Gamma Ray Attenuation Properties of Common Shielding Materials

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Revision 6.1

June 18, 2018

Introduction

Attenuation or shielding of gamma radiation is an important component of radiation safety programs aiming to reduce personnel exposure to ionizing radiation. Attenuation data for commonly used shielding materials is available in many resources, such at the National Institute of Standards (NIST) XCOM database of attenuation coefficients[1] and Health Physics and Radiological Health.[2] Ultimately, selecting the most appropriate shielding material for a given source of ionizing radiation will require knowledge of the source of radiation, application of attenuation data from available resources, understanding of the basic principles gamma ray interactions with matter. Also, other factors, such as cost and chemical compatibility must be considered. The basic information required for assessing the relative merits of a wide range of shielding materials will be covered in the following sections.

Definition of common terms

Gamma ray. High energy electromagnetic radiation typically emitted from the atomic nucleus during nuclear decay processes.

X-ray. Fundamentally the same as gamma rays, but originating from electrons outside the atomic nucleus. Some resources may also distinguish gamma rays and x-rays based on energy.

Photon. An elementary particle of electromagnetic radiation.

Intensity or Flux The number of photons detected or emitted over a time period.

Electon volt (eV). Unit of energy of gamma or x-ray photons, equal to 1.60×10^{-19} joules. More often expressed as 1,000 eV = **keV** or 1,000,000 eV = **MeV**.

Photopeak. Peak observed in gamma ray spectrometry resulting from the deposition of the entire energy of the gamma photon within the detector. The energy or energies of the gamma ray photopeak(s) for particular radionuclide can be used to identify the radionuclide. For example, Co-60 emits gamma ray photons with photopeaks at 1173 and 1333 keV.[3]

Primary Radiation. Similar to photopeak. Source radiation or radiation which passes through the shielding material without its energy diminished through any scattering interactions.

Secondary Radiation. Also referred to as scattered radiation. Radiation which passes through the shielding material at diminished energy after undergoing scattering interaction(s) or is produced as a byproduct of scattering or absorption of radiation.

Photoelectric effect. The complete transfer of energy from a gamma ray photon to an atomic electron of the shielding material. Photoelectric absorption is more common for lower energy gamma radiation (<500 keV) and for shielding materials constructed from high atomic number elements, such as tungsten, lead and bismuth.

Compton scattering. The transfer of part of the energy of a gamma ray photon to an atomic electron of the shielding material. After undergoing Compton scattering, the gamma photon may undergo further scattering or absorption interactions with the shielding material and/or emerge from the shielding material with diminished energy. Compton scattering is predominant at relatively high gamma energies (500-1500 keV) and for shielding constructed from low atomic weight materials (H_2O, Al, Fe).

Pair production. An interaction of a gamma ray photon with the nucleus of an atom which results in the creation of beta particle and a positron. The positron then undergoes an annihilation reaction with an electron to produce two 511 keV gamma rays. The incident gamma radiation must have a minimum enery of 1022 keV to undergo pair production. Pair production becomes an important attenuation interaction for very high energy radiation (>1500 keV).

Attenuation coefficient. A quantity that characterizes how easily electromagnetic radiation penetrates a material. The attenuation coefficient is often expressed in terms of unit area per mass (cm^2/g). The attenuation coefficient and the material density can be used to estimate the transmission of gamma radiation through a chosen thickness of shielding material or the thickness of a shielding material required to achieve a desired level of attenuation. Gamma attenuation coefficients are inversely dependent on gamma energy and directly proportional to the atomic number of the element(s) from which the shielding material is constructed.

Buildup Factor. A correction factor used to account for the increase of observed radiation transmission through shielding material due to scattered radiation. Buildup factors are dependent on the energy of the primary radiation, the composition of the shielding material, and the thickness of shielding material. Tables of buildup factors for many materials are available.[4,5]

Half Value Layer (HVL). Thickness of material required to reduce the intensity of radiation to one half of its original intensity (50% attenuation).

Tenth Value Layer (TVL). Thickness of material required to reduce the intensity of radiation to one tenth of its original intensity (90% attenuation).

Common Shielding Materials

Provided below are brief descriptions of the attenuation characteristics and physical properties of some materials commonly used to shield gamma radiation. The materials listed below can be applied alone, dispersed in a structural material, such as concrete, dispersed in a polymer and molded into custom shapes, or layered to maximize the effectiveness for shielding mixed sources of radiation.

Lead. Cheap. Malleable. Available in sheets, bricks, foils and blankets. High density and high gamma attenuation coefficients allow for thin layers to achieve high attenuation relative to other shielding materials, particularly for low energy gammas and x-rays. Impurities in lower grades of lead can neutron activate. Toxicity and restrictions on disposal as radioactive waste can limit some applications. High bremsstrahlung production when beta radiation is present. Low melting point can limit high temperature applications.

Bismuth. Similar shielding properties to an equal mass of lead, but lower density requires thicker shielding. More expensive than lead, but cost difference may be lessened when considering the low toxicity of bismuth and lower disposal costs. Good activation characteristics. Low melting point of the metal can limit high temperature applications. However, bismuth oxide may be an option for higher temperature applications.

Tungsten. Lower attenuation coefficients than lead or bismuth, but very high density allows for similar thickness to achieve the same attenuation. Expensive and difficult to machine. High density makes tungsten ideal for applications where powder is dispersed in a polymer. Good activation characteristics. Low toxicity. Low Reactivity. Good stability to high temperatures. Relatively high thermal neutron radiative capture cross-section (n,γ), compared to lead and bismuth, can lead to significant production of secondary gamma radiation in high neutron fields.

Iron and Steel. Cheap. Relatively high density. Strong structural material. Activates with neutrons. Thicker and heavier shields needed to achieve same attenuation of lead, bismuth or tungsten. Much lower bremsstrahlung production than lead or bismuth when beta radiation is present.

Water. Cheap. Transparent. Low density requires 10-20x thickness as lead or bismuth for gamma attenuation. Good neutron attenuation. Can leak or evaporate. Boric acid (H_3BO_3) may be added to improve neutron attenuation and minimize secondary photon production from neutron capture.

Borated paraffin or polyethylene. Relatively cheap. Low density requires 10-20x thickness as lead or bismuth for gamma attenuation. Good neutron attenuation. Addition of boron reduces gamma production from radiative capture (n,γ) due to the high (n,α) cross-section of boron-10.

Table 1. Physical Properties of Shielding Materials

Material	Density (g/cm^3)	Melting Point (^{o}C)	HVL (cm) Co-60
Water	1.00	0	18*
Aluminum	2.70	660	6.8**
Iron	7.86	1535	2.2*
Copper	8.96	1083	1.9**
Bismuth	9.8	271	1.4**
Lead	11.34	327	1.2*
Tungsten	19.3	3410	0.8*

*From Reference 2

**Extrapolated from data in Reference 2

Material	Density (g/cm^3)	HVL (cm) Co-60*
TFlex®-Fe	2.8	6.5
TFlex®-50	3.8	4.4
TFlex®-Bi	4.7	2.9
TFlex®-W	7.2	2.2

*Measured, 50% dose reduction

Radiation Sources and Attenuation Mechanisms

Several common sources of x-ray and gamma radiation are listed in table 2. When selecting the best shielding material for a particular source of radiation, it is important to understand the mechanisms through which the gamma radiation is attenuated. The most important factors that determine the relative importance of the mechanisms through which gamma radiation is attenuated are (1) the energy of the gamma radiation and (2) the atomic number of the element(s) from which the shielding is constructed. Three of most important mechanisms for x-ray and gamma radiation are photoelectric absorption, Compton scattering and pair production.

Table 2. Common Sources of Gamma and X-Ray Radiation

Radiation Source	Type	Half-Life	Primary Decay Mode	Photon Energy (keV)
Medical X-Ray	Medical Imaging	N/A	N/A	5-100
Tc-99m	Medical Imaging (SPECT)	6.02 hours	γ	140.5
Tl-201	Medical Imaging (SPECT)	73 hours	ε	135, 167
In-111	Medical Imaging (SPECT)	2.83 days	ε	171, 245
F-18	Medical Imaging (PET)	1.83 hours	β+	511
Ga-68	Medical Imaging (PET)	68 minutes	β+	511
Cs-137	Fission Product	30.17 years	β-	662
Co-58	Activation Product ^{59}Co(n,2n)^{58}Co, ^{58}Ni(n,p)^{58}Co	70.92 days	ε	511, 811
Co-60	Activation Product ^{59}Co(n,γ)^{60}Co	5.27 years	β-	1173, 1333
N-16	Activation Product ^{16}O(n,p)^{16}N	7.13 seconds	β-	6129, 7115

For most sources of gamma radiation (with energies less than 1500 keV) attenuation is dominated by photoelectric absorption and Compton scattering (Figure 1). Photoelectric absorption results in the complete removal of the gamma photon through the complete transfer of its energy to an electron in the shielding material. Compton scattering occurs when a gamma photon transfers only part of its energy to an electron in the shielding material. The lower energy scattered gamma photon can then undergo additional scattering reactions or absorption interactions and may emerge from the shielding material with reduced energy. As can be seen in Figure 1, photoelectric absorption is more important for high atomic number elements, such as lead and bismuth, particularly for low energy gamma and x-rays. Compton scattering is more important for low atomic number elements, such as iron, and for higer energy gamma radiation.

At higher gamma energies (greater than 1500 keV), produced by select nuclides, such as Nitrogen-16, or in high energy accelerators, pair production becomes an important mechanism for gamma attenuation. The relative contribution to attenuation by pair production for selected shielding materials for high energy gamma radiation is plotted in Figure 2. The relative importance shielding mechanisms will be important in later sections, discussing attenuation calculations and overall dose reduction.

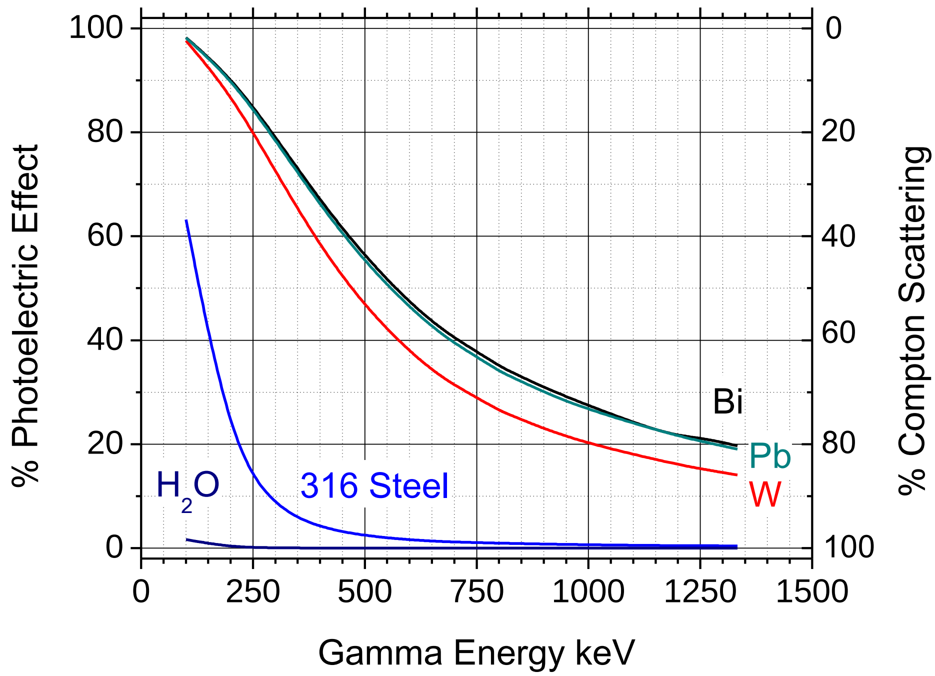

Figure 1. Relative % of attenuation by photoelectric absorption vs Compton scattering vs gamma energy

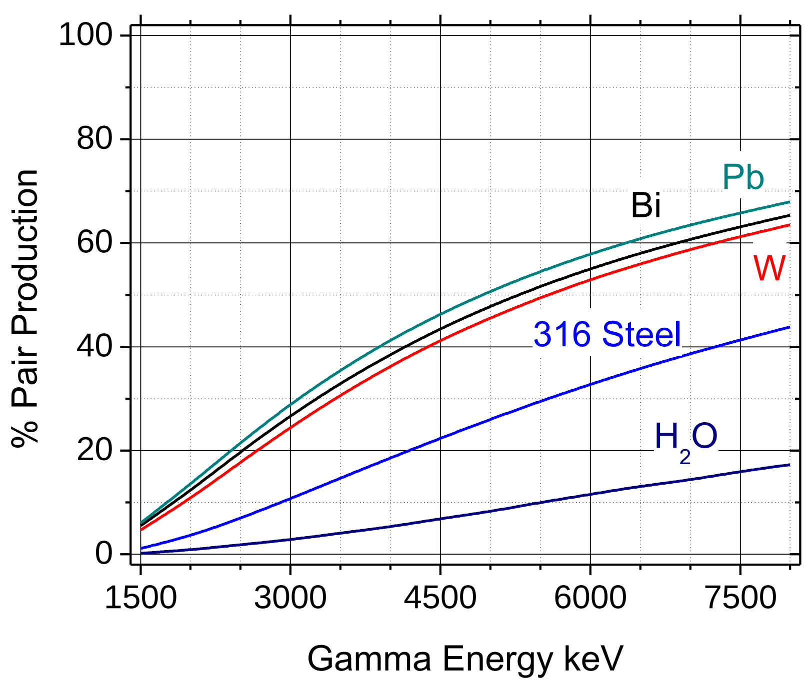

Figure 2. Relative % of attenuation by pair production vs gamma energy

Calculating Gamma Attenuation

For shielding materials where published data isn't available, attenuation can be estimated through calculation. The attenuation of gamma radiation (shielding) can be described by the following equation[2,6]:

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

where I = intensity after shielding, I_o = incident intensity, μ = mass absorption coefficient (cm^2/g), ρ = density of the shielding material (g/cm^3), and t = physical thickness of the shielding material (cm). A plot of the total mass attenuation coefficient vs. gamma energy for some common shielding materials is provided in Figure 3.

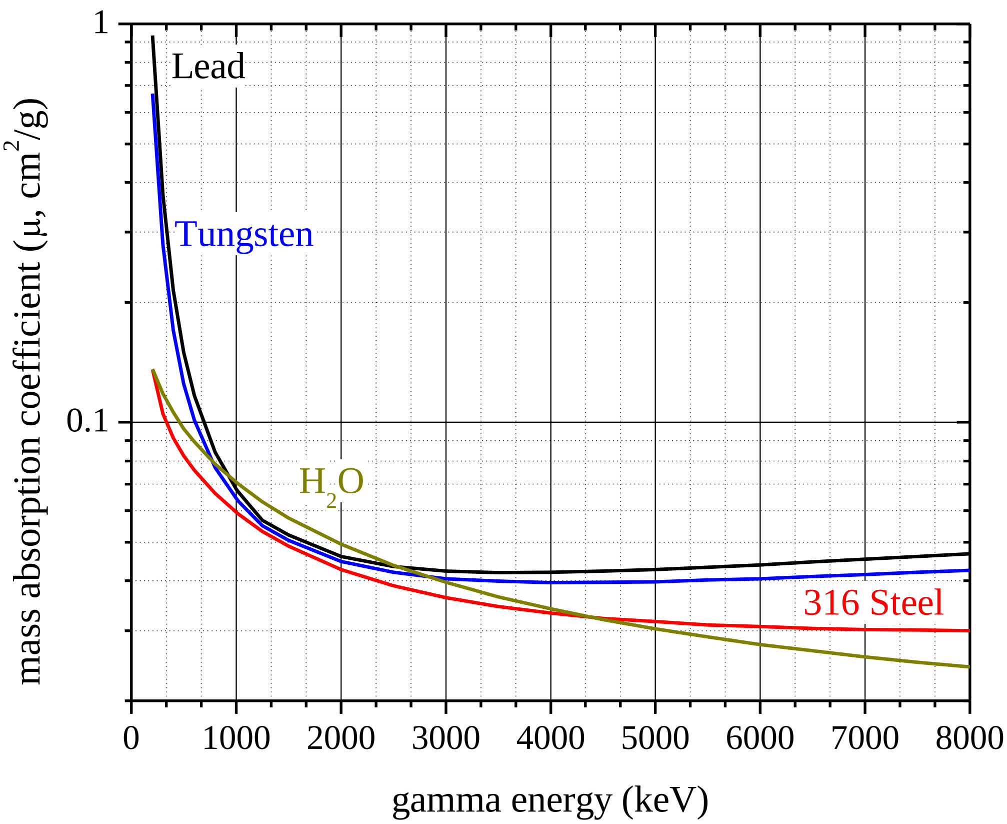

Figure 3. Mass attenuation coefficients vs gamma energy.

For low gamma energies (<500 keV), higher atomic number elements, such as lead, bismuth, and tungsten have much higher mass absorption coefficients and shield low energy gamma radiation and x-rays better than lower atomic weight elements, such as iron and aluminum. For gamma energies from 800-1400 keV, the mass attenuation coefficients for a wide range of material types including water, iron, tungsten and lead are very similar, suggesting that equal masses of lead and iron should have nearly identical attenuation properties. However, because the ratio of photoelectric absorption and Compton scattering is much different in lead than in iron, it is important to distinguish between the attenuation of primary radiation and dose attenuation, which also includes the contribution of scattered secondary radiation. The total mass absorption coefficient (μ or μ_{total}) is actually the sum of the attenuation coefficients for photoelectric absorption, Compton scattering, and any other mechanism that is important for a given gamma energy.

$$\mu_{total} = \mu_{photo} + \mu_{compton} + \mu_{pair\text{-}production}$$

As discussed earlier, attenuation via the photoelectric effect is more important for shielding constructed from high atomic number elements such as lead and bismuth and for gamma energies less than 500 keV. Attenuation via Compton scattering is more important for shielding constructed from low atomic number elements such as iron or aluminum and for gamma energies higher than 500 keV. So, for gamma energies of 800-1400 keV, shielding constructed from an equal mass of lead and iron will reduce the intensity of the main photopeak (primary) gamma radiation by similar amounts. However, the amount of Compton scattering will be much higher with the iron shielding, resulting in a significantly lower reduction in total gamma dose for the iron shielding vs. an equal mass of lead shielding. Because of the contribution of scattered gamma photons to gamma dose, attenuation calculations using the total mass absorption coefficient tend to overestimate the dose attenuation of a given mass of shielding, particularly for higher energy gamma radiation and lower atomic weight elements. Calculations of the amount of shielding required to achieve a desired reduction in gamma dose can be improved through the use of build-up factors,[4,5] the use of more sophisticated calculation programs such as Monte Carlo N-Particle Code (MCNP),[7,8] or by the use of experimentally determined dose attenuation factors.

Experimental measurement of attenuation

The experimental measurement of primary radiation attenuation and dose attenuation are described in the following section. Lead wool blankets, tungsten suspended in polymer (T-Flex® W, 88% by mass W), bismuth suspended in polymer (T-Flex® Bi, 85% by mass Bi), 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), 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).[3] Gamma radiation was measured using a high purity germanium (HpGe) detector (Ortec, Dspec Jr, 6 cm, 13% relative efficiency, liquid nitrogen cooled detector). Gamma dose measurements were performed using a Ludlum model 2241-2 survey meter equipped with either a model 44-9 standard pancake probe with dose equivalent filter or a model 133-2 gamma dose rate probe. Each dose measurement is the average of 300-500 data points collected using the Ludlum LMI224x logger program. Pancake type Geiger-Muller probes (Ludlum 44-9 or equivalent) have a non-linear dose response to low energy gamma radiation (20-150keV). Therefore, it is important to equip pancake probes with a dose equivalent filter when performing dose measurements. Removing the dose filter will enable the pancake probe to function more effectively in identifying contamination.

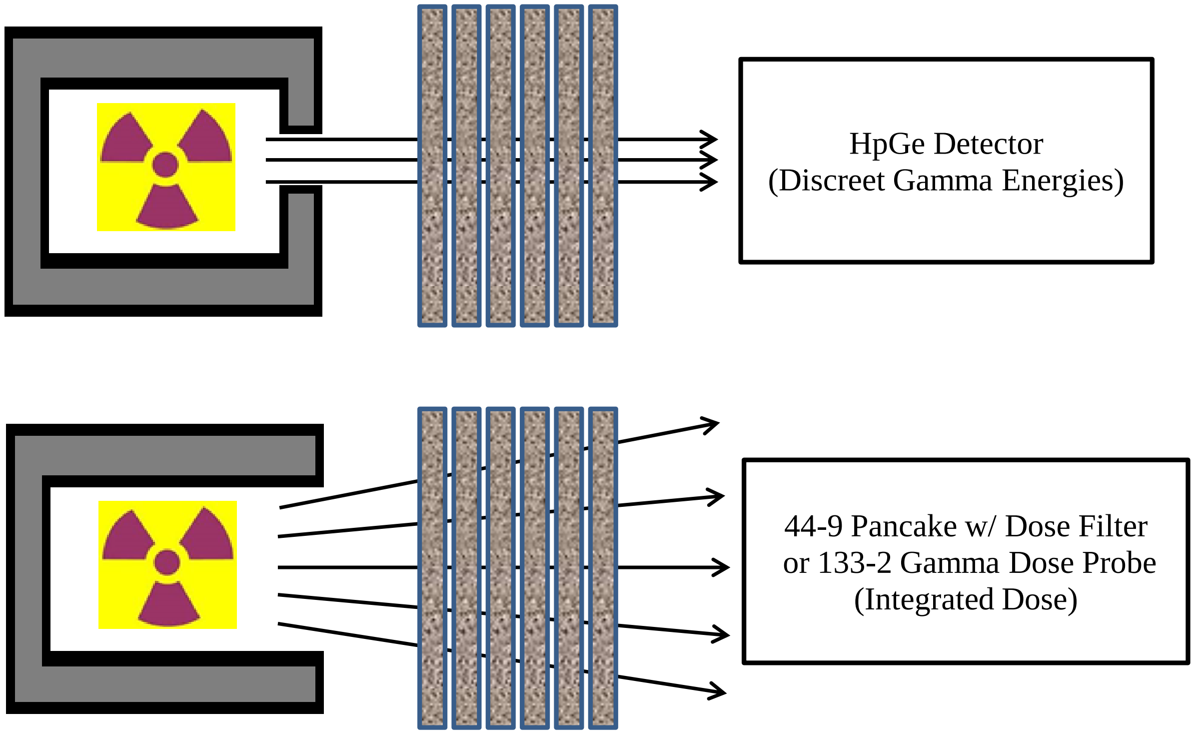

Figure 4. Experimental Design for Attenuation Measurements

The attenuation of gamma radiation was measured with the two different experiment designs depicted in Figure 4. The design depicted in the top of Figure 4 utilizes a well collimated point source of gamma radioactivity in a half inch lead pig with a 5 mm aperature. A high purity germanium detector (HpGe) was used to measure discreet gamma energies for the unshielded source and for 1-6 layers of shielding material. Data collected with this experimental design was used to confirm calculations using attenuation coefficients from the XCOM data base and equation 1. The results from these experiments (Figure 5 and 8) indicate the amount of primary radiation attenuated, but do not account for any secondary or scattered gamma radiation. Primary radiation attenuation measured using this design agreed to within 1-2% of the attenuation value calculated using mass attenuation coefficients and equation 1.

The design depicted at the bottom of Figure 4 utilizes a more diffuse, non-collimated source and two different dose meters to measure dose attenuation for layers of different types of shielding. Data collected with this experimental design (Figure 6 and 9) accounts for attenuation of primary radiation and any secondary radiation which passes through the shielding. Data for this experimental design is also more indicative of many real world industrial applications where the goal is overall dose reduction for personnel.

The difference in primary radiation attenuation and dose attenuation (Figure 7) is typically less than 10-15% for high atomic number materials, such as lead and bismuth and as high as 30-40% for lower atomic number elements, such as iron. This is consistent with the relative importance for the photoelectric and Compton scattering shielding mechanisms in these different materials.

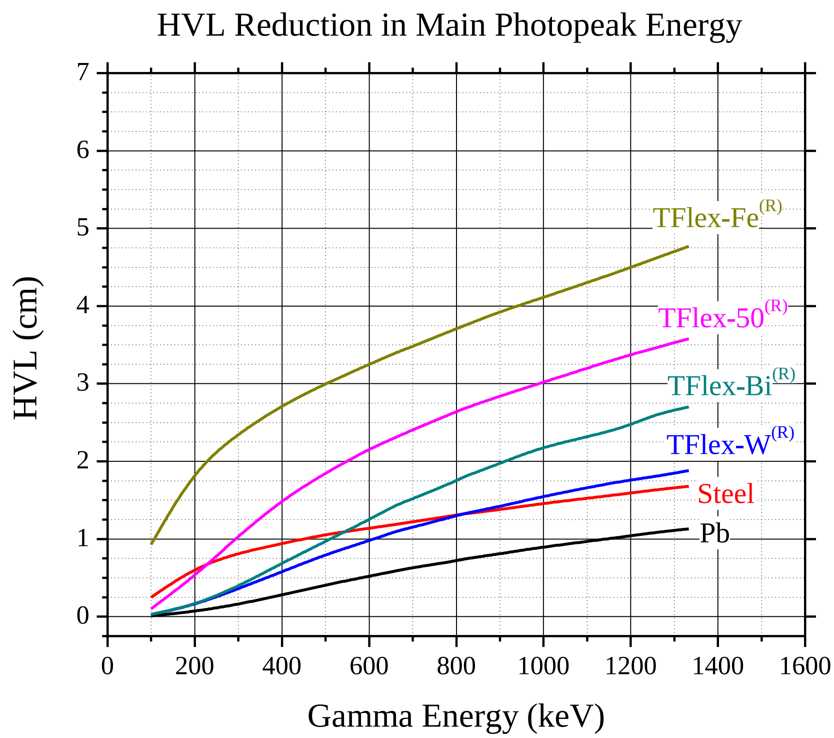

Figure 5. Shield thickness for 50% reduction in main Photopeak Energy

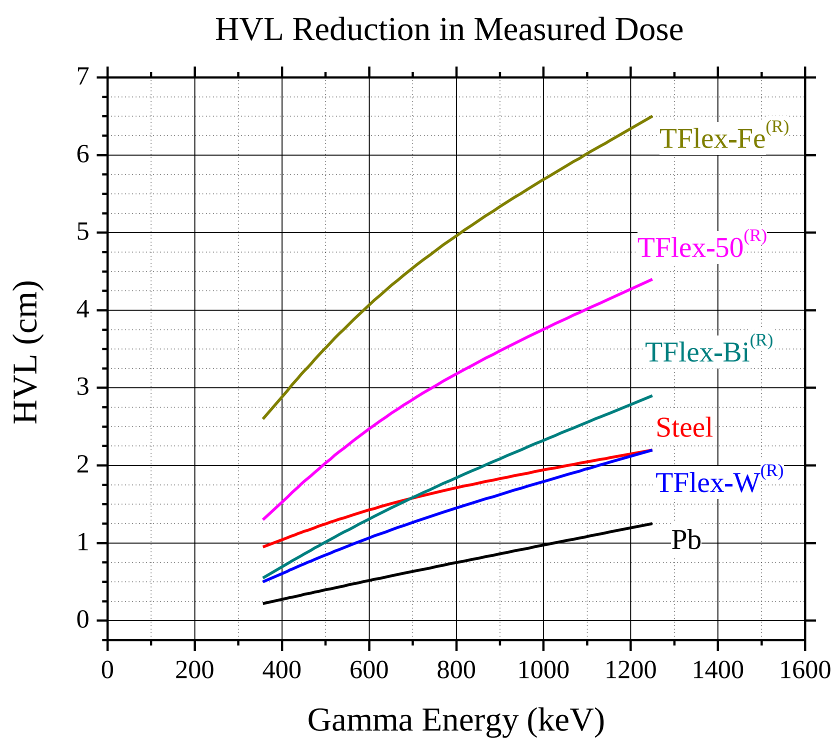

Figure 6. Shield Thickness for 50% reduction in measured dose

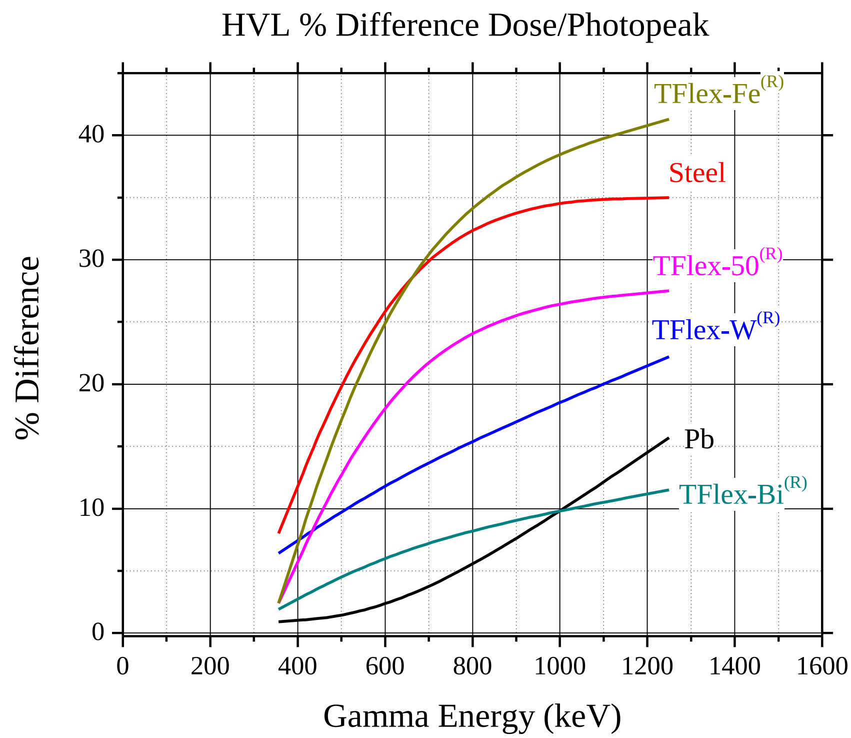

Figure 7. % Difference in Thickness for 50% reduction in Photopeak vs dose.

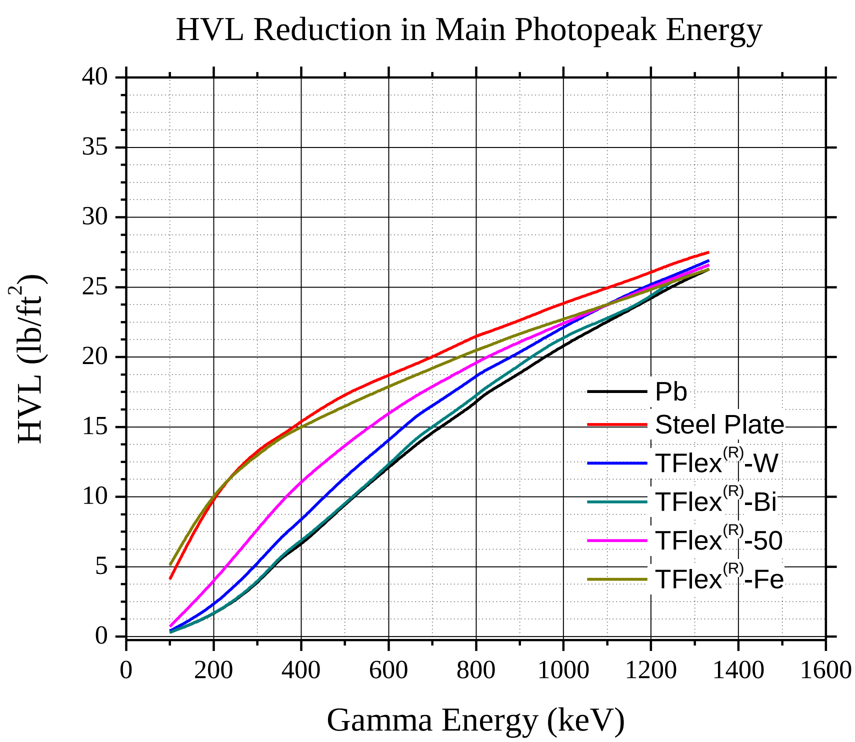

Figure 8. Mass (lb/ft^2) for 50% reduction in Photopeak.

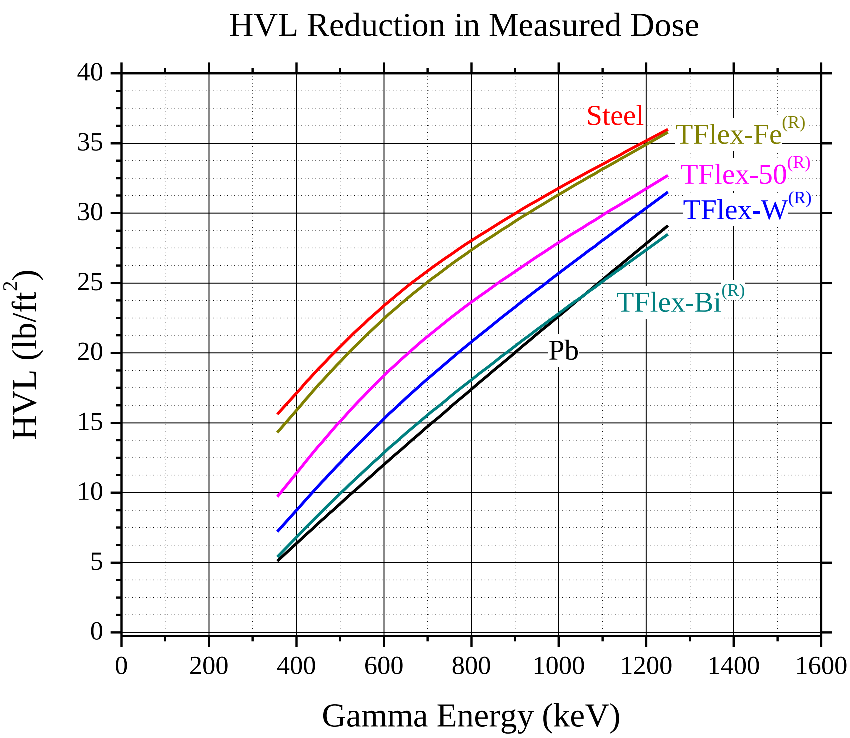

Figure 9. Mass (lb/ft^2) for 50% reduction in measured dose.

MCNP

Programs, such as MCNP[9], utilize sophisticated computer algorithms and up to date particle transport cross-sections to simulate the transport of radiation through materials. When applied correctly, MCNP allows the evaluation of shielding materials for conditions that cannot be readily produced experimentally. Appendix I. contains attenuation data for a wide range of materials and gamma energies produced via MCNP calculations. The MCNP calculations agree very well with experimental measurements for the attenuation of Co-60 and Cs-137 gamma radiation. The MCNP calculation algorithms include treatment of secondary scattered radiation, and therefore, more accurately predict the dose attenuation characteristics of materials than the simple calculations using total mass attenuation coefficients.

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. Dose attenuation properties of shielding materials can be estimated to within 10-40% using mass attenuation coefficients. When more accurate dose attenuation values are required, build-up factors can be used to improve calculations, more sophisticated calculation programs can be applied, or attenuation can be measured experimentally.

References

1) National Institute of Standard and Technology, Physical Measurements Laboratory, *XCOM Photon Cross-Sections Database*, http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html.
2) Thomas E. Johnson and Brian K. Birky, Health Physics and Radiological Health, 4th ed., Wolters Kluwer/Lippincott Williams and Wilkins, 2012.
3) National Nuclear Data Center. Brookhaven National Laboratory, https://www.nndc.bnl.gov/nudat2/
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5) A Survey of Empirical Functions Used to Fit Gamma-Ray Buildup Factors, D. K. Trubey, ORNL-RSIC-10. http://web.ornl.gov/info/reports/1966/3445600231354.
6) William D. Ehmann and Diane E. Vance, *Radiochemistry and Nuclear Methods of Analysis*, John Wiley and Sons, New York, 1991, pp 162-175.
7) J. Kenneth Shultis and Richard E. Faw, “Radiation Shielding Technology,” *Health Physics*, 88(4), 297-322 (2005).
8) R. H. Olsher, “A Practical Look at Monte Carlo Variance Reduction Methods in Radiation Shielding,” *Nuclear Engineering and Technology*, 38(3), 225-230 (2006)
9) “MCNP6 User’s Manual,” version 1.0, May 2013, LA-CP-13-00634, Rev. 0

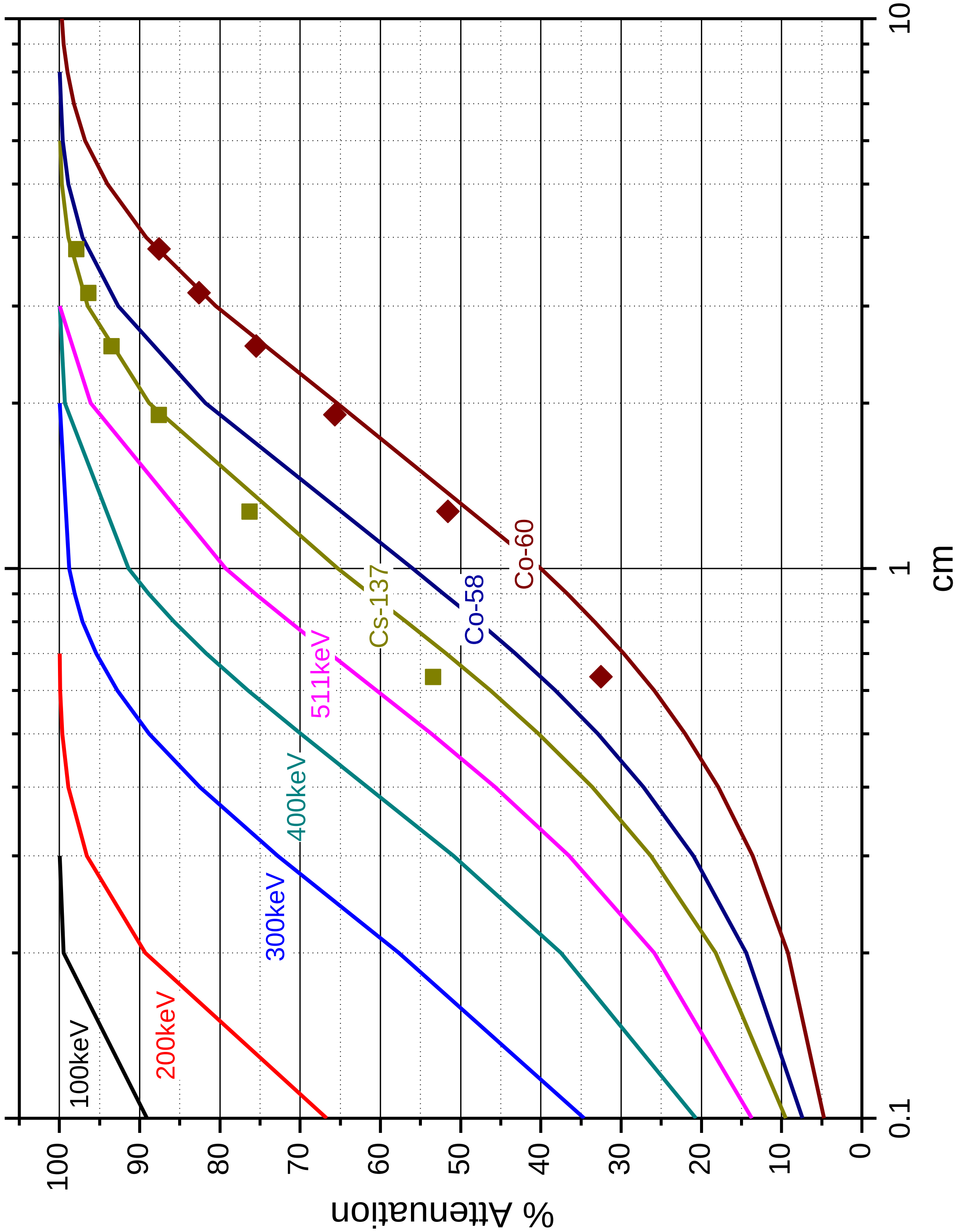
Appendix I.

Additional Data

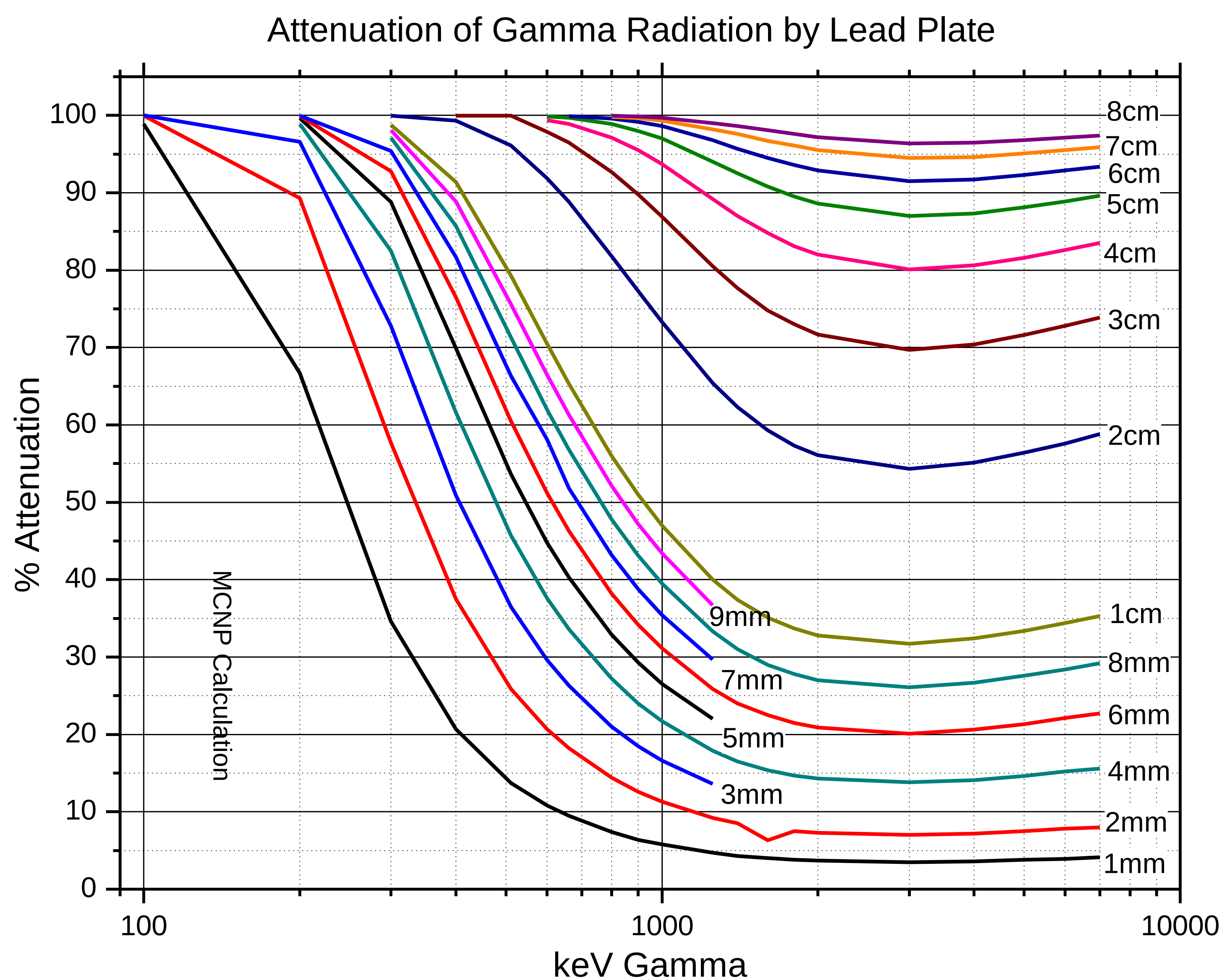
and

MCNP Calculations

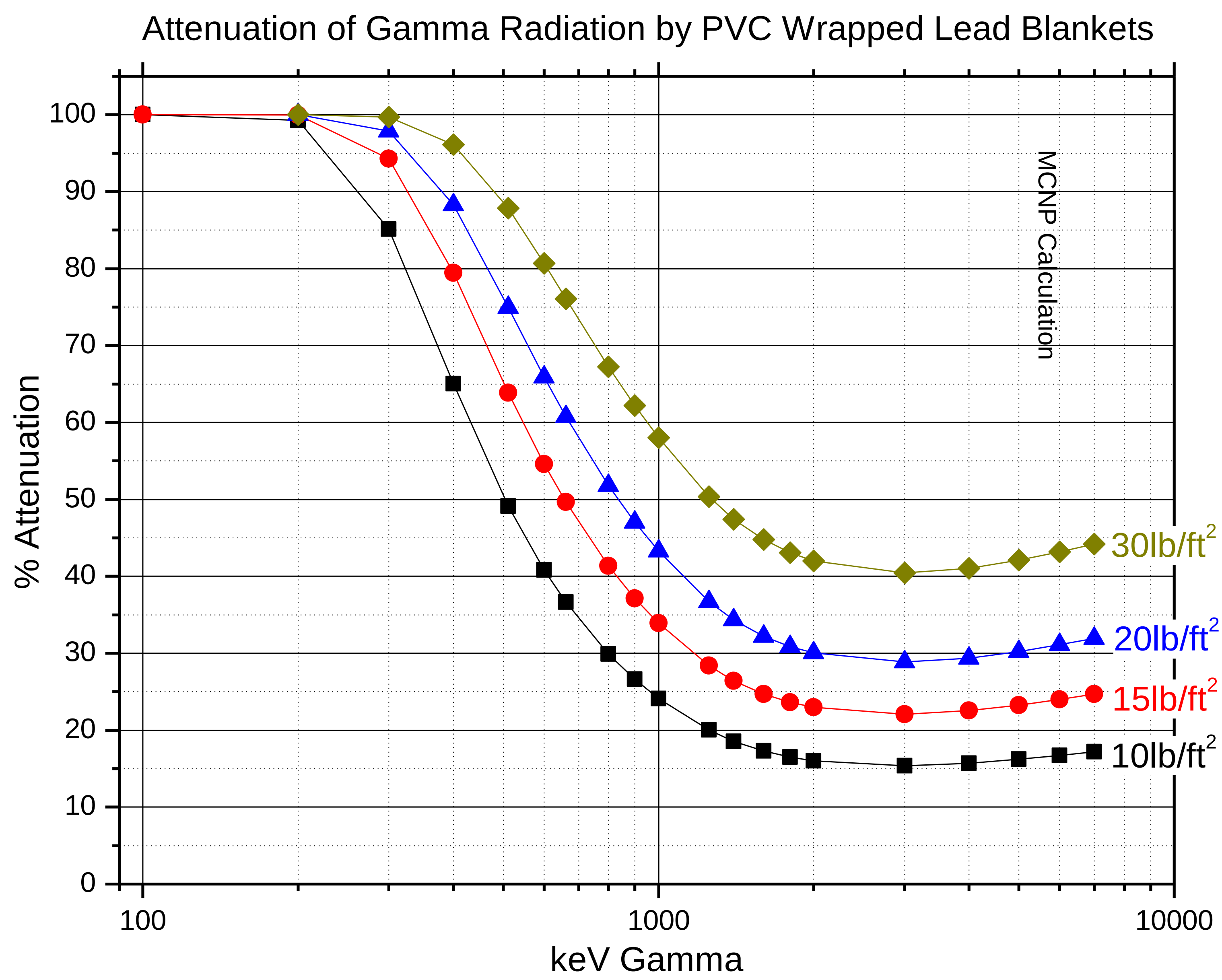
Attenuation of Gamma Radiation by Lead Sheet

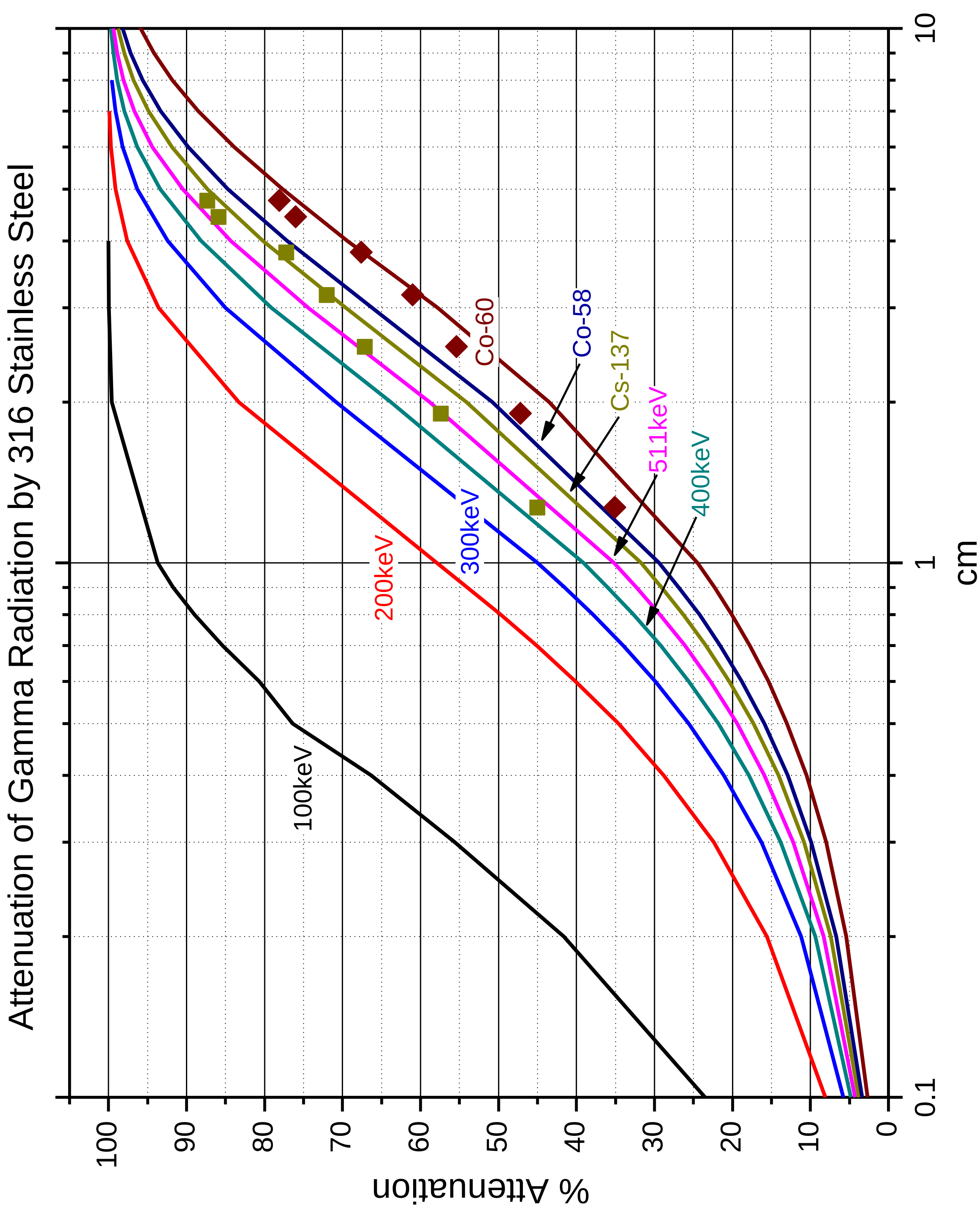


Solid lines = MCNP Calculation   Data points = experimental measurements

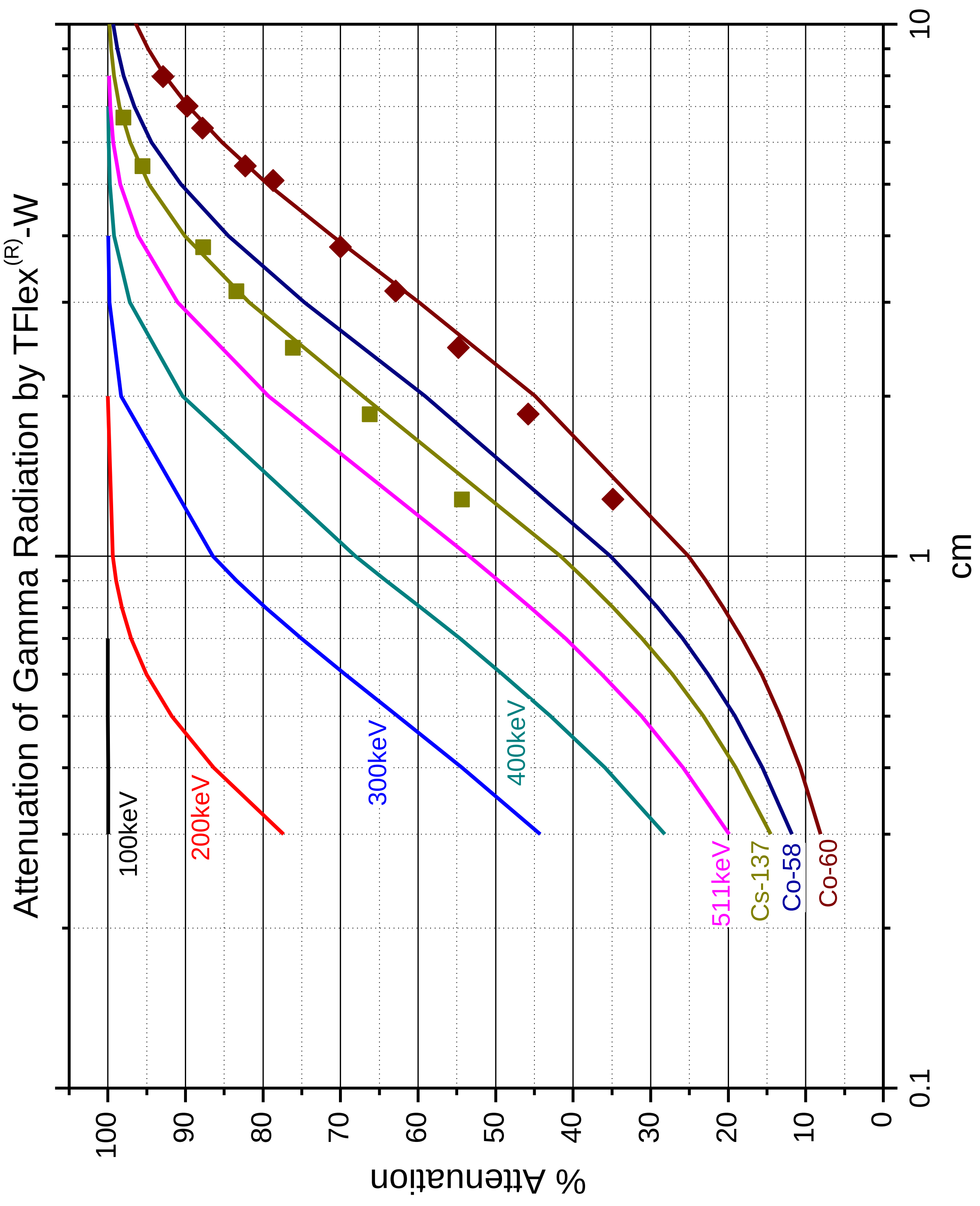


Attenuation of Gamma Radiation by Lead Plate
% Attenuation
keV Gamma
MCNP Calculation
8cm
7cm
6cm
5cm
4cm
3cm
2cm
1cm
9mm
8mm
7mm
6mm
5mm
4mm
3mm
2mm
1mm
0
10
20
30
40
50
60
70
80
90
100
100
1000
10000

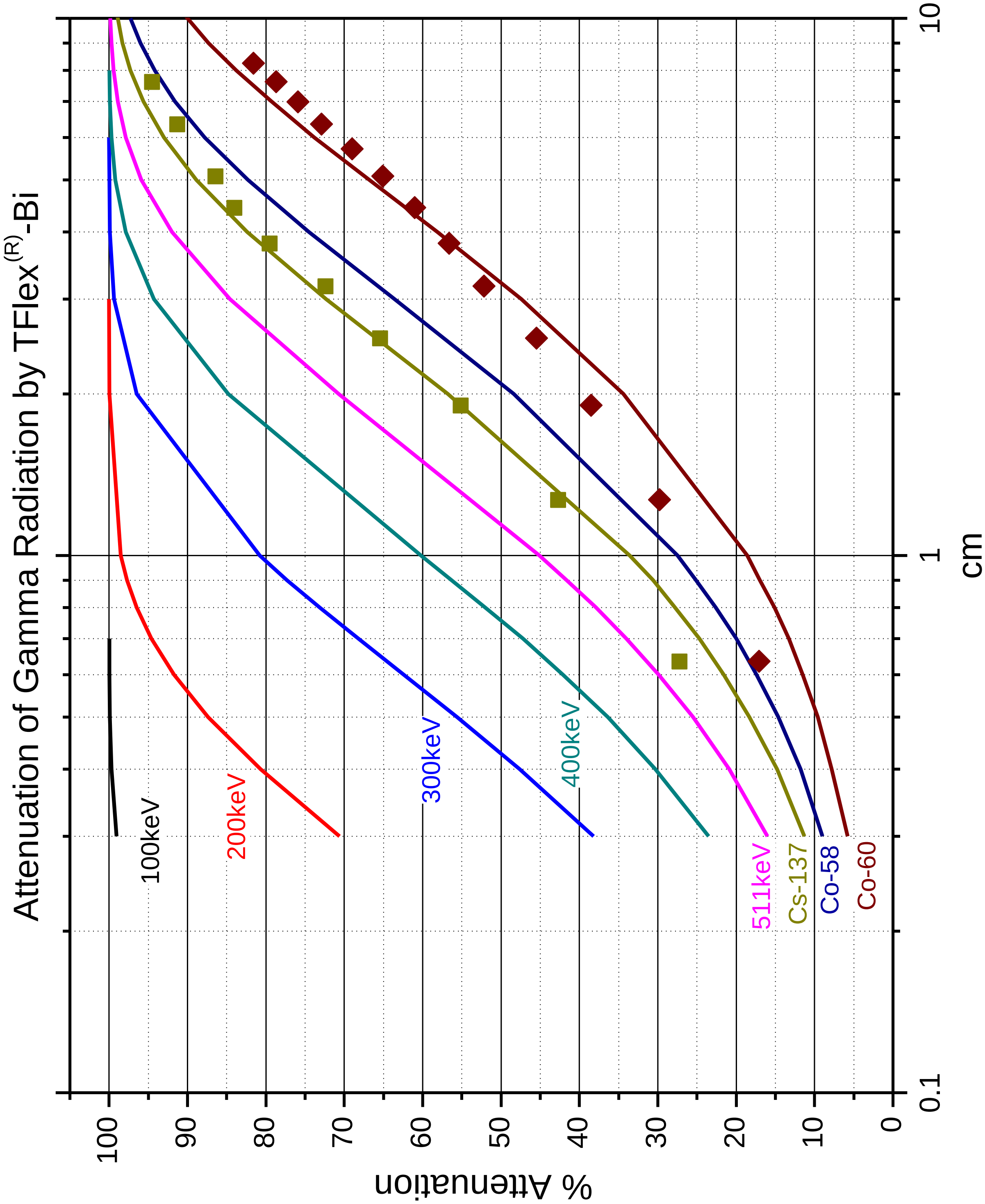

Attenuation of Gamma Radiation by PVC Wrapped Lead Blankets
MCNP Calculation
% Attenuation
keV Gamma
0
10
20
30
40
50
60
70
80
90
100
100
1000
10000
30lb/ft^2
20lb/ft^2
15lb/ft^2
10lb/ft^2



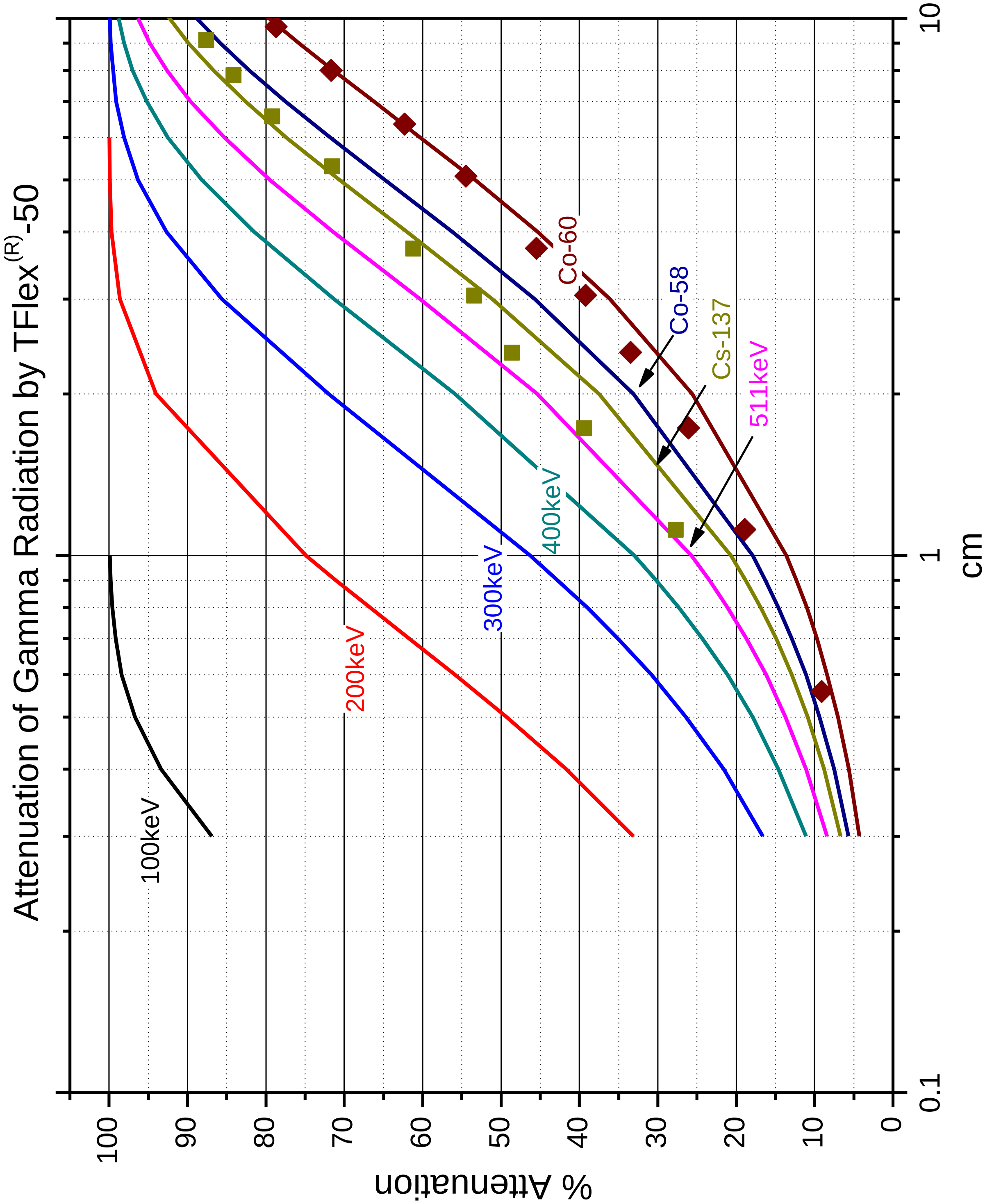
Solid lines = MCNP Calculation   Data points = experimental measurements



Solid lines = MCNP Calculation   Data points = experimental measurements

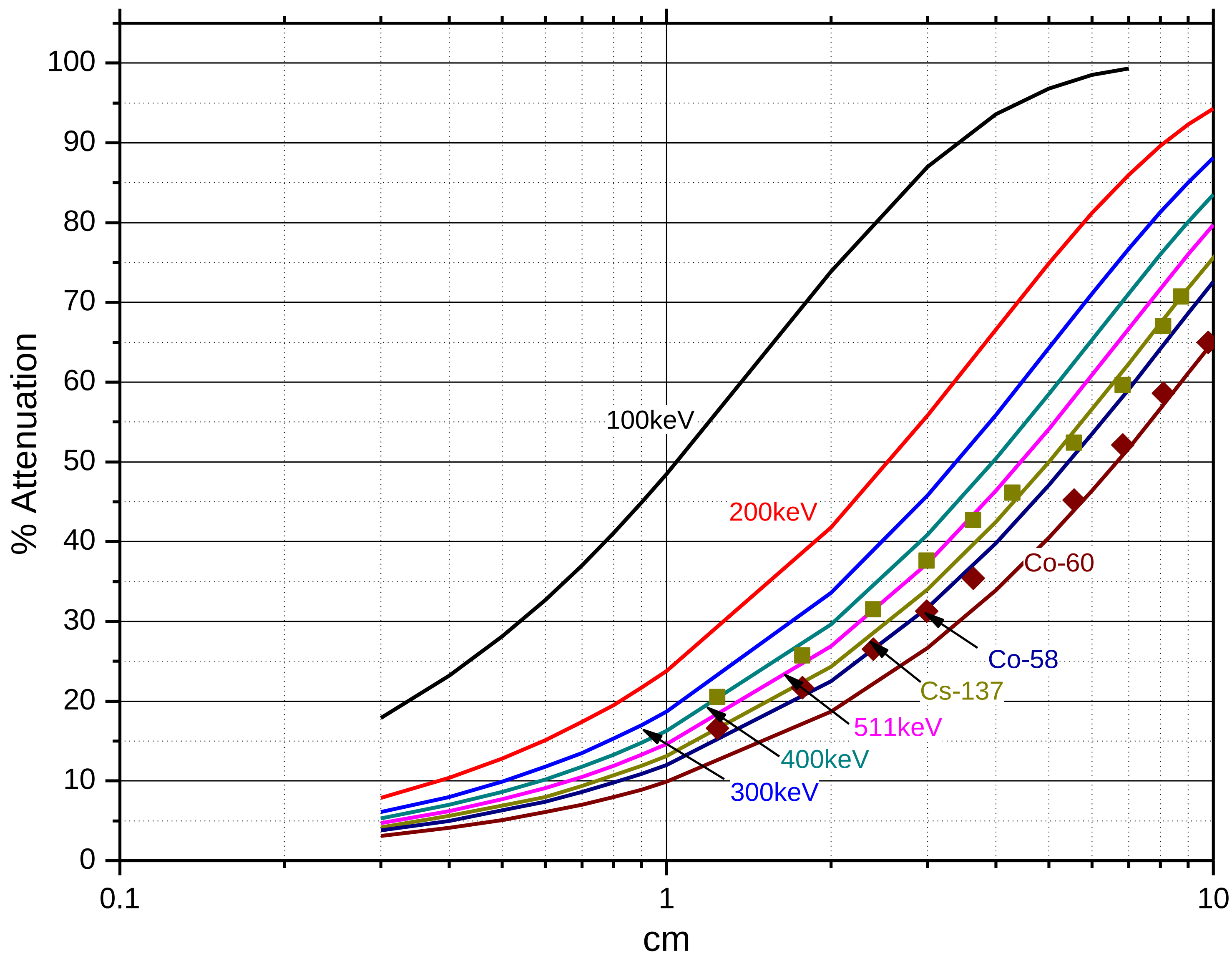


Solid lines = MCNP Calculation   Data points = experimental measurements



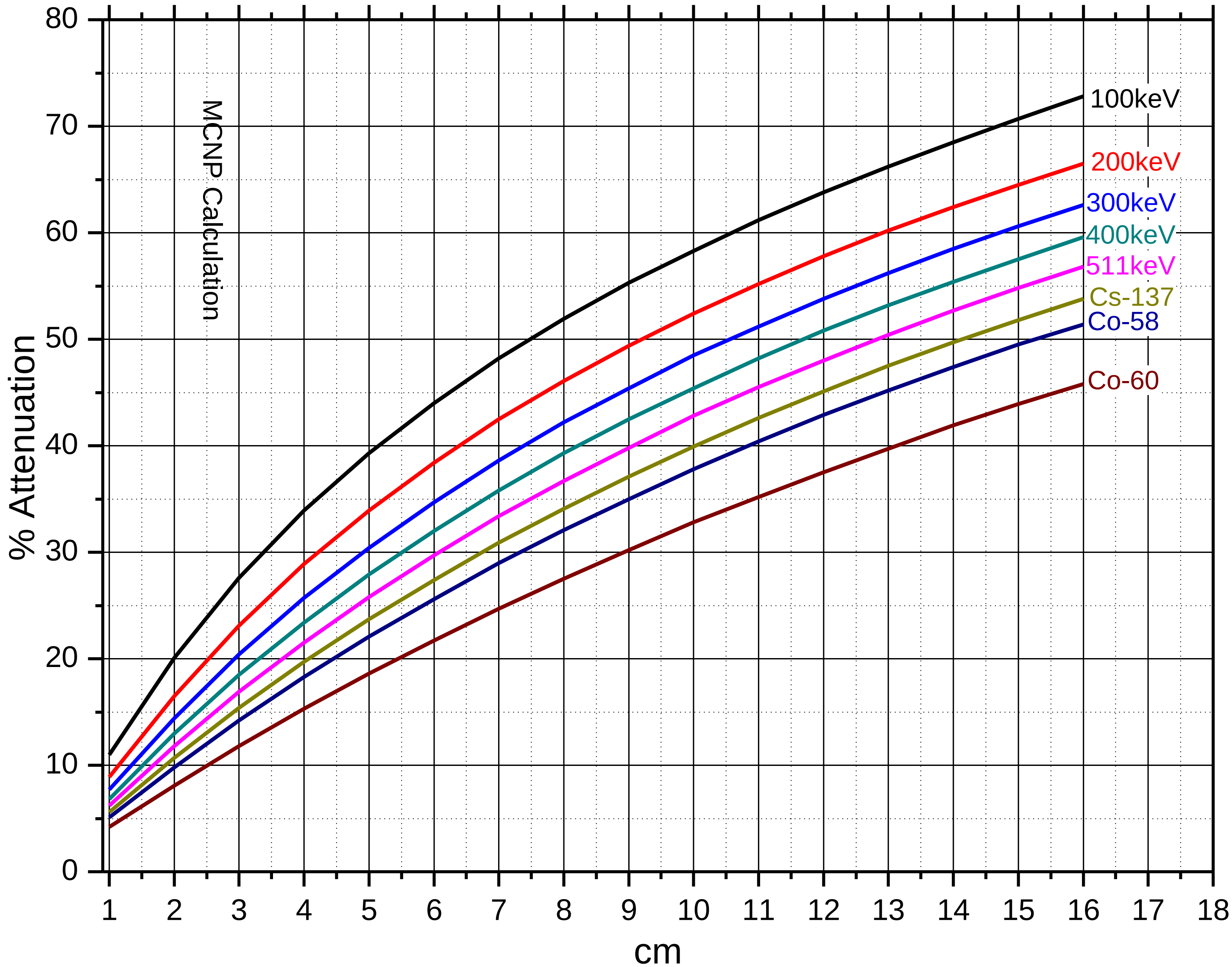
Solid lines = MCNP Calculation   Data points = experimental measurements

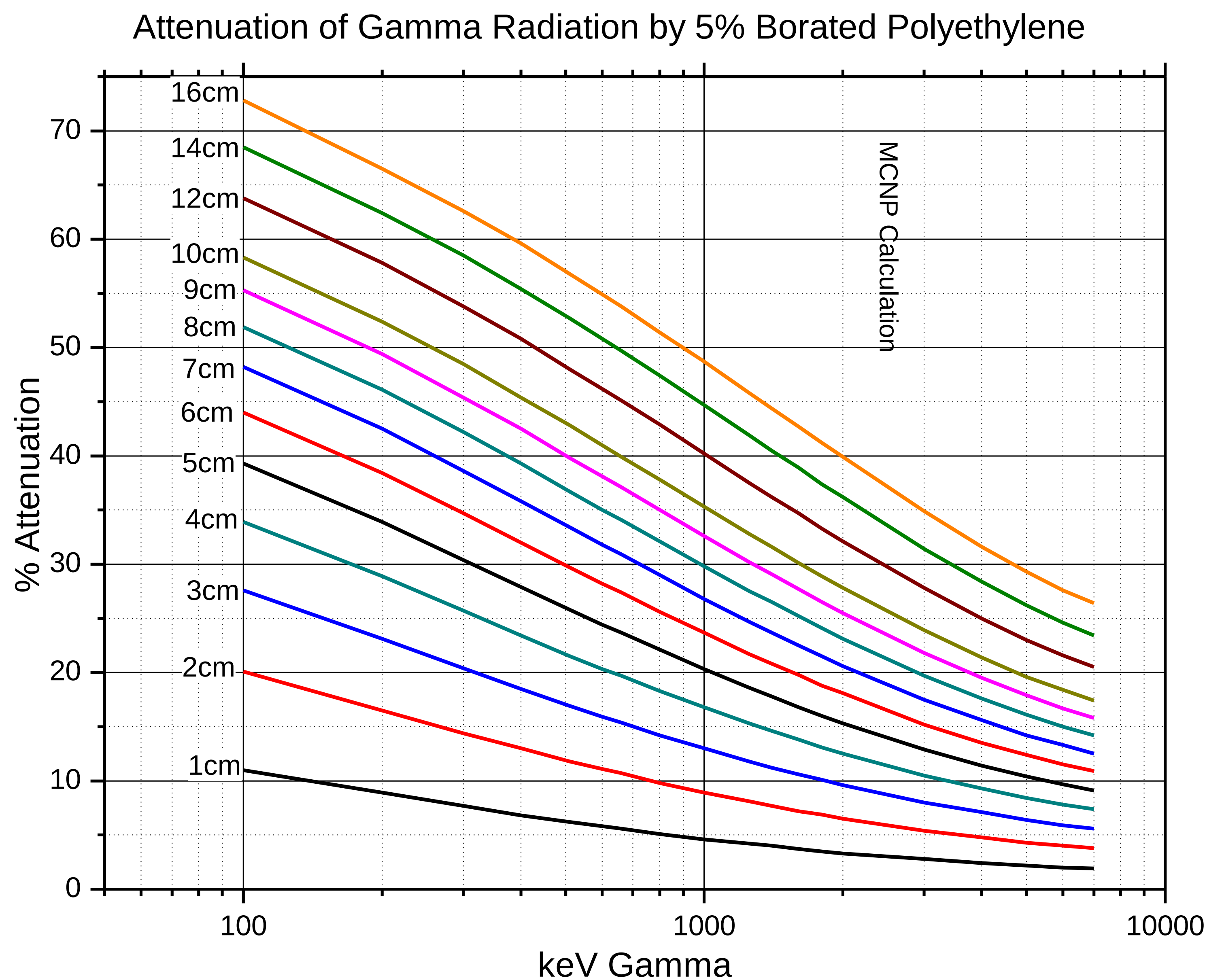
Attenuation of Gamma Radiation by TFlex(R)-Fe



Solid lines = MCNP Calculation Data points = experimental measurements

Attenuation of Gamma Radiation by 5% Borated Polyethylene





Attenuation of Gamma Radiation by 5% Borated Polyethylene
MCNP Calculation
16cm
14cm
12cm
10cm
9cm
8cm
7cm
6cm
5cm
4cm
3cm
2cm
1cm
% Attenuation
0
10
20
30
40
50
60
70
100
1000
10000
keV Gamma

MCNP Comparison TFlex(R) and Concrete