sigma_R/\rho)\rho t}$$

Neutron Shielding

Neutron Shielding Calculations

Another simple approach that might be possible is to employ the neutron transmission/attenuation curves of Allen and Futterer which can be found beginning on page 12 of PTP's Radiological Health Handbook.

These graphs provide dose reduction factors for neutrons of specified energies as a function of shield thickness. The shield is indicated to be polyethylene, but the graphs provide conversion factors for water, concrete and soil (NTS).

Gamma and Neutron Shields - General

Gamma and Neutron Shields - General

General

Consider the possible use of temporary shielding (mobile or fixed) rather than, or in addition to, permanent shielding.

Consider the consequences of the shield becoming contaminated or, if neutrons are present, activated.

If permanent shielding is used, consider the cost and ease associated with dismantling it – this might be necessary when the facility is decommissioned. Concrete shields are sometimes built with an inner (closest to the source) layer that is intended to be removed at the end of the facility's life.

Gamma and Neutron Shields - General

General

If a source emits gamma rays at a variety of energies, the high energy gamma rays sometimes determine the shielding requirements. For example, even though the 1764 and 2204 keV gamma rays of radium sources normally contribute very little to the exposure rate, they become the controlling radiation once the shield has eliminated the more predominant low energy photons. The HVL for Ra-226 is even larger than that for Co-60!

Gamma and Neutron Shields - General

General

Consider the possible use of local shielding inside shielded vaults/areas not normally occupied. For example shields might be installed inside accelerator vaults near those accelerator components most prone to activation. This reduces doses during maintenance when the area is temporarily occupied.

Gamma and Neutron Shields - General

Radiation Energy

The lower the energy of the gamma rays or neutrons, the easier it is to shield them (i.e., the thinner the shield needs to be).

If a source emits gamma rays at a variety of energies, the high energy gamma rays sometimes determine the shielding requirements. For example, even though the 1764 and 2204 keV gamma rays of radium sources normally contribute very little to the exposure rate, they become the controlling radiation once the shield has eliminated the more predominant low energy photons. The HVL for Ra-226 is even larger than that for Co-60!

Gamma and Neutron Shields - General

Shielding Material

For gamma rays, the higher the atomic number of the shield material, the greater the attenuation of the radiation.

For neutrons, the lower the atomic number of the shielding material, the greater the attenuation of the radiation.

For both radiations, the greater the density of the shield material the greater the attenuation of the radiation. Even though water and air have essentially the same effective atomic number, water is a better shield because it is denser.

Gamma and Neutron Shields - General

Shielding Material – Lead

For attenuating photons

- Advantages:
- high atomic number ($Z=82$)
 - moderately high density (11.34 g/cm^3)
 - easily machined and melted
 - relatively inexpensive

Disadvantages:

- lack of mechanical strength
- chemical toxicity (some facilities require gloves for handling) . Oxidized lead (white) is especially bad.
- “new” lead can be naturally radioactive (Pb-210)
- recycled lead is often contaminated

Gamma and Neutron Shields - General

Shielding Material – Lead

Lead is available in a variety of forms including:

- standard bricks (4" x 8" x 2" approx 25-30 lbs)
- interlocking bricks
- sheets (typically 1/64 to 1/8" thick), including lead backed drywall board and plywood
- tape
- wire
- pipe
- shot – for filling voids
- wool – for filling voids

Gamma and Neutron Shields - General

Shielding Material – Lead

Leaded hardware/items of various types:

- leaded louvers for vents
- leaded hinges and handles for doors
- lead covers for electrical switches and covers
- lead-headed nails for installing lead sheets
- lead plugs, caps for screw hole covers.
- batten strips for joints and corners
- lead glass for windows - it varies, but 4 mm of typical lead glass is roughly equivalent to 1 mm of pure lead

Gamma and Neutron Shields - General

Shielding Material – Tungsten Alloys

For attenuating photons. Tungsten alloys can contain iron, copper, cobalt and nickel.

- Advantages:
- tungsten's high atomic number ($Z=74$)
 - very high density (ca. 14 - 18 g/cm³)
 - strong
 - non-toxic
 - thinner shields possible than with lead

Disadvantages:

- very difficult to machine and fabricate
- expensive

Gamma and Neutron Shields - General

Shielding Material – Depleted Uranium

For attenuating photons.

- Advantages:
- very high atomic number ($Z= 92$)
 - very high density (19.1 g/cm^3)
 - good mechanical strength
 - thinner shields possible than with lead

Disadvantages:

- pyrophoric
- expensive, but less so than tungsten
- radioactive, hence there are regulatory issues with it

Gamma and Neutron Shields - General

Shielding Material – Water

For attenuating photons and neutrons

Advantages:

- completely fills all voids unlike a solid shield
- transparent
- can manipulate source and equipment in water
- inexpensive
- source leaks can be detected by sampling water

- Disadvantages:
- it can leak
 - it can evaporate
 - a leaking source can contaminate large volumes of the water

Gamma and Neutron Shields - General

Shielding Material – Concrete

For attenuating photons and neutrons

Advantages:

- can also serve a structural role
- can incorporate additives such as barium to improve its characteristics
- can be used to shield both neutrons and gamma rays

Disadvantages:

- very thick walls can be needed
- it can be difficult to modify and dismantle

Gamma and Neutron Shields - General

Streaming

Cracks or voids in the shield can allow narrow beams radiation to stream through the shield.

Such openings in a shield might be unavoidable, e.g., doors, penetrations for piping, ducts, cables ,etc.

Whenever possible, such openings should be curved or angled so as to prevent the radiation from having a straight shot through the shield. Even so, some gamma rays and especially neutrons can scatter their way through these openings.

Quantifying such streaming is best done with a computer.

Gamma and Neutron Shields - General

Streaming

Penetrations in the shield should generally be at least seven feet above the floor.

Consider filling any voids in such penetrations (e.g., with lead shot).

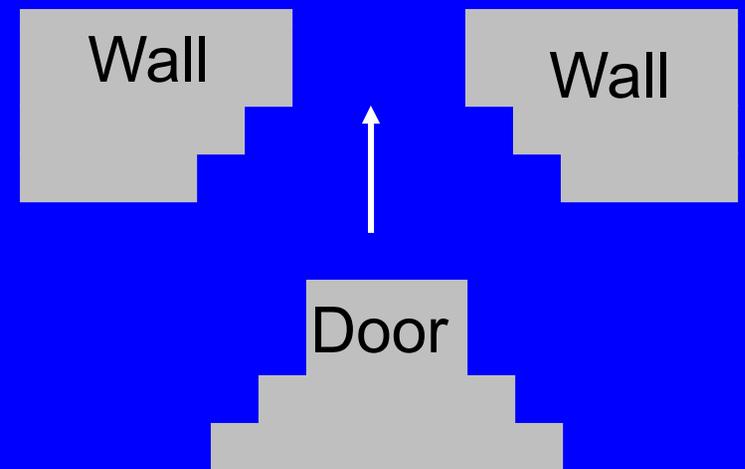
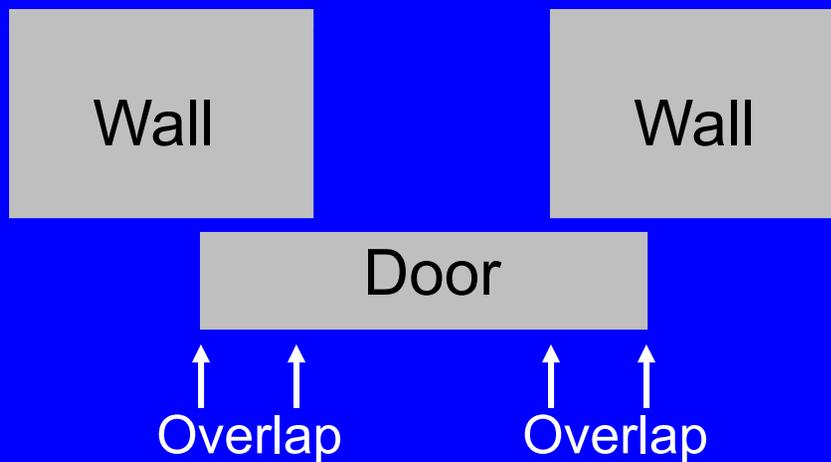
Penetrations should not be directed toward occupied areas or areas where there is traffic, e.g., stairways.

Determine if shields could be employed at ends of the penetration.

Gamma and Neutron Shields - General

Streaming – Door design

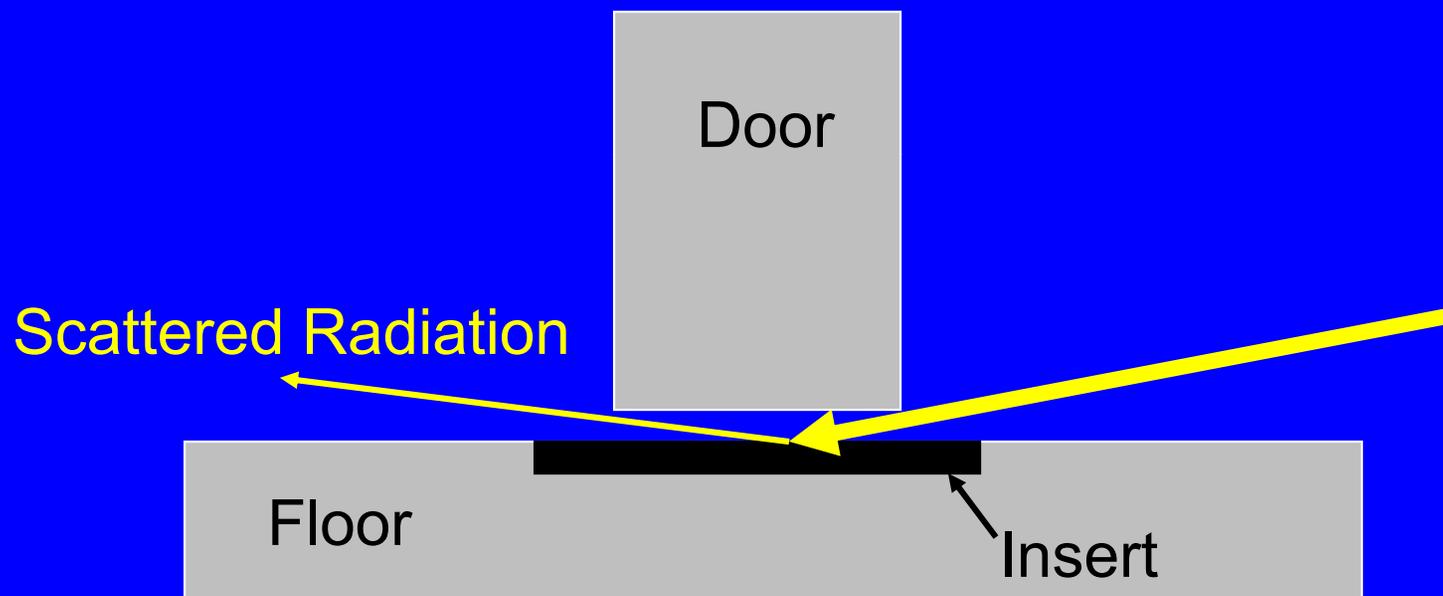
Neutron streaming can be harder to minimize than gamma streaming.



Gamma and Neutron Shields - General

Streaming – Door design

It can be very difficult to prevent radiation from going through the gap under a door.



High atomic number inserts under a door can minimize scattered gamma radiation.

Gamma and Neutron Shields - General

Streaming - Labyrinth

A labyrinth (aka maze) might be employed at the entrance to a shielded area.

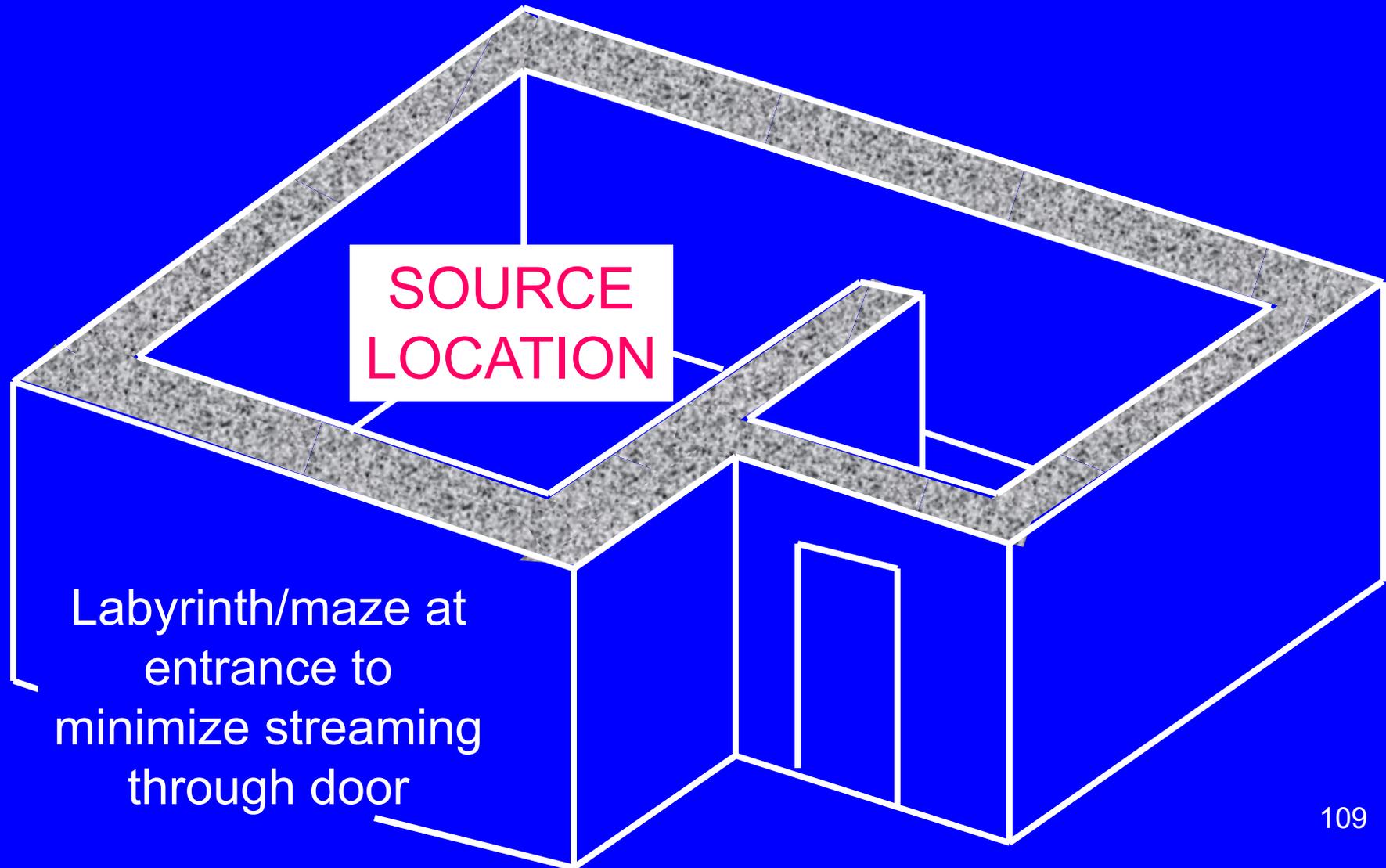
This labyrinth prevents a “line of site view” of the source while allowing equipment and material to be moved in or out with relative ease.

It avoids the need for complicated door designs like those shown in the previous slides.

The general rule is that the radiation must scatter at least twice to reach the entrance.

Gamma and Neutron Shields - General

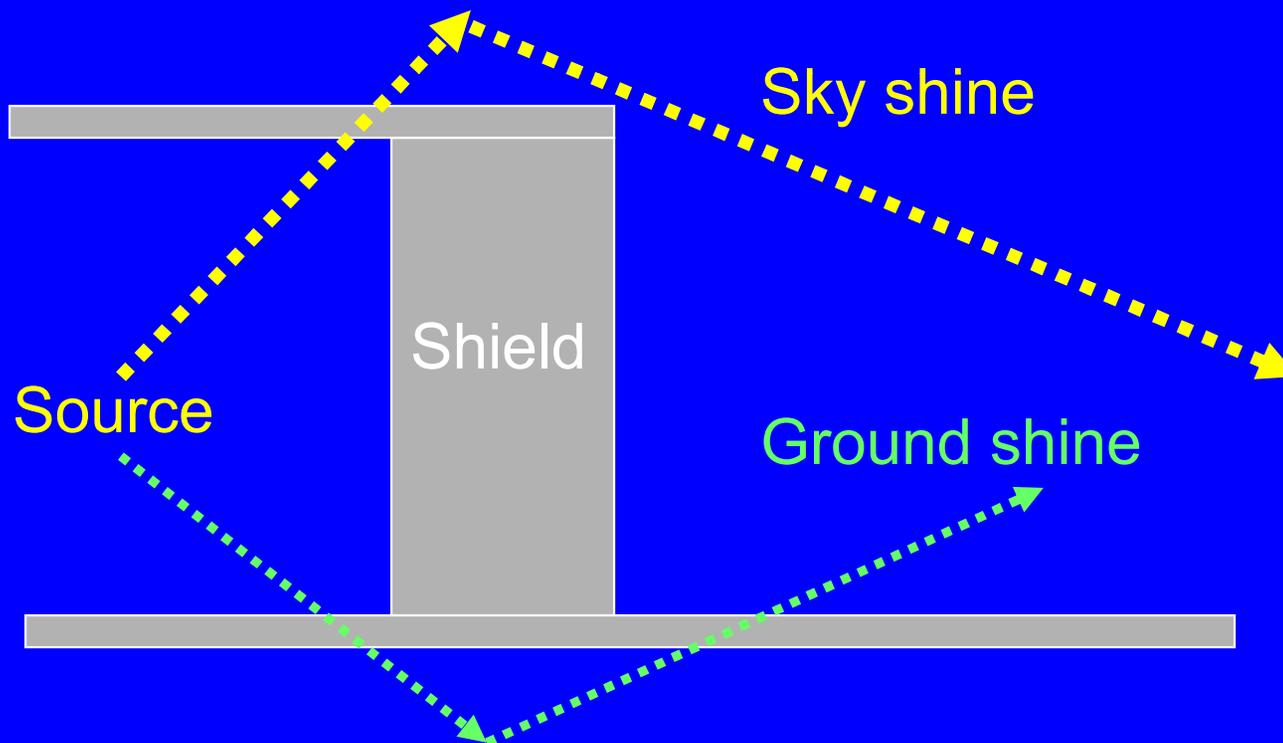
Streaming - Labyrinth



Gamma and Neutron Shields - General

Shine

Shine is a term that usually refers to radiation that has penetrated a weak spot in the shielding and scattered. One such weak spot is often the ceiling.



Gamma and Neutron Shields - General

Shine

Radiation that goes over the shield and scatters in the air towards the ground is known as sky shine.

Radiation that has gone through the floor and scattered upwards in the ground is known as ground shine. The latter is rarely a major concern.

The primary dose to the public near a nuclear facility (e.g., accelerator) is often due to sky shine. This is especially true for neutrons.

Appendices