Gamma Ray Attenuation Properties of Common Shielding Materials

Daniel R. McAlister, Ph.D.

PG Research Foundation, Inc. 1955 University Lane Lisle, IL 60532, USA

Introduction

In areas where people are likely to encounter ionizing radiation, it is often necessary to provide shielding to reduce exposure to gamma radiation. Common forms of shielding include rigid materials with limited portability, such as high density concrete, lead bricks, steel plates and cooling pools filled with water. The gamma attenuation of these materials has been widely studied, and the attenuation data is available in resources such as the Nation Institute of Standards and Technology (NIST) XCOM database[1]. In addition to these classic, well characterized shielding materials, composite materials are becoming increasingly available from shielding manufacturers. These composite materials range from simple advances, such as lead wool blankets with protective plastic covers, to more advanced materials, such as custom molded components constructed from high density metals dispersed in organic polymers. When evaluating the merits of these composite materials relative to the more classic forms of shielding, it is important to understand the basic principles that lead to gamma ray attenuation.

Put simply, shielding, or the attenuation of gamma radiation, occurs through the interaction of the gamma radiation with matter. The degree to which gamma radiation is attenuated is dependent upon the energy of the incident gamma radiation, the atomic number and density of the elements in the shielding material, and the thickness of the shielding. Composite materials may offer additional benefits in chemical resistance, physical durability, and portability. However, the composite material will not exceed the gamma attenuation characteristics of an equal mass of the components used in its construction. This principle is often referred to as "mass in the path". For example, a square foot of solid lead sheet will have essentially the same attenuation as a square foot lead wool blanket, as long as the two shields contain the same mass of lead. However, the lead wool blanket will be physically thicker than the solid lead sheet. A more detailed explanation of the principles of the attenuation of gamma radiation and additional examples of shielding types will be given in the following pages.

Attenuation of gamma radiation

The attenuation of gamma radiation (shielding) can be described by the following equation[2,3]:

$$I = I_o e^{-\mu\rho t} \qquad \text{or} \qquad I = I_o e^{-\mu d} \qquad \text{(equation 1)}$$

I = intensity after shielding
I_o = incident intensity
μ = mass absorption coefficient (cm^2/g)
d = thickness of absorber (g/cm^2)
ρ = density of absorber (g/cm^3)
t = physical thickness of absorber (cm)

In practical terms, I is the intensity of gamma radiation after interaction with the shielding material. I is dependent on I_o, the initial intensity of the gamma radiation (before shielding), μ, the mass absorption coefficient for the shielding material, and d, the "thickness (g/cm^2)" of the shielding material (alternatively written as a product of the density (g/cm^3) and the physical thickness (cm) of the shielding material).

The mass absorption coefficient is dependent on the energy of the incident gamma radiation and the elemental composition of the shielding material. Mass absorption coefficients can be determined by measuring I and I_o for a shielding material of known thickness (d) and are available for a wide range of elements and composite materials from the National Institute for Standards and Technology (NIST) XCOM database[1]. Once the mass absorption coefficient is known, the physical thickness (cm) of a given type of shielding material required to reduce the gamma radiation intensity to a desired level (ratio of I/I_o) can then be calculated by solving the shielding equation for t:

$$t = \ln(I/I_o) / (-\mu\rho) \qquad \text{(equation 2)}$$

Comparing the thicknesses of different materials needed to achieve the shielding requirements for a particular application, along with other factors, such as the cost, weight, and chemical and physical durability of the materials, will then allow one to choose the most appropriate type of shielding.

Physical interactions leading to attenuation

Shielding of gamma radiation primarily involves the interaction of gamma radiation with matter via three main processes[2,3]: 1) photoelectric effect, 2) Compton scattering, and 3) pair production. In the photoelectric effect, a gamma ray interacts with an atom resulting in the ejection of an electron from the atom. The electron receives all of the energy of the gamma ray,

minus its atomic binding energy, and may induce secondary ionization events. The probability of the photoelectric effect is proportional to the atomic number (Z) of the absorbing element and inversely related to the energy of the gamma ray. Therefore, the photoelectric effect is most important for low energy gamma rays interacting with heavy elements such as lead and tungsten.

Compton scattering is similar to the photoelectric effect, in that it involves the interaction of a gamma ray with an atomic electron, resulting in the ejection of the electron from the atom. However, in Compton scattering, only a portion of the energy of gamma ray is transferred to the electron. As with the photoelectric effect, the probability of Compton scattering is proportional to the atomic number of the absorbing element (Z) and inversely proportional to the energy of the gamma ray. Compton scattering is most likely to occur for gamma rays in the 600-4000 keV range and results in a continuum of scattered gamma ray energies from 250 keV below the highest energy of the incident gamma radiation (Compton gap) down to a minimum value dependent on the energy of the incident radition. The minimum energy resulting from Compton scattering can be determined using the following equation:

$$\text{Energy}_{minimum} \text{ (in keV)} = 511 * \text{Energy}_{incident} / (511 + 2 * \text{Energy}_{incident}) \qquad \text{(equation 3)}$$

Pair production is less common than the photoelectric effect or Compton scattering and occurs only for very high energy gamma rays (>1022 keV). In pair production, a gamma ray is transformed into matter near the nucleus of an absorber atom in the form of an electron-positron pair. Incident gamma energy in excess of 1022 keV is transferred to the electron-positron pair as kinetic energy. The positron will eventually undergo annihilation, producing two 511 keV gamma rays, and the electron may also induce addition ionization reactions. The likelihood of pair production, for gamma rays greater than 1022 keV, is proportional to the square of the atomic number of the absorbing atom and the logarithm of the incident gamma energy.

The contributions of Compton scattering, photoelectric absorption and pair production to the total mass absorption coefficient (μ) for each type of shielding, calculated using the NIST XCOM database, are plotted in Figure 1. The sum of these interactions is plotted as the total mass absorption coefficient. Lines in Figure 1 Represent the XCOM calculations, while data points correspond to experimental measurements obtained as described later in the manuscript. Shielding of 200-1500 keV gamma radiation with materials containing high Z components, such as lead and tungsten, is achieved with a significant contribution from both Compton scattering and photoelectric absorption. However, shielding with materials containing low Z components, such as iron and water, is achieved primarily with Compton scattering.
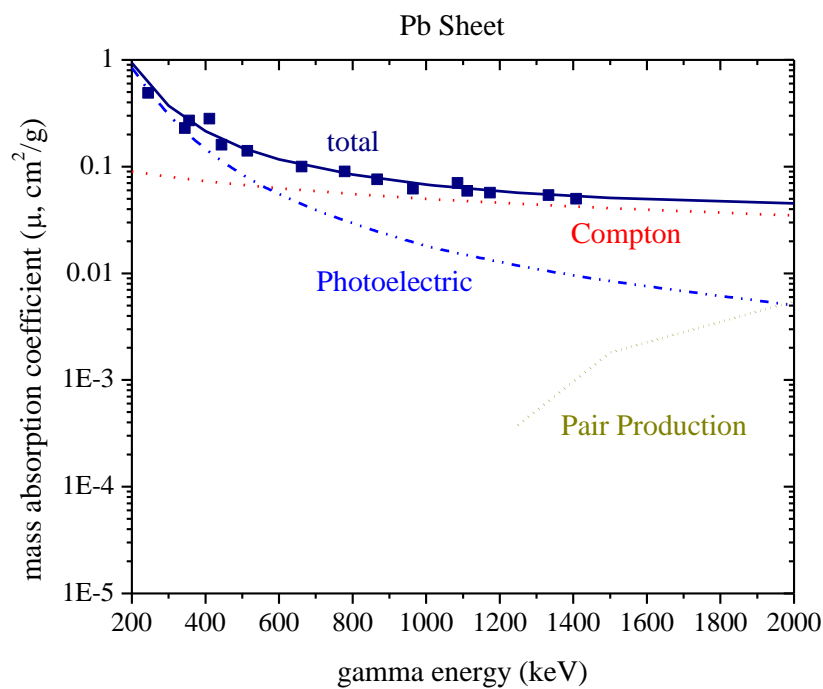
Pb Sheet

**Figure 1a. Attenuation of gamma radiation by solid lead sheet.
Measured values (squares). XCOM calculated values (lines)**
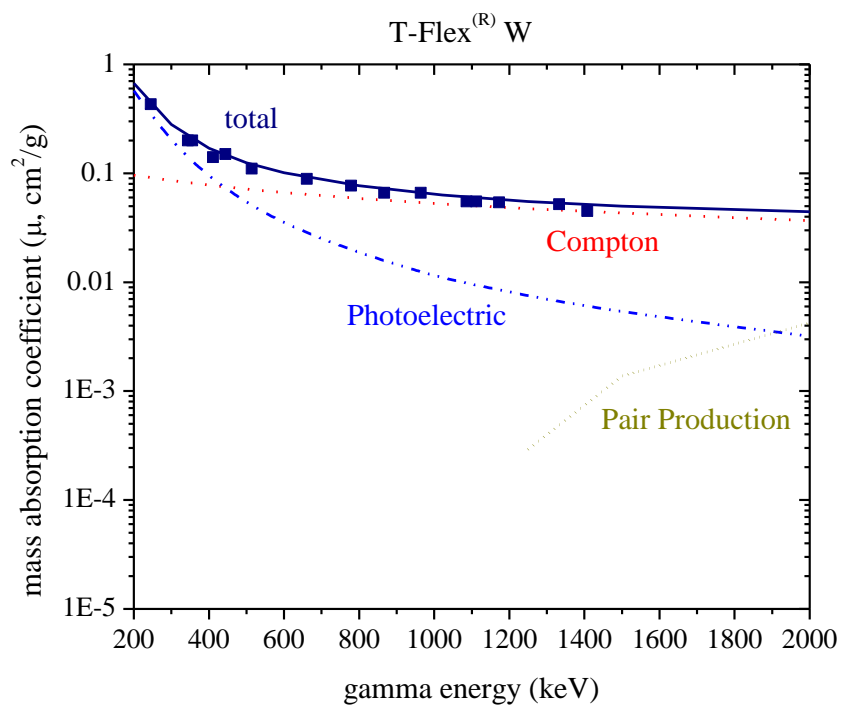
T-Flex[(R)] W

**Figure 1b. Attenuation of gamma radiation T-Flex[®] W. Measured
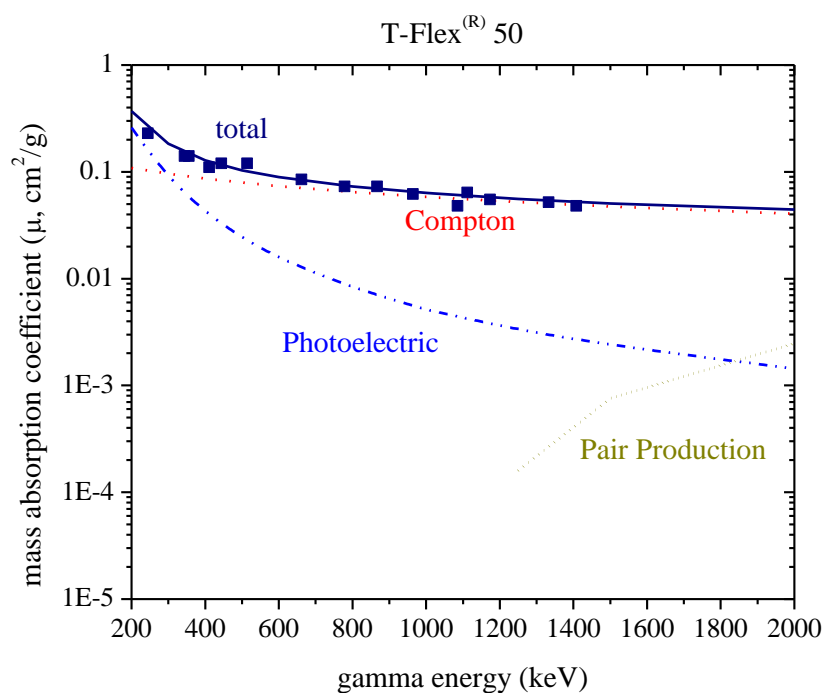values (squares). XCOM calculated values (lines)**

Figure 1c. Attenuation of gamma radiation T-Flex[®] 50. Measured values (squares). XCOM calculated values (lines)
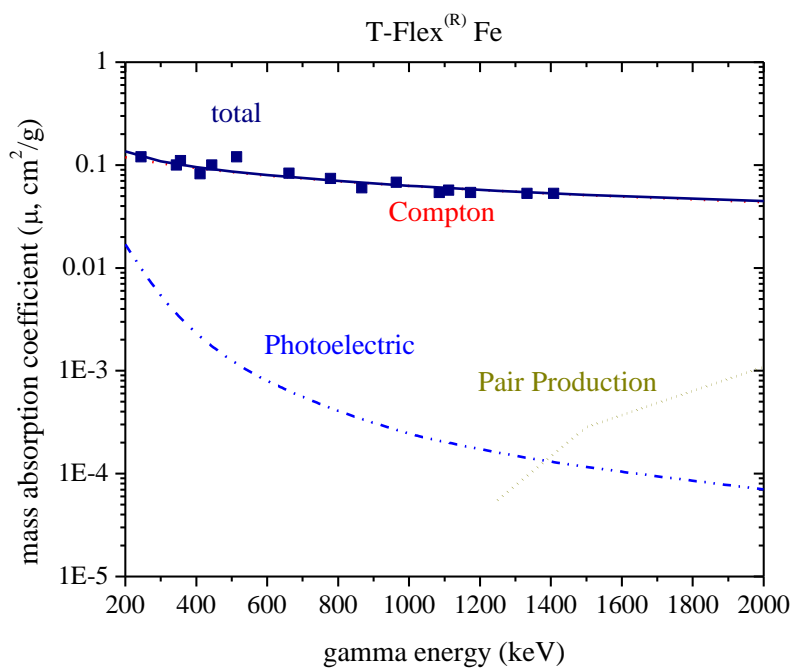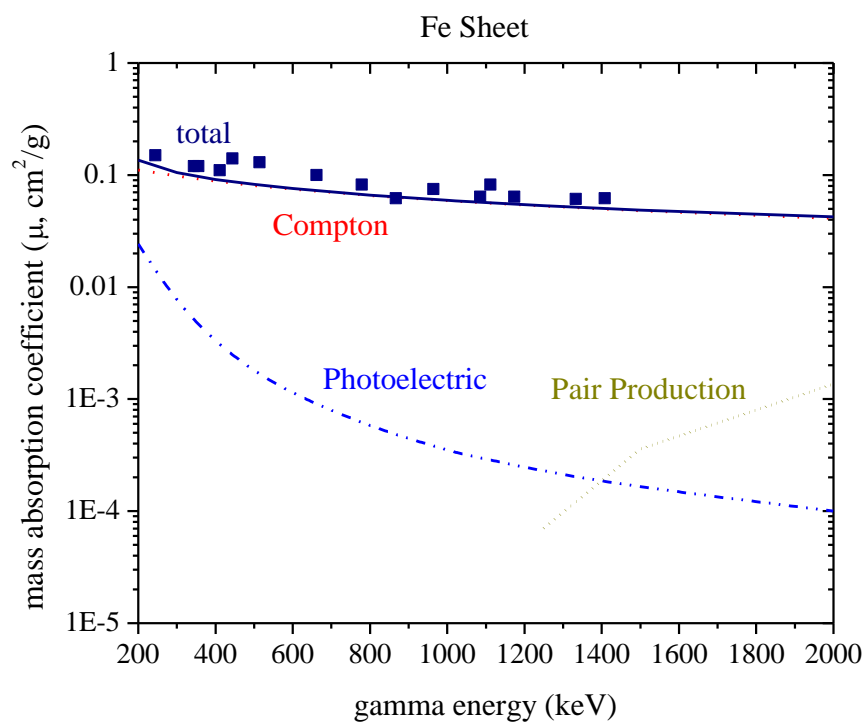

Figure 1d. Attenuation of gamma radiation T-Flex[®] Fe. Measured values (squares). XCOM calculated values (lines)

Figure 1e. Attenuation of gamma radiation solid iron sheet. Measured values (squares). XCOM calculated values (lines)
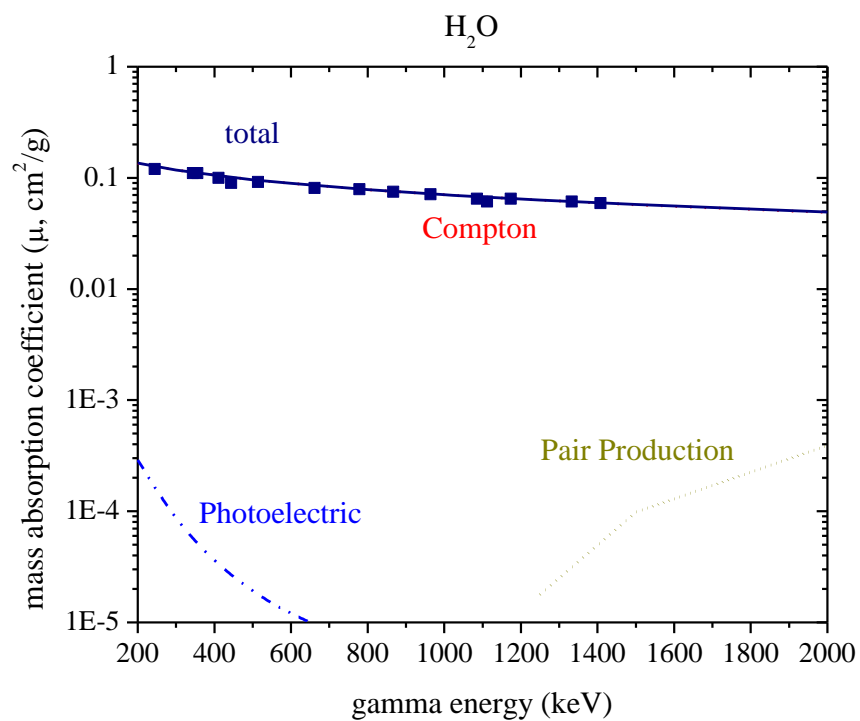

Figure 1f. Attenuation of gamma radiation by water. Measured values (squares). XCOM calculated values (lines)

Experimental measurement of attenuation

      Gamma ray attenuation for shielding materials constructed from solid lead and steel sheets, quilted lead wool, tungsten and iron suspended in a silicone polymer, and water were measured. Lead wool blankets, tungsten suspended in polymer (T-Flex® W, 88% by mass W), iron suspended in polymer (T-Flex® Fe, 69% by mass Fe), and a blend of tungsten and iron suspended in polymer (T-Flex® 50, 39% W and 39% Fe by mass) were obtained from Nuclear Power Outfitters (Lisle, IL). The energy of incident gamma radiation was varied using several gamma emitting sources: Ba-133 (355.99 keV)[4], Sr-85 (513.99 keV), Cs-137 (661.66 keV), Co-60 (1173.23 and 1332.50 keV) and Eu-152 (40.18, 121.77, 344.29, 778.92, 964.11, 1085.89, 1112.08, and 1408.00 keV). Gamma radiation was measured using a high purity germanium (HpGe) detector (Ortec, Dspec Jr, 6 cm, 13% relative efficiency, liquid nitrogen cooled detector), and the apparatus depicted in Figure 2. Using the measured I, I_o and d (g/cm2), the μ values for each type of shielding at the discreet gamma energies were calculated. Experimental μ values were compared to theoretical values calculated using the NIST XCOM database. The experimental μ values and theoretical μ values calculated using the XCOM database are plotted in Figures 1 and 3. In general, there is very good agreement between the experimental and theoretical μ values.
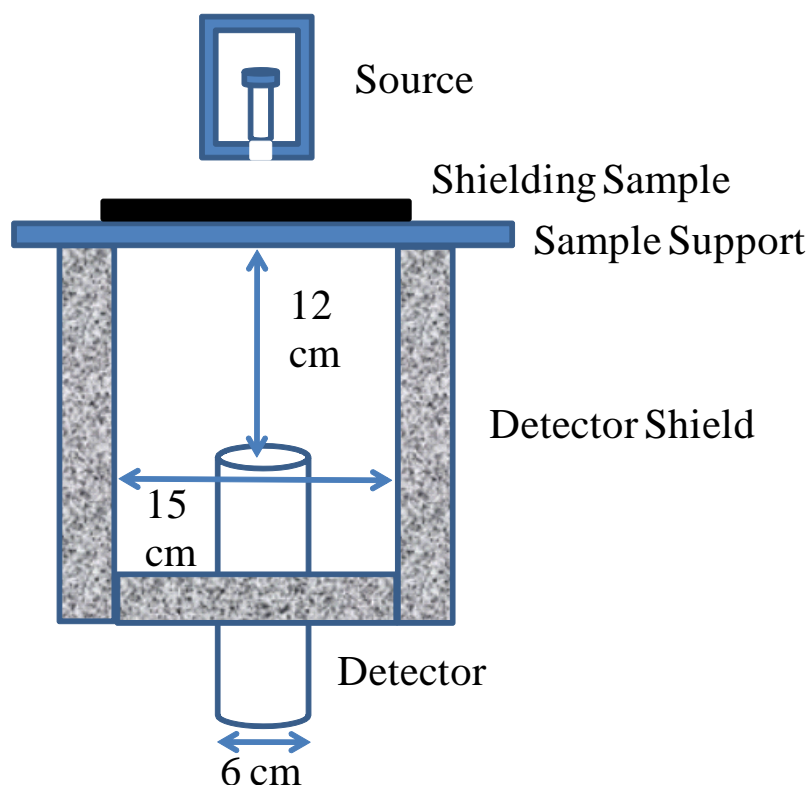

Figure 2. Attenuation measurement apparatus. Source: liquid source of radionuclide in 2mL borosilicate glass vial, enclosed in ½ inch lead pig with ¼ aperture at bottom. Sample support: ¼ inch polypropylene sheet. Detector shield: 1.5 inch lead with 1/8 inch copper lining. Detector: Ortec HpGe gamma detector (13% relative efficiency).
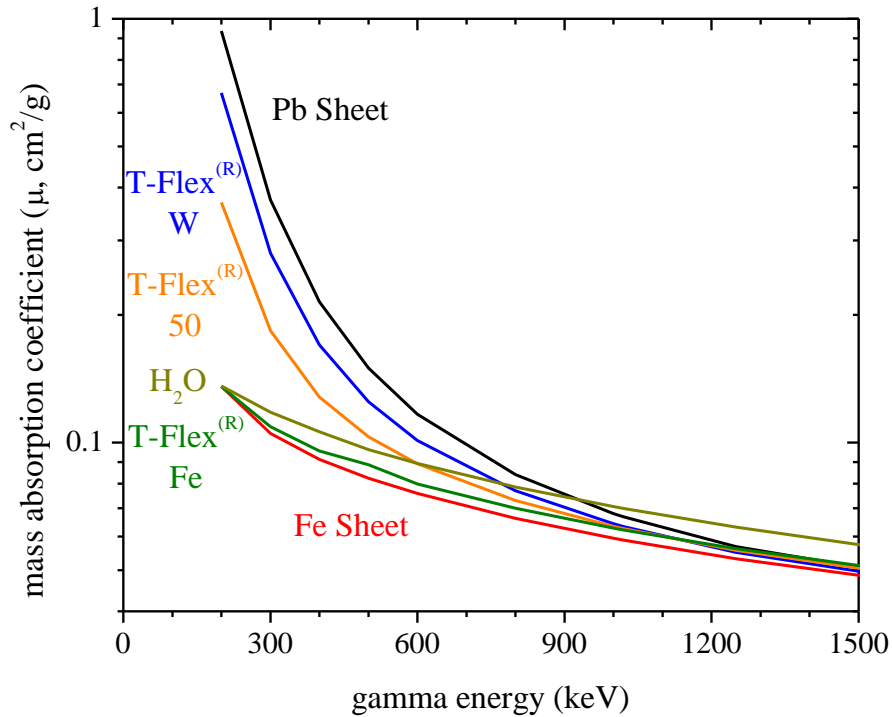
Figure 3. Mass absorption coefficient versus gamma radiation energy for selected shielding types.

Using the mass absorption coefficient and the known density of the shielding material, many other parameters, such as the attenuation for ½ inch thickness of shielding (Figure 4), the thickness of shielding required for 50% attenuation (Figure 5), and the mass of shielding required for 50% attenuation (Figure 6), can be calculated. As is illustrated in Figures 4-6, for a given thickness of shielding, materials prepared from high Z, high density components, such as lead or tungsten, offer superior attenuation to less dense, low Z materials, such as iron and water. However, when comparing the actual mass of shielding (g/cm^2) required to achieve a desired level of attenuation, the difference between the shielding materials is less dramatic. So, in applications where large volumes of shielding can be tolerated, such as cooling pools for spent nuclear fuel, water may be preferred over lead shielding. However, in other applications, where more physically rigid, compact shielding is required, lead and tungsten may be preferred.
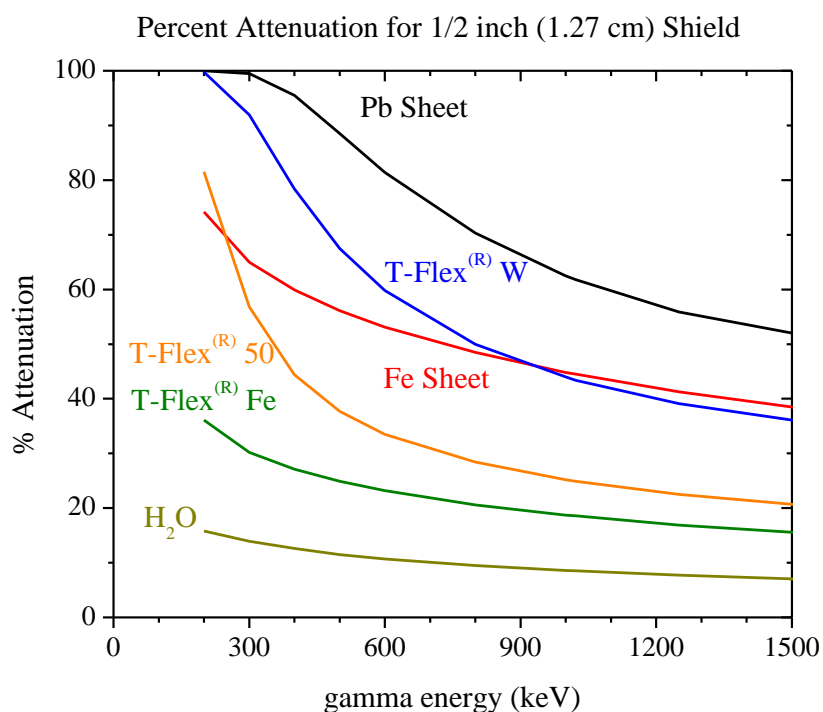
Percent Attenuation for 1/2 inch (1.27 cm) Shield

Figure 4. Percent attenuation of gamma radiation versus gamma energy for half inch (1.27 cm) thicknesses of selected shielding types.

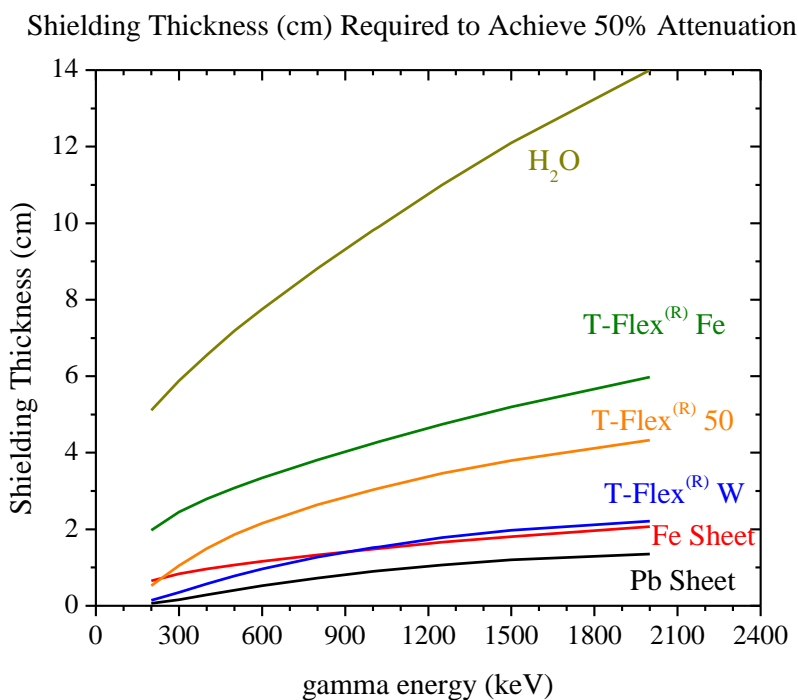Shielding Thickness (cm) Required to Achieve 50% Attenuation

Figure 5. Thickness (cm) of shielding required to achieve 50% attenuation versus gamma radiation energy for selected shielding types.

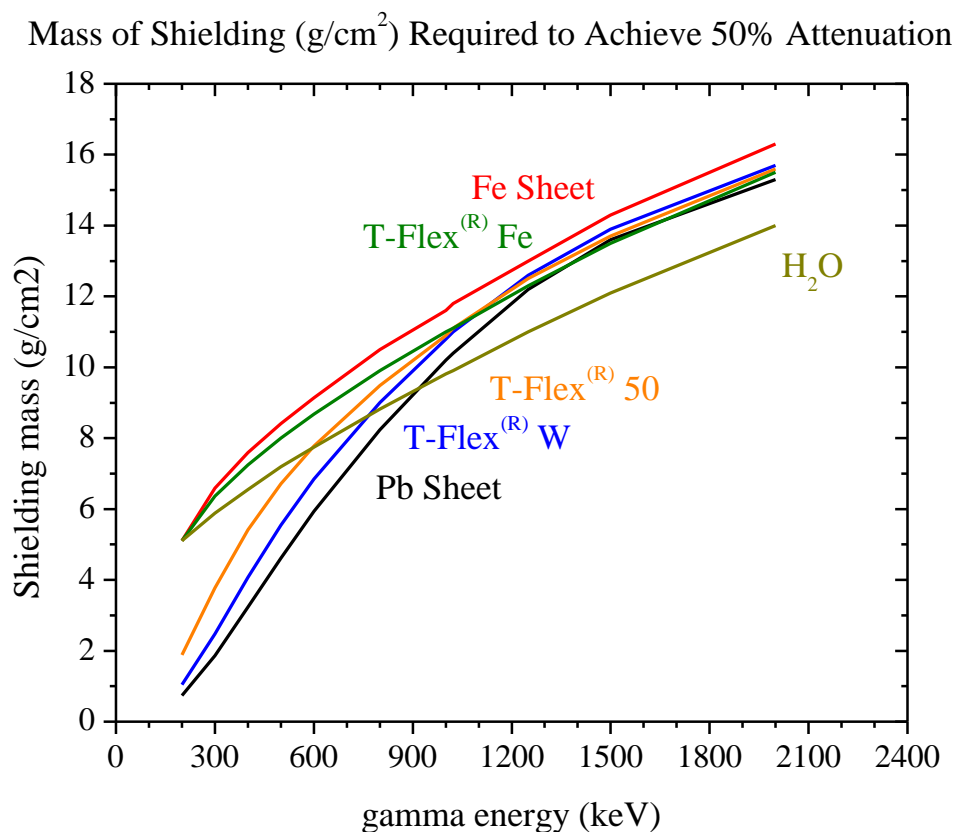Mass of Shielding (g/cm^2) Required to Achieve 50% Attenuation

Figure 6. Mass of shielding per surface area (g/cm^2) required to achieve 50% attenuation versus gamma radiation energy for selected shielding types.

Data for the mass absorption coefficient (μ) of solid metal shielding versus composite shielding constructed from, lead, tungsten and iron is plotted in Figures 7-9, respectively. In all cases, the m values for the solid metal and the composite materials are essentially identical.

Conclusion

The attenuation of gamma radiation can be achieved using a wide range of materials. Understanding the basic principles involved in the physical interactions of gamma radiation with matter that lead to gamma attenuation can help in the choice of shielding for a given application. Utilizing this understanding and considering the physical, chemical and fiscal constraints of a project, will lead to better application of resources to develop the most appropriate type of shielding.
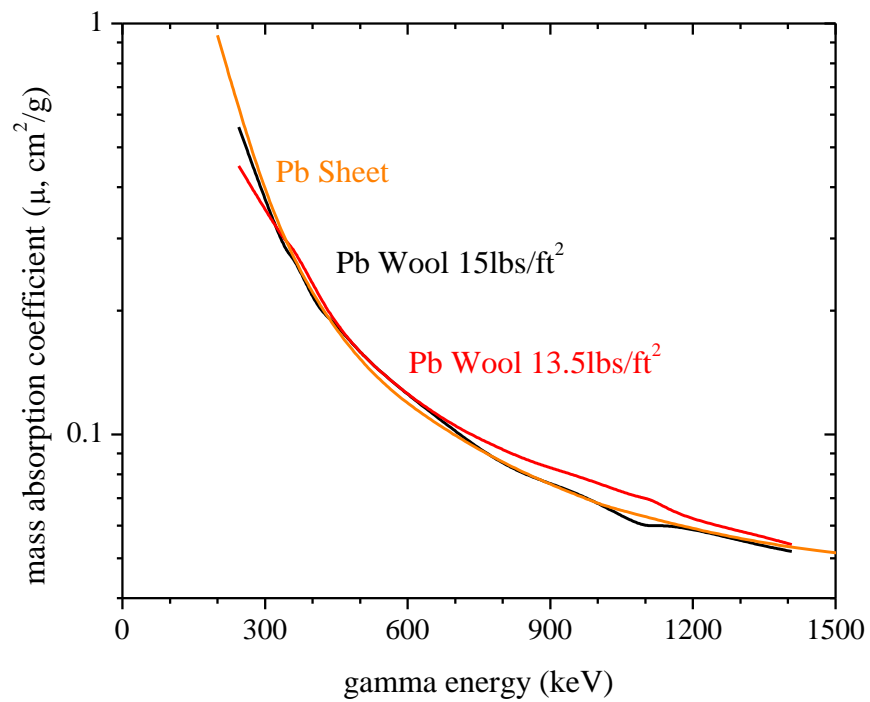
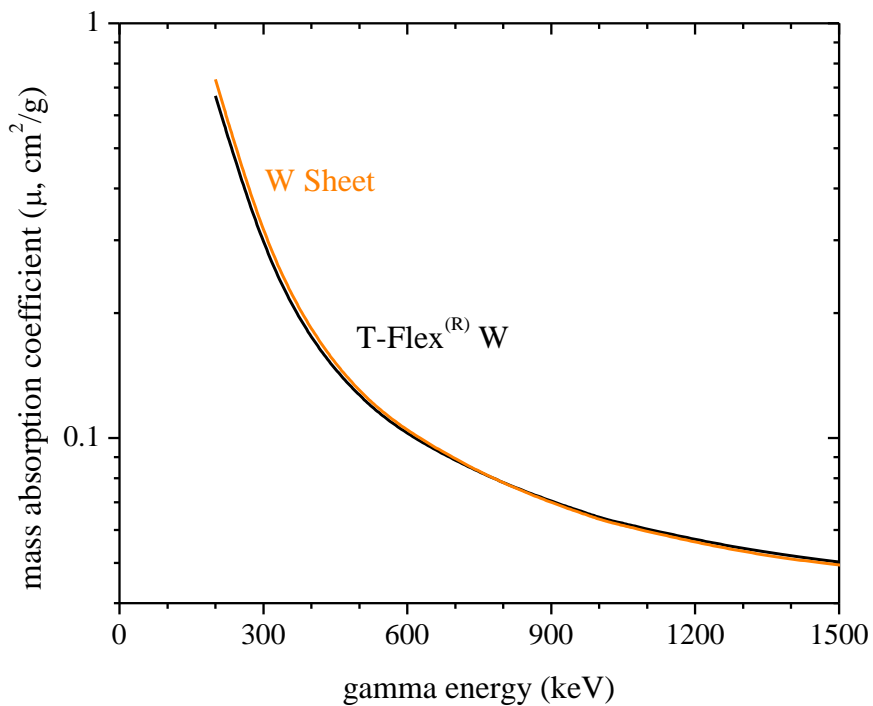**Figure 7. Mass absorption coefficient versus gamma radiation energy for lead materials.**

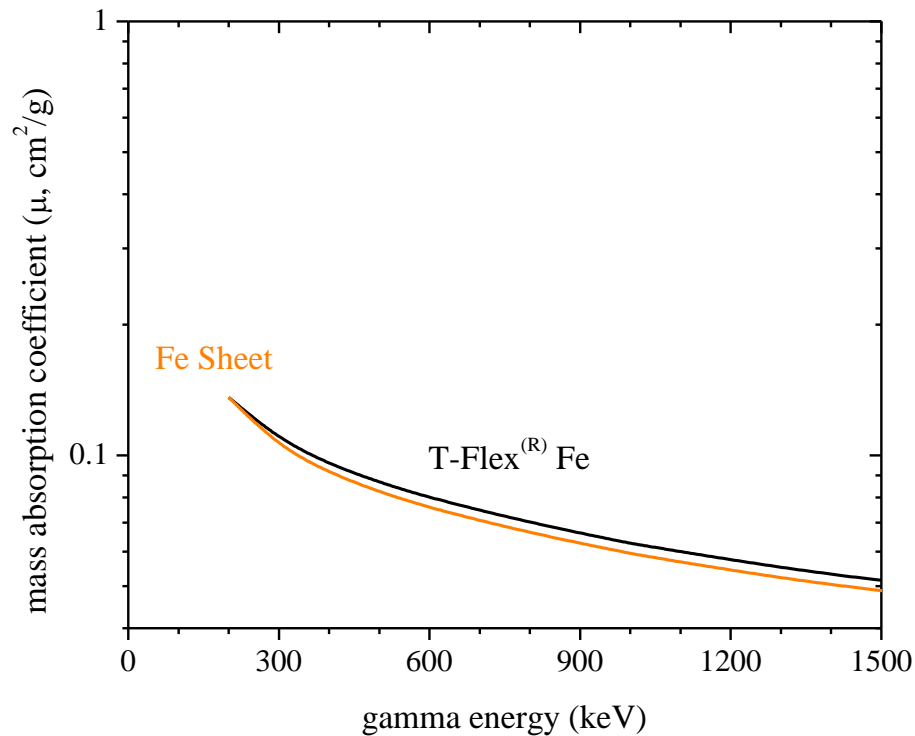**Figure 8. Mass absorption coefficient versus gamma radiation energy for tungsten materials.**

Figure 9. Mass absorption coefficient versus gamma radiation energy for iron materials.

References

1) National Istitute of Standard and Technology, Physical Measurements Laboratory, *XCOM Photon Cross-Sections Database*, http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html.
2) William D Ehmann and Diane E. Vance, *Radiochemistry and Nuclear Methods of Analysis*, John Wiley and Sons, New York, 1991, pp 162-175.
3) G. Nelson, D. Reilly "Gamma-Ray Interactions with Matter", in *Passive Nondestructive Analysis of Nuclear Materials*, Los Alamos National Laboratory, NUREG/CR-5550, LA-UR-90-732 ,1991, pp. 27-42.
4) Edgardo Browne, Richard B. Firestone, *Table of Radioactive Isotopes*, Editor Virginia S. Shirley, John Wiley and Sons, New York, 1986.