Gamma Ray Attenuation Memorandum

31 March 2010

To: Norman Titlebaum—Project STRUT
From: Joseph Lukens, Brandon Reid, Andrew Tuggle—Ants of Aegina
Re: Gamma Ray Shields
Date: 31 March 2010

1 Background

You have stated that safety is a primary concern of your project, and your record has so far been spotless. We would like to point out one area, however, in which we believe the implemented measures are insufficient to guard the well-being of some of your employees. The aluminum-walled trucks in which your ^{137}Cs samples are transported do not significantly shield the drivers or the public from the gamma radiation produced by the samples' natural decay process.

We have investigated the capacities of several materials to shield these gamma rays, which can be dangerous to humans. Since we must often transport quantities of ^{137}Cs, we would like to find the most effective shielding material for the insides of our trucks, so as to best protect our drivers. Our finding indicate that lead may be a more appropriate gamma radiation shield.

2 Theory

^{137}Cs, a radioactive isotope with a half-life near 30 yr, beta decays (i.e. emits an electron) into ^{137}Ba which emits a detectable 662 keV gamma ray. We can detect the gamma ray with a scintillation counter, which contains a detecting material that fluoresces each time it is struck by ionizing radiation. The flash of light is captured by a photomultiplier tube, which effectively converts light signals into electrical signals that can be recorded by a computer. The average rate of beta decay in ^{137}Cs is quite steady, but the individual emissions are aparently independent of each other.[1]

Large doses of gamma rays can be harmful to living health, and even small doses build up over time. But gamma rays can be blocked—or 'shielded'—by matter. Shielding mechansims within a material can look like a lot of things—reflection, absorbtion, scattering, &c.—but a material's overall effectiveness at screening radiation is closely related to both the mass density and atomic mass of the shielding element, and is also energy-dependent.

3 Procedure

To obtain our spectra we utilized a Spectech UCS30 spectrometer with NaI detector;[2] a schematic of the complete experimental setup is located in the appendix. After funning an auto-calibration with a ^{137}Cs source, data collection ensued. To allow for the insertion of various shielding materials between the source and the detector, the ^{137}Cs sample was placed in a slotted detector housing. With no shielding in place, we ran a spectrum for 300 s, recording the total number of photon counts at the peak of 662 keV.

A sheet of Pb, whose thickness was measured via calipers, was then inserted between the source and detector, and another 300 s spectrum obtained. Wee recorded the attenuated count total of 662 keV photons. Thereafter, another lead sheet was placed on the first, and the above procedure was repeated; this process continued for successive Pb thickness until the count total dropped below one-third of its unattenuated value. Then, in identical fashion, we investigated the effectiveness of aluminum shielding; however, the entire Al supply was exhausted before obtaining the desired relative intensity of one-third. And lastly, copper sheets received examination; the aforementioned method was once again replicated, and we increased thickness until the intensity fell below one-third of unshielded value.

To examine the energy dependence of the mass attenuation coefficient, a ^{57}Co source replated the ^{137}Cs in the original setup. Measurements of the detector counts at 122 keV gave totals for the unshielded case and later for Pb thicknesses of one and two sheets; no more were necessary, for the attenuation coefficient proved much larger—an entire order of magnitude—at this lower energy. And with these sets of data, the desired density-normalized mass attenuation coefficients for Pb, Al, and Cu at 662 keV could be obtained, as well as that of Pb at 122 keV.

4 Discussion of Analysis

The attenuation of gamma rays through a given medium has at its source multiple processes. For example, a photon may be absorbed by an electron via the photoelectric effect; at sufficiently high energies, it can obliterate itself and create an electron-positron pair; and via the Compton effect, it can impart some of its energy to a free electron and deflect from its original path. Yet for many purposes, the complete characterization for a given material can be expressed compactly in its mass attenuation coefficient μ, which represents the net effect of all causes of attenuation. The the emergent intensity I of the beam follows:

$$I = I_0 \exp\left(\frac{\mu}{\rho}\rho x\right),$$

where I_0 is the incident intensity, and x the material thickness; the medium density ρ has be inserted to yield the quantity μ/ρ, the more familiar *density-normalized* mass attenuation coefficient. Although this equation implies an intrinsic inability to completely eliminate gamma rays—the exponential function is everywhere positive—the biological dangers of gamma absorption for a given duration diminish with intensity, so the attenuation coefficient is of utmost importance. To ascertain this value, our experiment measures the ratio I/I_0 at a particular material thickness x. With accepted values for density, the factor μ/ρ can be determined, which provides a gauge of the effectiveness of a given shield material.

But since the atomic processes involved in gamma ray absorption vary strongly with photon energy, the mass attenuation coefficient is only defined at a specified energy value. Confirmation of this phenomenon is obtained by examining the relative intensities at peaks of different energies. Thee same equation holds as before, and the above analysis again gives μ/ρ for each energy level; any variation in this coefficient therefore verifies such energy dependence. And so our experiment seeks to confirm and calculate the functional dependence of the density-normalized mass attenuation coefficient on both medium and photon energy.

5 Data Analysis

In accordance with the formula

$$\log \frac{I}{I_0} = -\frac{\mu}{\rho}\rho x,$$

a plot of $\log I$ versus ρx was taken in order to determine the slope $-\mu/\rho$. (Intensity I was taken as the number of counts in a 300 s interval at the peak energy, e.g. 662 keV for ^{1}37Cs.) The results had a linear fit, as expected, with all lines having a coefficient of determination $r^2 \geq 0.973$. The method yielded values of $0.09 \pm 0.02\,{}^{\mathrm{cm}^2}\!/_{\mathrm{g}}$ for lead, $0.06 \pm 0.02\,{}^{\mathrm{cm}^2}\!/_{\mathrm{g}}$ for copper, and $0.069 \pm 0.006\,{}^{\mathrm{cm}^2}\!/_{\mathrm{g}}$ for aluminum, comparing reasonably well with the accepted values of $0.1248\,{}^{\mathrm{cm}^2}\!/_{\mathrm{g}}$, $0.07625\,{}^{\mathrm{cm}^2}\!/_{\mathrm{g}}$, and $0.7802\,{}^{\mathrm{cm}^2}\!/_{\mathrm{g}}$ respectively.

Uncertainty was calculated as follows: from the placement of points about the best-fit line, it is possible to calculate the uncertainty in the slope $-\mu/\rho$. Uncertainty is taken as $\sigma_y\sqrt{N\delta^{-1}}$, where N is the number of points (usually five or six), and $\delta = N\sum(\rho x)^2 - \left(\sum \rho x\right)^2$, where ρx, of course, is the x-coordinate of the graph. We define

$$\sigma_y \overset{\mathrm{def}}{=} \sqrt{\frac{1}{N-2}\sum\left(\log I_i - A + \frac{\mu}{\rho}\left(\rho x\right)_i\right)},$$

where A is the y-intercept. This formula was used for copper and aluminum but σ_y for lead was based on error in actual measurement, which was significantly greater in lead.

Additional systematic error may have been propagated by errors in measurement of the thickness of the shields. For instance, the lead samples were particularly lumpy and therefor difficult to determine the precise thickness. Since it was difficult to measure the thickness of a sheet, we took all sheets to have a standard thickness (1.7 mm in the case of lead) and any error in that measurement may have been propagated in each sheet added, making the data even less reliable than would seem from the calculated uncertainties.

Other systematic error may include the fact that more of a metal meant less air for the gamma rays to travel through, negating part of the control run. It was sometimes difficult to place the chips directly over the gamma source, so it may have been possible for gamma rays to leak around the edges. Any one measurement is also subject to some uncertainty, usually on the order $\sqrt{N}$, but this has been at least partially dealt with in the uncertainty-in-slope calculations.

Material	$\frac{\mu}{\rho}$ [${}^{\mathrm{cm}^2}\!/\!{}_{\mathrm{g}}$]	Uncertainty [${}^{\mathrm{cm}^2}\!/\!{}_{\mathrm{g}}$]
Pb	0.09	0.02
Cu	0.06	0.02
Al	0.069	0.006

6 Conclusions

We think it should be fairly clear, then that lead lining in the ^{137}Cs transport trucks would much better protect drivers from incident gamma rays than the current aluminum truck-walls.

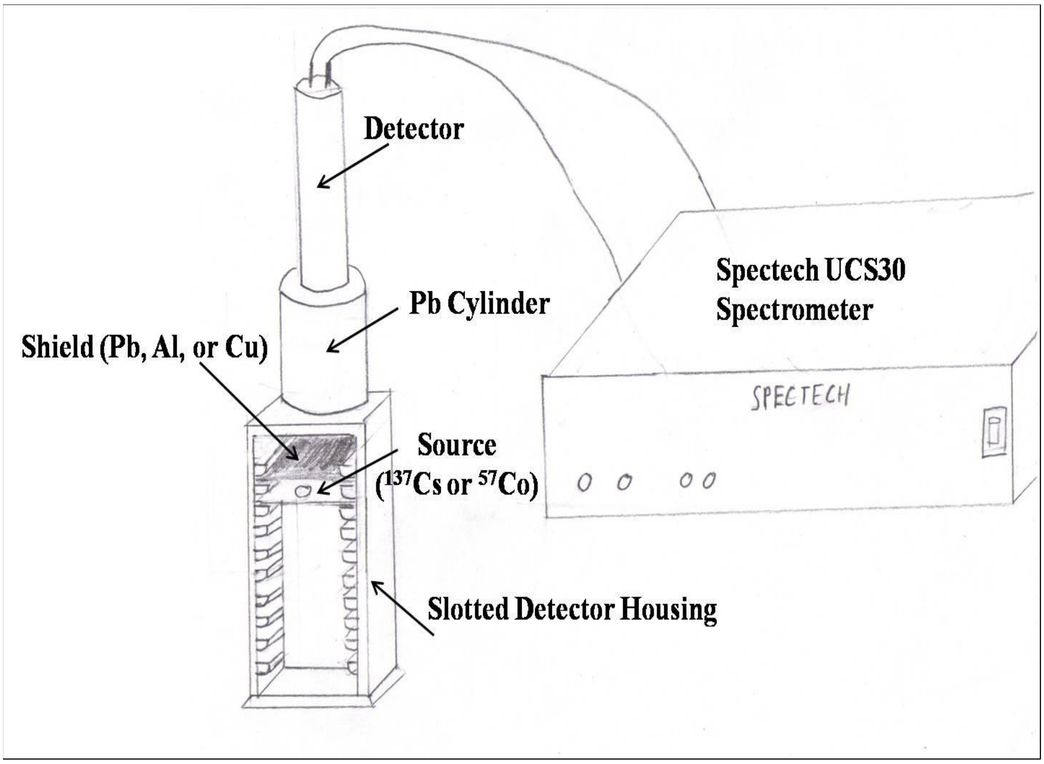
Notes

[1] J. Lukens, B. Reid, A. Tuggle. *Counting Statistics Memorandum. Unpublished work. 15 February 2010.*

[2] Our procedure followed closely that put forth in the lab manual; this document should be examined for any additional clarification: P. LeClair, "PH 255: Modern Physics Laboratory," Spring 2010, 145–158.

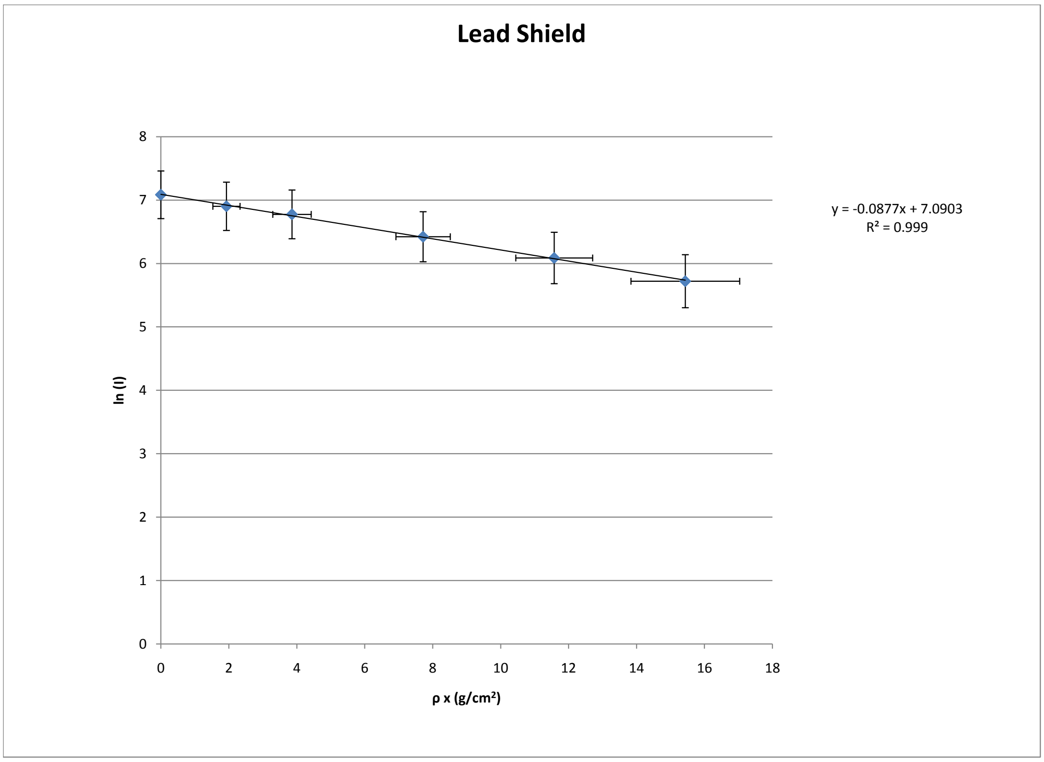
7 Appendix A—Experiment Schematic

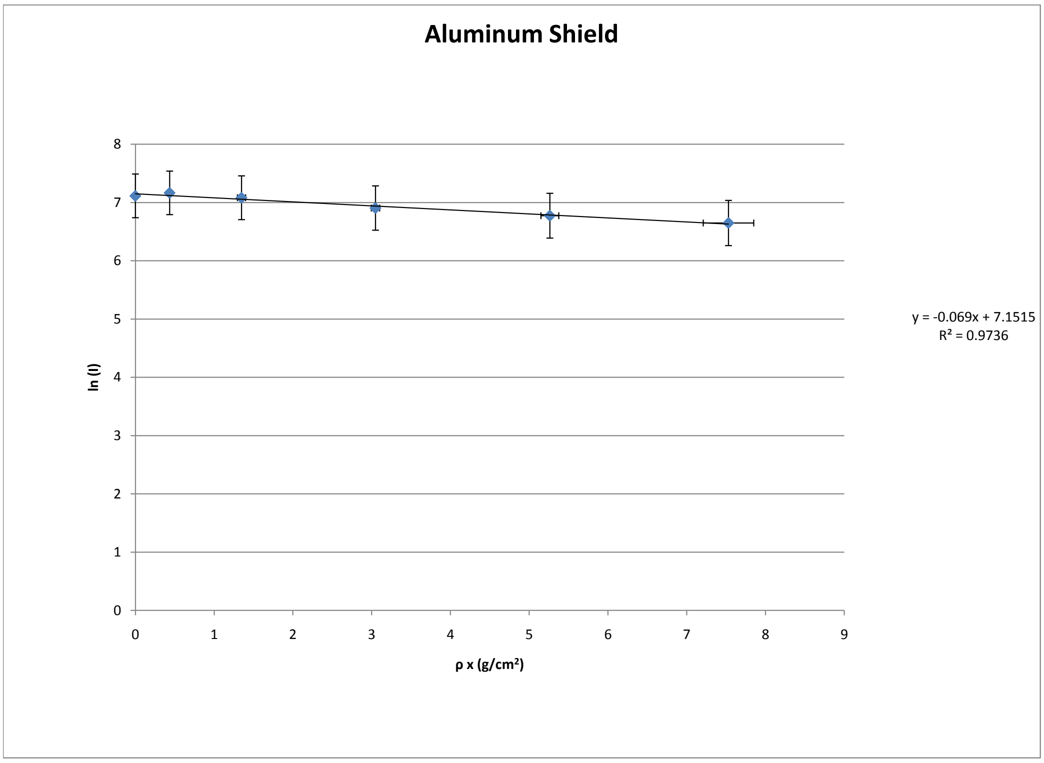
Figure 1: A schematic representation of the experimental setup. The spectrometer was connected to a computer as well, which is not shown.

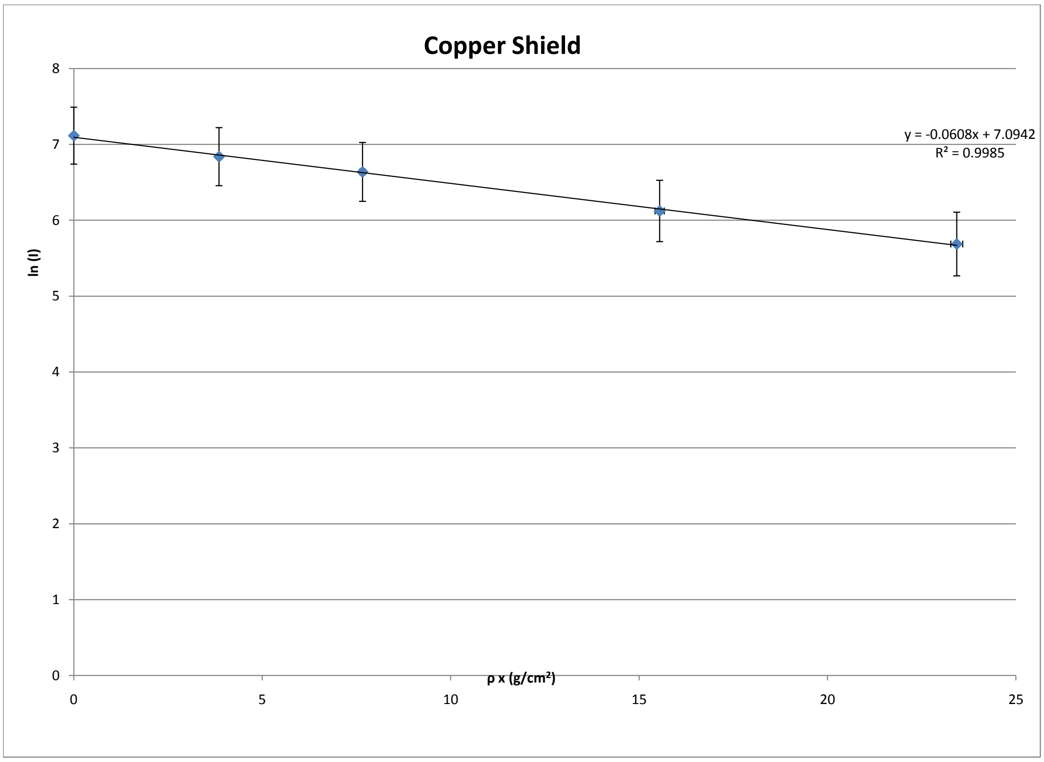


8 Appendix B—Plots

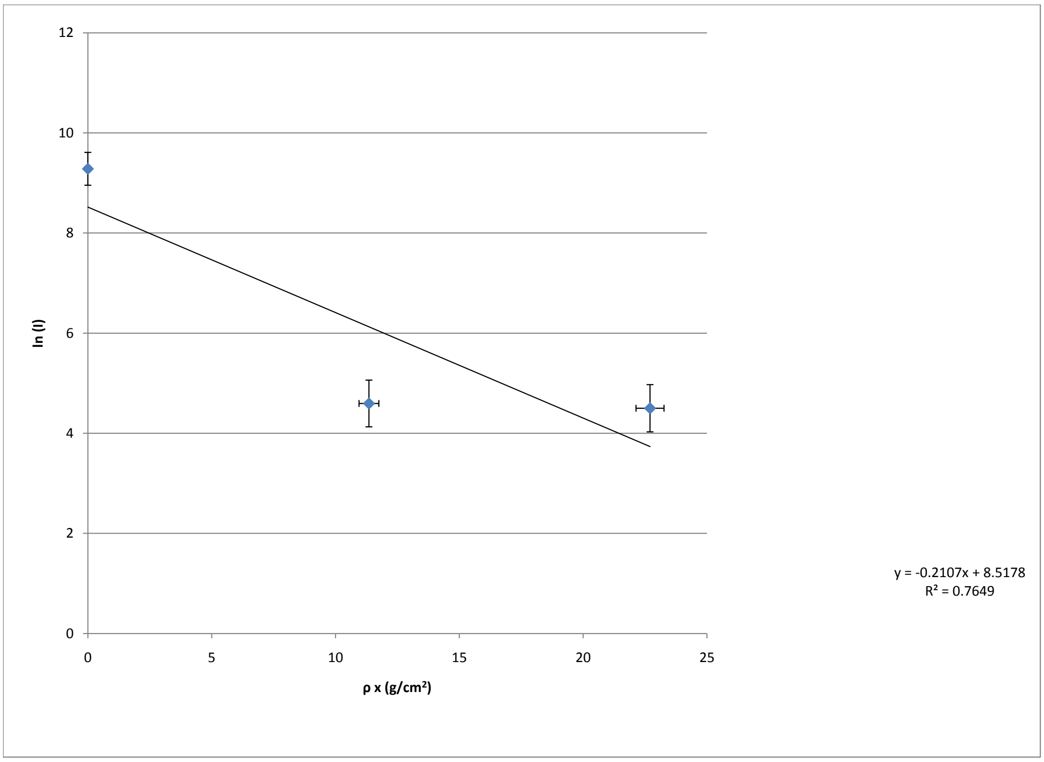
These first three graphs measure the natural log of the number of 662 keV ^{1}37Cs gamma rays passing through each shield over a period of 300 s.


Lead Shield
8
7
6
5
4
3
2
1
0
ln (I)
0
2
4
6
8
10
12
14
16
18
ρ x (g/cm²)
y = -0.0877x + 7.0903
R² = 0.999


Aluminum Shield
8
7
6
5
4
3
2
1
0
ln (I)
0
1
2
3
4
5
6
7
8
9
ρ x (g/cm²)
y = -0.069x + 7.1515
R² = 0.9736



This last graph measures the same natural log of intensity, but at a much lower gamma ray energy, 122 keV.


12
10
8
6
4
2
0
ln (I)
0
5
10
15
20
25
ρ x (g/cm²)
y = -0.2107x + 8.5178
R² = 0.7649