Project Memorandum

To : Jebediah Q. Dingus, Gamma Products Inc.
From : Patrick R. LeClair, Material Characterization Associates, Inc.
Re : 662 keV Gamma ray shielding
Date : January 5, 2010

1 Background

We have received your request to evaluate the gamma ray attenuation properties of candidate shielding materials. In you original request, you wished to obtain a guarantee for the minimum thickness of candidate materials required for a factor of ten reduction in 662 keV gamma radiation. Our firm has analyzed Al, Cu, and Pb candidate materials, and we report the requested minimum thicknesses here. Of the candidate materials, we conclude that Pb shielding offers the best performance at a given thickness, with the caveat that additional costs would be incurred due to the Restriction of Hazardous Substances Directive (RoHS). The RoHS directive restricts the use of Pb-based materials in the manufacture of various types of electronic and electrical equipment. It is closely linked with requirements that set collection, recycling and recovery targets. Copper shielding offers the next-best performance, and though substantially thicker shielding would be required, ROHS-related costs may make Cu a more attractive option than Pb.

Suggestions for further characterization are given, in the event that more extensive knowledge of gamma ray shielding properties (e.g., other energies and other shielding materials) are required.

2 Gamma Ray Attenuation

In the simplest model, the relative loss of gamma ray photons after passing through a material of thickness x with density ρ and mass absorption coefficient μ can be expressed as

$$\frac{\Delta N}{N_o} = e^{-(\rho x)(\mu/\rho)} \tag{1}$$

An exponential law is not unexpected in this case, one obtains the same solution for any system in which the primary quantity grows or diminishes at a fixed rate. Typically, one deals with the density-normalized mass attenuation coefficient μ/ρ, which has units of cm^2/g, rather than the raw mass attenuation coefficient. Similarly, the quantity ρx is known as the “mass thickness,” with units of g/cm^2. These two reduced quantities determine the gamma ray attenuation for a given material. Given the much larger density of Pb and Cu compared to Al, it is expected that Al will offer poor shielding characteristics.

We should note that μ is a strongly energy-dependent quantity, generally decreasing as energy increases. The results quoted in the memorandum are specific to 662 keV incident radiation, and further testing would be required to assess minimum shielding requirements at other energies.

3 Experimental Procedure

3.1 Spectrometer Calibration

The spectrometer was calibrated using the known energy of the ^{137}Cs gamma, viz., 662 keV, and verified by examining the gamma spectrum of ^{57}Co. An example ^{137}Cs spectrum is shown in Fig. 2 in the Appendix.

3.2 Gamma Ray Attenuation

The basic procedure used was as follows:

1. Once the calibration is finished, the NaI detector was placed at a fixed distance from a ^{137} source, with a lead cylinder around it for environmental shielding.
2. A spectrum of the ^{137}Cs source alone was collected for 120 s to assess the incident intensity.
3. With successive sheets of Pb, Cu, or Al inserted between detector and source, additional spectra of 120 s duration were recorded. Sheet thicknesses were determined with a calipers accurate to ~ 0.1 mm.

4 Results and Discussion

As discussed briefly above, a narrow beam of monoenergetic photons with an incident intensity I_o[i], penetrating a layer of material with thickness x and density ρ emerges with intensity I given by an exponential attenuation law

$$\frac{I}{I_o} = \exp\left[-\left(\frac{\mu}{\rho}\right)(\rho x)\right] \tag{2}$$

We can put this in a form more amenable to analysis by taking the natural logarithm of both sides:

$$\ln I = \ln I_o - \frac{\mu}{\rho}(\rho x) \tag{3}$$

Given a material of known density and thickness, it is clear that if we plot $\ln I$ (y-axis) versus ρx (x-axis), we will obtain a straight line of slope $-\mu/\rho$. Thus, by measuring the gamma ray intensity as a function of intervening material, we can extract the density-normalized mass attenuation coefficient.

For each attenuating material, a table recording the thickness of the material and the corresponding counts at the peak position was populated. This included data for zero thickness, i.e., the detector and source along, to assess the incident intensity. From this table, a plot with $\ln I$ on the y axis and the product of thickness and density (ρx) on the x axis was created for each material. A linear regression analysis was used determine the slope of the plot, which gives $-\mu/\rho$. In order to easily compare with the NIST standards, we have used thickness in cm, and the material density in g/cm^3 (material densities

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[i] Intensity is proportional to the number of photons detected, so this is not at odds with our previous discussion.

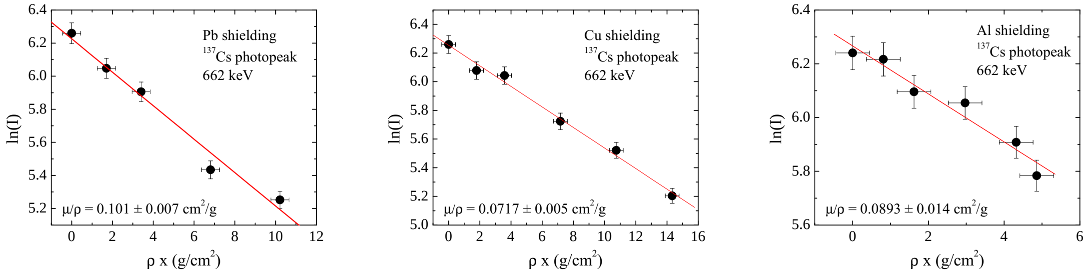

Figure 1: *Natural logarithm of* ^{137}*Cs gamma ray (*661 *keV) intensity as a function of material mass thickness* ρx.

can be found in Sec. A). Uncertainties in the determination of μ/ρ arise from peak counting statistics and thickness uncertainty (~ 0.1 mm). Plots for all three materials are shown in Fig. 1. In all cases, r^2 for the linear fit was above 0.97. The accepted values of μ/ρ for Pb, Cu, and Al are, respectively, 0.1248, 0.07625, and 0.07802 cm^2/g.

Once μ/ρ is known at 662 keV for each material, it is a simple matter to calculate the thickness required for a factor of 10 reduction in 662 keV gamma intensity from Eq. 2. If the required thickness is x_{10}, simple algebra yields

$$x_{10} = \frac{-\ln 0.1}{(\mu/\rho)\,\rho} \approx \frac{2.303}{(\mu/\rho)\,\rho} \tag{4}$$

where x_{10} is in cm if μ/ρ is in cm^2/g and ρ is in g/cm^3. A secondary consideration is the mass per unit area for the given thickness x_{10}, which is given by ρx_{10}. Table 1 summarizes our analysis.

Table 1: *Thickness for factor 10 reduction in* 662 *keV gamma intensity*

Material	x_{10} (cm)	ρx_{10} (g/cm^2)
Al	9.55	25.8
Cu	3.58	32.1
Pb	2.01	22.8

5 Conclusions

As mentioned above, while Pb has superior shielding properties for a given thickness, smallest minimum thickness, and lowest weight at minimum thickness, the ROHS directive makes its use problematic. The use of a Cu shield incurs a 50% increase in weight, but the extra cost may be offset by considerable savings in processing, safety, recycling, disposal, etc.

6 References

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A Density of shielding materials

Table 2: *Densities of absorber materials*

Element	Density (g/cm^2)
Al	2.70
Cu	8.96
Pb	11.35

B Additional data for ^{137}Cs

A ^{137}Cs nucleus can decay via two routes to the ^{137}Ba ground state, shown schematically in Fig. 2. First, a single beta emission of 1.176 MeV can occur with no subsequent gamma emission, bringing the ^{137}Cs directly to the ground state. However, this single-step process occurs for only about 6.5% of all nuclei. The other 93.5% decay via two-step process. First, a 514 keV beta is emitted, resulting in metastable and short-lived ^{137}Ba*. The metastable ^{137}Ba* subsequently (2.55 min half life) decays to the ^{137}Ba ground state by emission of a 662 keV gamma.

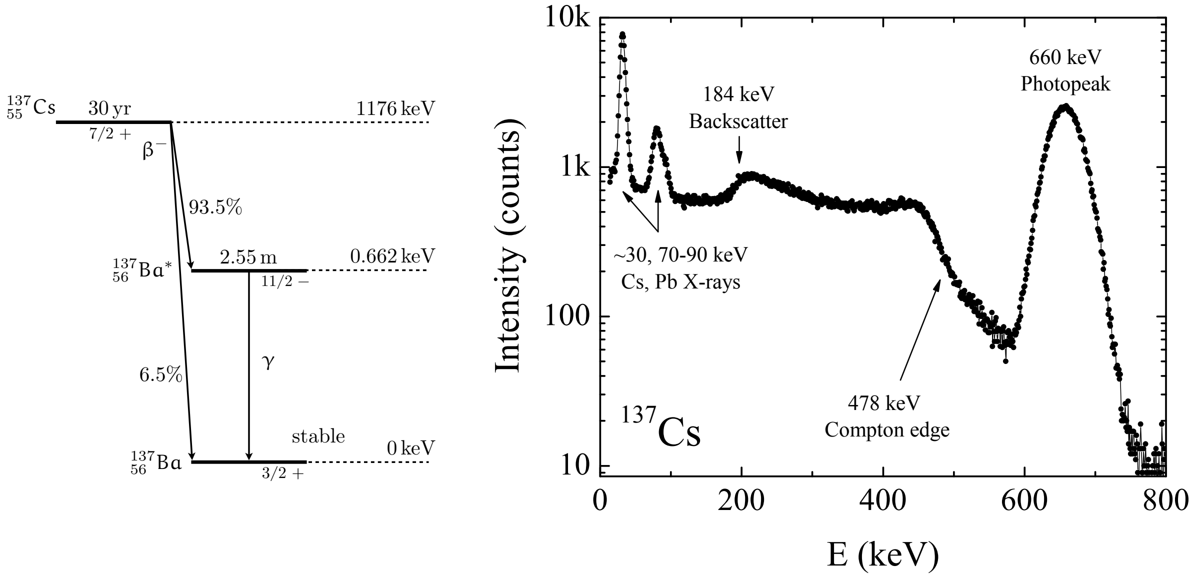

Figure 2: Left: *Energy level diagram showing the decay of* ^{137}*Cs to* ^{137}*Ba. The* ^{137}*Cs decays via two paths,* 93.5% *follow a two-step process resulting in the emission of a* 662 *keV gamma ray. The decay of the Ba nucleus from its excited state is an internal transition, and contributes to the decay percentages but not the gamma decay factor.* **Right:** *Gamma spectrum of* ^{137}*Cs. Aside from the main photopeak at* ≈ 660 *keV, clear Compton edge and backscatter features are visible, as well as X-ray absorption edges. Note the logarithmic scale on the vertical axis.*