# Gamma Attenuation Benchmarking Study:

## A comparison of various materials from multiple manufacturers

TEAM®

**Team Industrial Services**

**Edwardsville, IL**

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# Executive Summary:

A benchmarking study was conducted to evaluate the attenuation of Co-60 gamma dose achieved by various commercially available shielding materials. Multiple replicates (n = 3 – 9) of products made from lead, tungsten, bismuth, and iron were compared to each other and to a solid lead plate benchmark. The attenuation directly correlated with a single factor, cross-sectional density of the shielding material (or mass of shielding material in the path of the gamma radiation, *mass-in-the-path*). Neither the physical format of the shield (solid lead, lead blanket, or flexible shielding) nor the identity of the supplier ((redacted) or NPO®) had a significant impact on the results obtained in this study.

The observed attenuation ranged from (redacted) to 25% for the NPO's T-Flex® Bismuth sample (actual cross-sectional density = 10.2lb/ft$^2$). Most of the materials evaluated had densities of ~10lb/ft$^2$ and provided attenuation in the range of 22-25%. (Redacted)

Table A.

| | | | @30cm | | |
|---|---|---|---|---|---|
| **Shielding Material** | **Thickness (in)** | ***Mass in the Path* (lb/ft$^2$)** | **Dose Rate (mRem/hr)** | **Attenuation %** | **Lead Equivalent (10lb/ft$^2$)** |
| Plexiglass ($\beta^-$ shielding) | N/A | N/A | 8.89 | N/A | N/A |
| Lead sheet | 0.2 | 10.7 | 6.83 | 23 ± 3% | 100% |
| NPO T-Flex® Tungsten | 0.275 | 9.9 | 6.90 | 22 ± 1% | 97% |
| NPO T-Flex® Bismuth | 0.45 | 10.2 | 6.66 | 25 ± 1% | 108% |
| NPO T-Flex® Iron | 0.76 | 10.1 | 6.80 | 24 ± 4% | 102% |
| Pb wool blanket (10lb/ft$^2$) | 0.625 | 9.7 | 6.94 | 22 ± 3% | 95% |

## Study Objective

A benchmarking study was conducted to compare the radiation attenuation performance of various commercially available products. Standard shielding materials (lead, steel, borated polyethylene) and custom materials (flexible shielding made from silicone and metal powder) from two shielding manufacturers were tested. The objective of the study was to assess what differences exist in the attenuation efficiency of the various materials. To the extent possible, products were manufactured with a normalized mass per cross sectional area. In particular, most samples tested were 10 lb/ft$^2$ of cross-sectional density (4.5kg/900cm$^2$.) To achieve this normalized *mass-in-the-path*, less dense materials were prepared with greater thickness. In three cases this normalization was not possible (15 lb/ft$^2$ blankets from Nuclear Power Outfitters (redacted)

## Location of Testing

Team industrial: 131 Enterprise Dr, Edwardsville IL 62025

## Testing date

June 8, 2021

## Gamma Source (See *Table 1 - Figure 10*)

Cobalt 60 – 66mCi (2.4GBq)

## Dose Rate Monitor (See *Table 1 - Figure 11*)

Tracerco T402, single halogen, energy compensated Geiger Muller tube, (calibrated for dose measurements in mRem/Hr?)

## Materials Tested (See *Table 3 – Sample Dimensions for more detailed information.)*

Plexiglass

Lead sheet. Four individual pieces, 12 x 12 x 0.2" (300 x 300 x 5.1mm)

Carbon steel, 16.5 x 8 x 0.25" (419 x 203 x 6.4mm)

T-Flex® Tungsten flexible shielding, 12 x 12 x 0.275" (300 x 300 x 7.0mm), obtained from Nuclear Power Outfitters, Lisle, IL

T-Flex® Bismuth flexible shielding, 12 x 12 x 0.45" (300 x 300 x 11.4mm), obtained from Nuclear Power Outfitters, Lisle, IL

T-Flex® Iron flexible shielding, 12 x 12 x 0.76" (300 x 300 x 19.3mm), obtained from Nuclear Power Outfitters, Lisle, IL

Lead wool blanket – 12 x 36" (300mm x 900cm), 10 $lb/ft^2$, obtained from Nuclear Power Outfitters, Lisle, IL

Lead wool blanket – 12 x 36" (300mm x 900cm), 15 $lb/ft^2$, obtained from Nuclear Power Outfitters, Lisle, IL

Borated (5%) polyethylene – 12 x 12 x 1.92" (300 x 300 x 49mm), obtained from Nuclear Power Outfitters, Lisle, IL.

(Redacted)

**Testing Procedure**

1 Each sample was labeled, measured (tape measure for length and width, calipers for thickness), and weighed. The actual density was calculated. (See *Table 1 – Figure 1* and *Table 3 – Sample Dimensions*)

2 Three-foot long blankets were marked to indicate distinct one-foot sections. Each section was treated as a separate replicate in the attenuation measurements.

3 The source probe was placed on the floor and secured with tape. (See *Table 1 - Figure 2*)

4 A lead cave was built around the source probe to reduce the impact of radiation scattered around the shielding material on the dose measurement. This "collimation" of the Co-60 source likely also produces some lower energy scattered photons, so the measured attenuation results will likely be higher than expected for the pure Co-60 photon emissions (1172 and 1332 keV). The top opening of the cave was covered with a thin sheet of plexiglass (thickness?) to "harden" the source, limiting the impact of beta emissions and very low energy photons on the dose measurements. (See *Table 1 - Figure 3*)

5 The Co-60 source was inserted into source probe. (See *Table 1 - Figure 4*)

6 The dose rate monitor was placed in contact with the plexiglass. The dose rate was read on the monitor (mRem/Hr) and recorded as the unshielded contact dose rate. (See *Table 1 - Figure 5*)

7 Each individual shielding sample material was placed on top of the plexiglass. The contact dose rate was measured as in step 6 above with the dose rate monitor. One square foot samples were measured three times. Three-foot long blankets were measured once in each of the three one-foot sections indicated in step 2 above. (See *Table 1 - Figure 6*)

8 The dose rate monitor was then secured at a fixed location 30 cm above the plexiglass. (See *Table 1 - Figure 7*)

9 The dose rate was read on the monitor and recorded as the unshielded 30cm dose rate. (See *Table 1 - Figure 8*)

10 Each individual shielding sample was placed on plexiglass, and the dose rate was read from the dose meter. One square foot samples were measured three times. Three-foot long blankets were measured once in each of the three one-foot sections indicated in step 2 above. (See *Table 1 - Figure 9*)

## Results and Discussion

The dimensional and weight measurements of all samples tested are recorded in Table 2. It should be noted that due to the more irregular shape of lead wool blankets, their dimensions were not physically measured. The values reported in Table 2 are nominal values provided by Nuclear Power Outfitters (hereafter referred to as NPO), the manufacturer. (redacted)

As mentioned in the objectives section above, to the extent possible, the weight of all test samples was normalized so that the gamma radiation travelling from the Co-60 source to the dose meter detector would encounter the same mass of attenuating material. A normalized material density of 10 pounds per square foot of cross-sectional area was chosen as the target. This is indicated in data tables in this report as *'mass-in-the-path'* density. As a result of this normalization of cross-sectional density, the thickness of shielding materials varied in inverse relationship to the shielding material. For example, the lead sheet sample tested (material density = 0.38lb/in$^3$) was 0.20" thick, while the T-Flex Iron samples (material density = 0.092lb/in$^3$) was 0.76" thick.

While the mass of attenuating material is not the only factor impacting how effectively a shield will attenuate gamma radiation, it is a major factor and has been used as a rule of thumb in shielding design.

It can be seen in Table 2, that the *'mass-in-the-path'* density for most of the shielding products analyzed was in the range of 9.7 – 10.7lb/sq. ft. (redacted)

Results of all measurements are presented in Table 3 (contact dose rates) and Table 4 (30cm dose rates). The attenuation was calculated as the percent reduction in dose rate as compared to the unshielded (plexiglass) dose rate. The attenuation factors relative to lead (average of four lead sheet samples, approximately 0.2"/5.1mm thick) were also calculated and are presented in the tables.

Averages of dose rate measurements, on contact and at 30cm, for replicates for each sample material are presented in Table 5, along with the calculated attenuation, both absolute and relative to lead. It should be pointed out that, for the 'on contact' dose rate measurements, the distance from the source to the detector could not be held constant due to the variable thickness of the shielding material. As there would be some reduction in the measured dose rate from simply moving the dose meter further away from the source, it would be misleading to compare these "contact" attenuation values for different materials since the distance parameter (between the gamma source and the detector) could not be held constant. Our discussion will focus on the 30cm results where the experimental set-up allowed for the distance to be held constant. In this case, variation in the dose measurements would be due solely to differences in the shielding materials.

Table 6 shows the average measured dose rates for the materials with cross sectional density ~10lb/ft$^2$ (i.e., *'mass-in-the-path'*) omitting the results for steel and borated polyethylene. All of the non-excluded samples at this density resulted in attenuation of Co-60 in the range of 22 – 25%. The slight variations in the results might be attributable to the slight differences in mass in the path density or due to different shielding efficiency of the materials used in each sample.

Steel and borated polyethylene were omitted from further discussion as these materials were much different than the other types of shielding characterized in this study. The steel sample is very thin and compose of low atomic number (Z) elements that tend to scatter Co-60 photons more than the higher Z lead and bismuth materials. The results obtained for the attenuation of Co-60 with steel are also much lower than expected, indicating that there may be some issue with the measurements with this sample type. The attenuation observed for borated polyethylene is more in line with what would be expected for Co-60.

The results in Table 6 are grouped according to shielding type (lead sheet, lead wool blanket, and flexible shielding.) It should be noted that no distinctions are to be observed in the results from different shielding types or manufacturers. The *'mass-in-the-path'* density is the predominant factor in the level of gamma radiation attenuation for the photon emissions from Co-60 (1173 and 1332 keV). For lower photon energies, a clearer distinction in favor of high Z materials (Pb and Bi) would be expected.

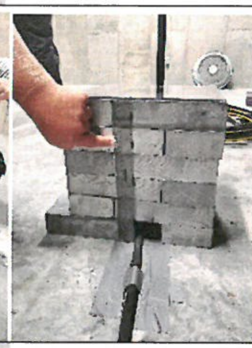
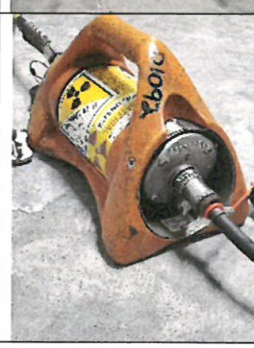
Table 7 shows a comparison of measured dose rates for materials of different mass in the path densities. As expected, the attenuation percent is related to the cross-sectional density of the material. Four shielding materials with ~10lb/ft$^2$ cross-sectional mass density are grouped and unhighlighted in the table. Two shielding materials with higher densities exhibit higher attenuation of gamma radiation. [29% attenuation for the 14.4lb/ft$^2$ lead wool blanket from NPO and (redacted)

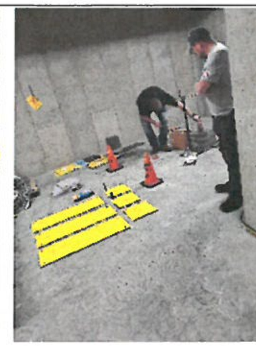
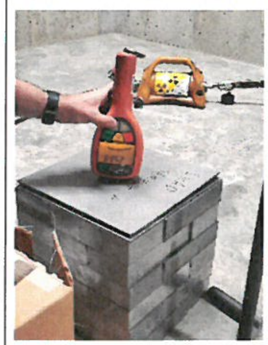
Figure 1 is a graph of attenuation vs. '*mass-in-the-path*' density for all the shielding materials listed in Table 7. The logarithmic regression analysis of the data indicates that cross-sectional density of the shielding material accounts for all the variation in attenuation ($R^2$ = 0.97) and that material type is irrelevant.

## Conclusions

One parameter, the cross-sectional density or *mass-in-the-path*, was found to be the predominant contributing factor in the effectiveness of shielding materials for attenuating gamma radiation from a Co-60 source. Regardless of composition, product type, or manufacturer, shielding materials constructed with similar mass densities exhibited similar levels of attenuation of Co-60 gamma radiation. Those with higher densities exhibited higher gamma attenuation and those with lower densities exhibited less gamma attenuation.

## Table 1 – Testing Setup and Procedure

| Figure # | Description | |
|---|---|---|
| 1 | • A tape measure was used to obtain length and width.<br>• Calipers were used to obtain thickness.<br>• A scale was used to obtain weight.<br>• Blankets were marked in one-foot sections |   |
| 2 | • Source probe was placed and secured on the floor with duct tape. |   |
| 3 | • A lead cave (1' x 1') was built of 2" x4" x 8" lead bricks around the source.<br>• The opening on the top section was 4"x4".<br>• Thin sheet of plexiglass added to reduce the impact of beta radiation interference. |   |
| 4 | • Connected source container to source probe.<br>• Retracted to safe distance and remotely placed source in source probe. |   |

| | | |
|---|---|---|
| 5 | • Recorded contact dose rate on top of plexiglass to provide controlled unshielded condition. |   |
| 6 | • Samples were placed on top of plexiglass.<br>• Dose measurements were taken at contact. |   |
| 7 | • Detector was placed 30cm from plexiglass.<br>• Location was secured with duct tape |   |
| 8 | • Recorded dose rate 30cm from top of plexiglass to provide controlled unshielded condition. |  |

| | | |
|---|---|---|
| 9 | • Samples were placed on top of plexiglass.<br>• Dose rates were measured at 30cm from plexiglass. |   |
| 10 | • Source: Co-60 Source – 66 mCi<br><br>• Background: 0.006 mRem/hr |    |
| 11 | Detector:<br>Tracerco T402 Radiation Monitor<br><br>Detector Type: Single halogen, energy compensated Geiger-Muller tube |  |

## Table 2 – Measured Sample Dimensions and Calculated Densities

| Shielding Material | Sample ID | Weight (lb) | Width (in) | Length (in) | Thickness (in) | *Mass in the Path* ($lb/ft^2$) | Density (lb/in3) |
|---|---|---|---|---|---|---|---|
| Plexiglass | 1 | N/A | N/A | N/A | N/A | N/A | N/A |
| Lead sheet | 2 | 10.74 | 12 | 12 | 0.204 | 10.74 | 0.366 |
| Lead sheet | 3 | 10.54 | 12 | 12 | 0.197 | 10.54 | 0.372 |
| Lead sheet | 4 | 10.77 | 12 | 12 | 0.196 | 10.77 | 0.382 |
| Lead sheet | 5 | 10.53 | 12 | 12 | 0.191 | 10.53 | 0.383 |
| Carbon steel | 6 | 9.29 | 16.5 | 8 | 0.25 | 10.14 | 0.282 |
| T-Flex® Tungsten | 7-A | 29.77 | 12 | 12 | 0.275 | 9.92 | 0.251 |
| T-Flex® Tungsten | 7-B | 29.77 | 12 | 12 | 0.275 | 9.92 | 0.251 |
| T-Flex® Tungsten | 7-C | 29.77 | 12 | 12 | 0.275 | 9.92 | 0.251 |
| T-Flex® Bismuth | 8-A | 30.66 | 12 | 12 | 0.45 | 10.22 | 0.158 |
| T-Flex® Bismuth | 8-B | 30.66 | 12 | 12 | 0.45 | 10.22 | 0.158 |
| T-Flex® Bismuth | 8-C | 30.66 | 12 | 12 | 0.45 | 10.22 | 0.158 |
| T-Flex® Iron | 9-A | 10.11 | 12 | 12 | 0.76 | 10.11 | 0.092 |
| T-Flex® Iron | 9-B | 10.11 | 12 | 12 | 0.76 | 10.11 | 0.092 |
| T-Flex® Iron | 9-C | 10.11 | 12 | 12 | 0.76 | 10.11 | 0.092 |
| Pb wool blanket (10lb/sqft) | 10-A | 29.00 | *12 | *36 | *0.625 | 9.67 | 0.107 |
| Pb wool blanket (10lb/sqft) | 10-B | 29.00 | *12 | *36 | *0.625 | 9.67 | 0.107 |
| Pb wool blanket (10lb/sqft) | 10-C | 29.00 | *12 | *36 | *0.625 | 9.67 | 0.107 |
| Pb wool blanket (15lb/sqft) | 11-A | 43.29 | *12 | *36 | *0.625 | 14.43 | 0.160 |
| Pb wool blanket (15lb/sqft) | 11-B | 43.29 | *12 | *36 | *0.625 | 14.43 | 0.160 |
| Pb wool blanket (15lb/sqft) | 11-C | 43.29 | *12 | *36 | *0.625 | 14.43 | 0.160 |
| Borated (5%) polyethylene | 12 | 10.09 | 12 | 12 | 1.92 | 10.09 | 0.037 |
| Borated (5%) polyethylene | 13 | 10.06 | 12 | 12 | 1.92 | 10.06 | 0.036 |
| Borated (5%) polyethylene | 14 | 10.08 | 12 | 12 | 1.92 | 10.08 | 0.036 |

*Dimensions for lead wool blankets are nominal, as supplied by the manufacturer.

## Table 3 –Dose Rate Measurements – On Contact

| Shielding Material | on contact | | | |
|---|---|---|---|---|
| | Sample ID | Dose Rate (mRem/hr) | Attenuation % | Lead Equivalent (10lb/ft²) |
| Plexiglass | 1 | 35.5 | N/A | N/A |
| Lead sheet | 2 | 25.68 | 27.66% | 117.43% |
| Lead sheet | 3 | 27.53 | 22.45% | 95.31% |
| Lead sheet | 4 | 27.84 | 21.58% | 91.60% |
| Lead sheet | 5 | 27.50 | 22.54% | 95.67% |
| Carbon steel | 6 | 27.35 | 22.96% | 97.46% |
| T-Flex® Tungsten | 7-A | 25.67 | 27.69% | 117.55% |
| T-Flex® Tungsten | 7-B | 27.10 | 23.66% | 100.45% |
| T-Flex® Tungsten | 7-C | 28.68 | 19.21% | 81.55% |
| T-Flex® Bismuth | 8-A | 23.29 | 34.39% | 146.01% |
| T-Flex® Bismuth | 8-B | 24.51 | 30.96% | 131.42% |
| T-Flex® Bismuth | 8-C | 26.50 | 25.35% | 107.62% |
| T-Flex® Iron | 9-A | 27.90 | 21.41% | 90.88% |
| T-Flex® Iron | 9-B | 25.23 | 28.93% | 122.81% |
| T-Flex® Iron | 9-C | 28.00 | 21.13% | 89.69% |
| Pb wool blanket (10lb/sqft) | 10-A | 27.37 | 22.90% | 97.22% |
| Pb wool blanket (10lb/sqft) | 10-B | 26.58 | 25.13% | 106.67% |
| Pb wool blanket (10lb/sqft) | 10-C | 26.79 | 24.54% | 104.16% |
| Pb wool blanket (15lb/sqft) | 11-A | 23.88 | 32.73% | 138.95% |
| Pb wool blanket (15lb/sqft) | 11-B | 23.22 | 34.59% | 146.85% |
| Pb wool blanket (15lb/sqft) | 11-C | 24.53 | 30.90% | 131.18% |
| Borated (5%) polyethylene | 12 | 21.46 | 39.55% | 167.89% |
| Borated (5%) polyethylene | 13 | 19.87 | 44.03% | 186.91% |
| Borated (5%) polyethylene | 14 | 21.61 | 39.13% | 166.10% |

## Table 4 – Dose Rate Measurements - @30cm

| Shielding Material | @30cm<br>Sample ID | Dose rate (mRem/hr) | Attenuation % | Lead Equivalent (10lb/ft²) |
|---|---|---|---|---|
| Plexiglass | 1 | 8.894 | N/A | N/A |
| Lead sheet | 2 | 7.14 | 19.74% | 85.10% |
| Lead sheet | 3 | 6.94 | 22.03% | 94.94% |
| Lead sheet | 4 | 6.81 | 23.39% | 100.80% |
| Lead sheet | 5 | 6.44 | 27.65% | 119.17% |
| Carbon steel | 6 | 7.72 | 13.22% | 56.99% |
| T-Flex® Tungsten | 7-A | 6.99 | 21.44% | 92.42% |
| T-Flex® Tungsten | 7-B | 6.77 | 23.87% | 102.88% |
| T-Flex® Tungsten | 7-C | 6.95 | 21.89% | 94.35% |
| T-Flex® Bismuth | 8-A | 6.69 | 24.78% | 106.81% |
| T-Flex® Bismuth | 8-B | 6.65 | 25.20% | 108.60% |
| T-Flex® Bismuth | 8-C | 6.63 | 25.48% | 109.81% |
| T-Flex® Iron | 9-A | 6.95 | 21.89% | 94.35% |
| T-Flex® Iron | 9-B | 6.43 | 27.75% | 119.60% |
| T-Flex® Iron | 9-C | 7.02 | 21.05% | 90.72% |
| Pb wool blanket (10lb/sqft) | 10-A | 7.27 | 18.26% | 78.70% |
| Pb wool blanket (10lb/sqft) | 10-B | 6.817 | 23.35% | 100.65% |
| Pb wool blanket (10lb/sqft) | 10-C | 6.73 | 24.33% | 104.87% |
| Pb wool blanket (15lb/sqft) | 11-A | 6.606 | 25.73% | 110.88% |
| Pb wool blanket (15lb/sqft) | 11-B | 6.498 | 26.94% | 116.11% |
| Pb wool blanket (15lb/sqft) | 11-C | 5.849 | 34.24% | 147.56% |
| Borated (5%) polyethylene | 12 | 6.64 | 25.39% | 109.43% |
| Borated (5%) polyethylene | 13 | 6.18 | 30.48% | 131.38% |
| Borated (5%) polyethylene | 14 | 6.57 | 26.15% | 112.72% |

## Table 5 – Summary of Average Dose Rate Measurements

| Shielding Material | On Contact Dose Rate (mRem/hr) | On Contact Attenuation % | On Contact Lead Equivalent (10lb/ft²) | @30cm Dose Rate (mRem/hr) | @30cm Attenuation % | @30cm Lead Equivalent (10lb/ft²) |
|---|---|---|---|---|---|---|
| Plexiglass | 35.50 | 0.0% | 0.0% | 8.89 | 0.0% | 0.0% |
| Lead sheet | 27.14 | 23.6% | 100.0% | 6.83 | 23.2% | 100.0% |
| Carbon steel | 27.35 | 23.0% | 97.5% | 7.72 | 13.2% | 57.0% |
| T-Flex® Tungsten | 27.15 | 23.5% | 99.9% | 6.90 | 22.4% | 96.6% |
| T-Flex® Bismuth | 24.77 | 30.2% | 128.4% | 6.66 | 25.2% | 108.4% |
| T-Flex® Iron | 27.04 | 23.8% | 101.1% | 6.80 | 23.6% | 101.6% |
| Borated (5%) polyethylene | 20.98 | 40.9% | 173.6% | 6.46 | 27.3% | 117.8% |
| Pb wool blanket (10lb/sqft) | 26.91 | 24.2% | 102.7% | 6.94 | 22.0% | 94.7% |
| Pb wool blanket (15lb/sqft) | 23.88 | 32.7% | 139.0% | 6.31 | 29.0% | 124.9% |

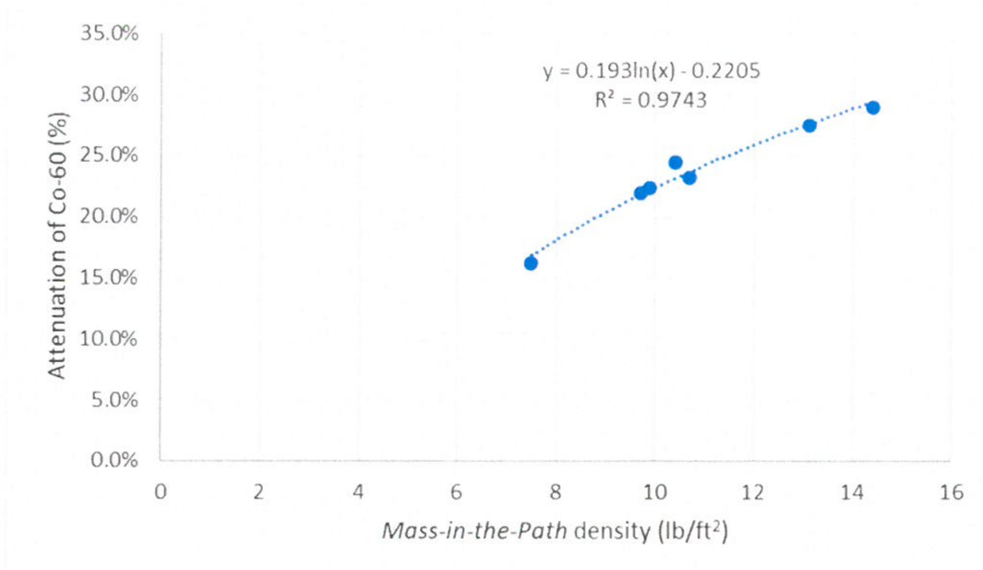
## Table 6 – Summary of Dose Rate Measurements – Constant Density

| Shielding Material | *Mass in the Path* (lb/ft²) | Thickness (in) | n = | At 30 cm Dose Rate (mRem/hr) | At 30 cm Attenuation % | At 30 cm Std Dev |
|---|---|---|---|---|---|---|
| Unshielded | | | 1 | 8.89 | 0.0% | - |
| Lead sheet | 10.7 | 0.20 | 4 | 6.83 | 23.2% | 3.3% |
| | | | | | | |
| T-Flex® Tungsten | 9.9 | 0.28 | 3 | 6.90 | 22.4% | 1.3% |
| T-Flex® Bismuth | 10.2 | 0.45 | 3 | 6.66 | 25.2% | 0.4% |
| T-Flex® Iron | 10.1 | 0.76 | 3 | 6.80 | 23.6% | 3.6% |
| Pb wool blanket (10lb/sqft) | 9.7 | 0.625 | 3 | 6.94 | 22.0% | 3.3% |

## Table 7 – Summary of Dose Rate Measurements – Density comparison

| Shielding Material | *Mass in the Path* (lb/ft²) | Thickness (inch) | n = | At 30 cm Dose Rate (mRem/hr) | At 30 cm Attenuation % | At 30 cm Std Dev |
|---|---|---|---|---|---|---|
| Unshielded | | | 1 | 8.89 | 0.0% | - |
| | | | | | | |
| Pb wool blanket (15lb/ft²) | 14.4 | 0.625 | 3 | 6.31 | 29.0% | 4.6% |
| | | | | | | |
| Lead sheet | 10.7 | 0.20 | 4 | 6.83 | 23.2% | 3.3% |
| 15lb/ft² Pb wool replacement | 10.4 | 0.45 | 3 | 6.70 | 24.5% | 2.5% |
| Pb wool blanket (10lb/ft²) | 9.7 | 0.625 | 3 | 6.94 | 22.0% | 3.3% |
| T-Flex® Tungsten | 9.9 | 0.28 | 3 | 6.90 | 22.4% | 1.3% |

Figure 1.



y = 0.193ln(x) - 0.2205
R² = 0.9743
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
Attenuation of Co-60 (%)
0
2
4
6
8
10
12
14
16
Mass-in-the-Path density (lb/ft²)