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Effectiveness of Multilayer Graded-Z Forms of Radiation Shielding

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Abstract

This study explored how different forms of radiation shielding were more or less effective than standard single-layer shielding. Beta and gamma radiation sources were used and measured using a Geiger counter to determine how well the various forms of shielding protect against the radiation. The shielding effectiveness of standard homogeneous materials (e.g., graphite, carbon/epoxy composites, aluminum, and lead) of various thicknesses for different radiation sources was measured to provide standards for comparison. Once a basis of effective shielding was established, the study can go into greater depth into how to use shielding materials to be more effective, to better shield from secondary radiation (e.g., Bremsstrahlung x-rays), or allow controlled amounts of radiation to penetrate. Measurements investigated whether interleaved layering of different high-Z and low-Z shielding materials can be more effective or have different benefits than using a single material for shielding. Braided cabling and mesh materials were used to determine how much radiation, if any, still penetrated through such shielding configurations. The study provides a basis to understand the nature of multilayer graded-Z or braided cable coaxial radiation shielding proposed for the use in high radiation space environments.

Introduction

Radiation can be detrimental to human bodies and sensitive electrical equipment. In high radiation environments understanding proper ways to protect from various forms of radiation is essential. Astronauts in low earth orbit or beyond are subject to solar energetic particles. While usually comprised of electrons and protons, solar energetic particles can also contain high energy other heavy ions. This makes it a dangerous form of radiation as it is highly penetrative. As this radiation penetrates the human body it causes damage to cells and DNA. In serious instances it can lead to short-term radiation poisoning [1]. Along with creating damage to the human body, radiation will damage electrical equipment. Issues with the electrical equipment can be observed if the electrical equipment is running, but also while it is turned off. Typically, beta radiation does affect the equipment in a significant way. However, gamma radiation can render equipment unusable. Diodes and computer chips are especially sensitive. As the system is exposed to long periods of gamma radiation the crystalline-like composition inside the electrical system is disrupted. It is degraded until it eventually fails. Materials used in the design of electrical equipment can also be subject to failure when exposed to gamma radiation. Sensitive materials will become more brittle after periods of exposure. This does not directly affect the system unless the system is made mobile. Movement of brittle materials can cause them to break, and they will be made useless [2].

The applications on Earth's surface are similar. While high radiation environments are not common natural occurrences on Earth, they are common man-made occurrences. The most relatable example of this is within a hospital. Different sections of the hospital have specially designed rooms to house different kinds of radiation. Different uses of radiation in hospitals are: radiography, fluoroscopy, computed tomography, nuclear medicine, mammography, and x-ray diagnostics [3]. Most of these uses of radiation involve gamma rays, which as stated above can cause serious issues if not properly prepared for.

The effect of radiation is a well-known issue. There are methods of radiation shielding used to protect people and equipment in radioactive environments. When it comes to radiation shielding, more mass between the object and the radiation source is beneficial. Denser materials are optimal for radiation shielding. Materials such as lead (Pb) and concrete provide effective radiation shielding. However, bulk protection is not always viable. Where space travel is concerned, astronauts are still subject to doses of harmful radiation. Using bulk protection of lead or concrete on a spacecraft would create problems with weight, fuel, and cost. On Earth there are other issues related to bulk radiation shielding. Hospital rooms that are equipped to store or work with radiation have lead shielding built into the walls, doors, and ceilings. This effectively protects anything outside of the room from harmful radiation. In the room itself though, equipment or people are subject to scatter radiation even when wearing protection. The mobile shielding barriers, like weighted vests or leaded glasses, block some radiation but do not offer full coverage and are prone to creating more scatter radiation. Lead lined vests are also heavy and difficult for specialists to wear for long periods of time [3]. The medical equipment used in these rooms is also subject to damage, but it may not be reasonable to cover this equipment with bulk high graded materials such as Pb or concrete. This is why research in all of the options available in radiation shielding is important. It is necessary to find a form of radiation shielding that is both effective and efficient.

This study investigates a different approach to radiation shielding. It explores the levels of effectiveness of using different graded-Z materials. In order to accomplish this, the study will use the layering of materials with differing atomic numbers. In this instance the term “graded” is used to describe the varying layers of composition, where Z is the average atomic number. Each layering combination is a different level of grading on a scale of high refraction to low refraction. This same grading scale applies to singular materials. Higher Z materials will typically have a higher atomic number, which means the material has higher mass and electron densities. Therefore, a high-grade material would provide more shielding from radiation. By using multiple materials, the bulk method of radiation can be cut down significantly by including low graded materials that are alternated with the high graded materials. This study also investigates braided moderately graded materials. Braided shielding offers a wider variety of usages for radiation shielding. Braided materials are lighter and more flexible. This makes it easier to work with and incorporate into equipment.

Theory

Different types of radiation are inhibited by different levels of graded-Z materials. Alpha particle radiation is a heavy particle consisting of two protons and two neutrons. Because it is a heavy charged particle it does not penetrate materials as much as other forms of radiation. Low Z materials such as carbon, hydrogen, or oxygen effectively shield from this type of radiation. Beta radiation is a lighter charged particle. Beta radiation occurs when an electron is emitted from an atom. While more penetrative than an alpha particle, a beta particle is still easily shielded by about 2 centimeters of a low Z material. Neutron radiation has no charge and is found in the nuclei of an atom. It can travel far and is highly penetrative. Water or multiple feet of concrete are needed to shield this type of radiation. Finally, gamma radiation is massless

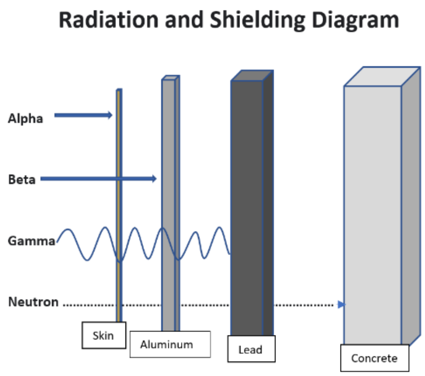


Figure 1- Radiation and Shielding Diagram

electromagnetic radiation that is emitted from an unstable nucleus of an atom during radioactive decay. They are penetrative and higher Z materials are more effective to shield from this type of radiation [4]. Figure 1 demonstrates the different types of radiation and effective shielding for each. For this study only beta and gamma radiation were considered.

Through a process called Bremsstrahlung free electrons emit x-rays when they are slowed down or collide with another material [5]. Pb bulk shielding is highly effective at blocking beta radiation. A large quantity of hard to shield x-rays are produced when using high Z materials than low Z materials. This can be determined by the Bremsstrahlung equation for power produced.

$$P_{Br}\left(\frac{W}{m^3}\right) = \frac{Z^2 n_e n_c}{(7.07 * 10^{18} m^{-3})^2} (k_B T_e)^{\frac{1}{2}} * 6(y_p) \qquad (1)$$

This gives the conclusion that the Bremsstrahlung power is proportional to Z^2. For any given number of incident electrons Pb produces more Bremsstrahlung power than PE. To find approximately how much more power the equation below can be used:

$$P_{Br} = \left(\frac{Z_{Pb}}{Z_{PE}}\right)^2 \qquad (2)$$

This is problematic because the x-rays are harder to shield from than the original beta particles. This is why this study introduces the idea of using layered high Z and low Z materials. The theory is that the low Z polyethylene (PE) shield will absorb some of the beta radiation rather than reflect it back. The high Z Pb will then stop the excess radiation that penetrates through the polyethylene. This will reduce the number of x-rays created from the shielding and will reduce the scatter radiation.

The braided materials were also tested. Instead of focusing on limiting the x-ray emissions, the braided materials were tested to see how a braided material would perform against a solid shield. Braided materials are easier to work with, but the concern is that since there are gaps in the material it would not be as effective at blocking the radiation. Layering the braided material could result in better shielding and still allow the shielding to be flexible. This was also tested.

A simple Geiger counter (The Nucleus, Model 500 Nuclear Scaler) was used to measure the radiation penetrating each shield figuration. A Geiger counter uses a Geiger-Müller tube to detect radiation. A Geiger-Müller tube is a sealed tube filled with helium, neon, or argon gas along with a positively charged wire through the middle of the tube. When radiation particles enter the tube, they will ionize the gas. The wire attracts electrons and when an ion pair interacts with it an electric pulse is sent to the Geiger counter. This is what the Geiger counter registers as a count. Figure 2 shows the Geiger counter used in the lab and how it was set up. The Geiger counter measured counts for a

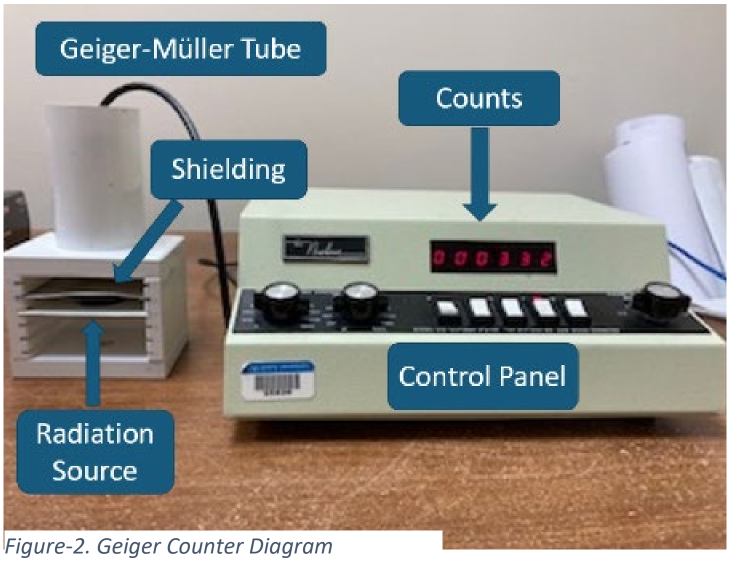


Figure-2. Geiger Counter Diagram

set amount of time and therefore the amount of radiation entering the tube can be quantified as a dose rate in counts per minute [6].

Methods

The Geiger counter and the sources were tested first. This was to ensure that both the Geiger counter was functional and that the sources were valid to be used for testing. This was done as a precaution because the Geiger counter and the sources have not been used recently. To test this the GM-tube was placed on a stand with slots, while the source was placed on a tray that could be moved to each slot. At each position the Geiger counter was set to run for 30 seconds and record the counts. Radiation should fall off at a rate of $\frac{1}{r^2}$, where r is the distance from the source. When presented on a graph the curve should be a decreasing exponential function. The ^{137}Cs (gamma) and ^{90}Sr (beta) were determined to follow this trend as shown in Figure 3 and 4.

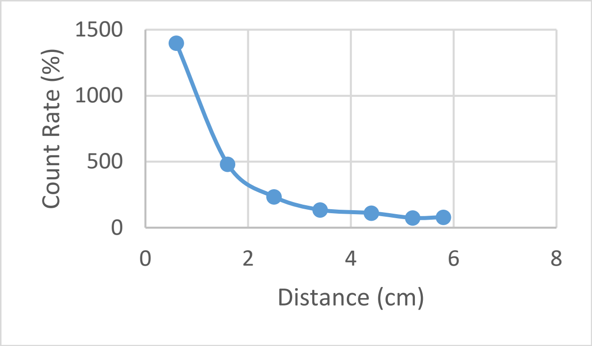
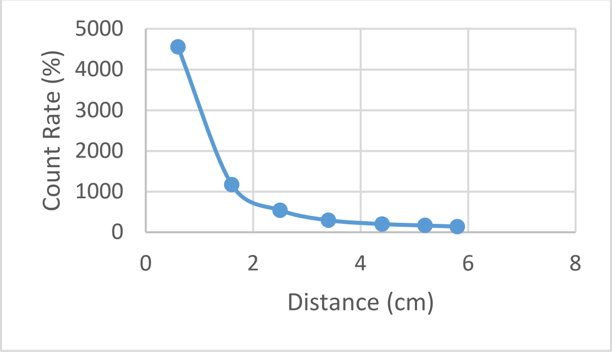


Figure-3. Cs-137 Radiation Distance Fall of Graph

Figure-4. Sr-90 Radiation Distance Fall of Graph



Using the equation

$$N(r) = N_0 r^{-2} \qquad (3)$$

Where N is the number of counts and r is the distance from the source to the Geiger counter tube, it was derived:

$$log \frac{N(r)}{N(r_0)}] = -2\log(r) - 2\log(r_0) \qquad (4)$$

In this equation -2 was determined to be the slope and $-2\log(r_0)$ was determined to be the intercept. This new equation was then used to determine if the graphs in figures 3 and 4 did in fact have a slope of -2. For figure 3 the slope was found to be -2.53±0.5 and for figure 4 it was found to be -1.98±0.5. These findings concluded that the Geiger counter was operational along with the sources being viable.

Each source was then tested to find an operating voltage. The Geiger counter has a positively charged wire that is controlled by the Geiger counter control panel. Each radiation source has a unique threshold voltage at which the ionized gas will interact with the wire and register a count. Each source needs to be tested at the threshold voltage and in increasing intervals to determine the best voltage for collecting data. This must be down because if the voltage is too low some radiation may not be accounted for. If the voltage is too high the wire can spontaneously discharge creating false counts. To find the operating voltage each source was tested with the voltage set to 200 V. The Geiger counter was then set to run, and the voltage was slowly increased until the Geiger counter started detecting radiation. This point was marked as a threshold voltage. For both sources the threshold voltage was 340 ± 10 V. Each source was placed under the Geiger counter at 340 V and was set to run for 30 seconds. The results were recorded, and the process was repeated with an increase of 20 V each time. The data were then graphed, and the operating voltage was determined to be the middle point of the plateau as shown in Figures 5 and 6.

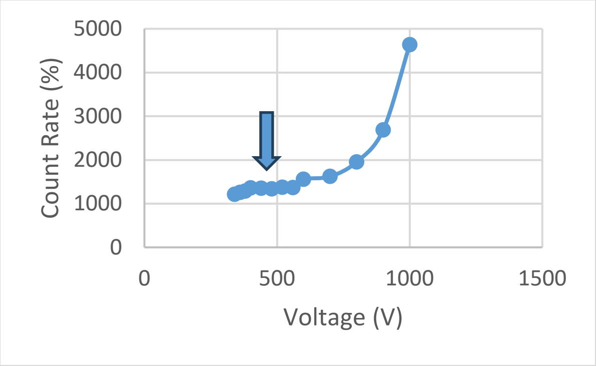


Figure-5. Cs-137 Threshold Voltage and Plateau

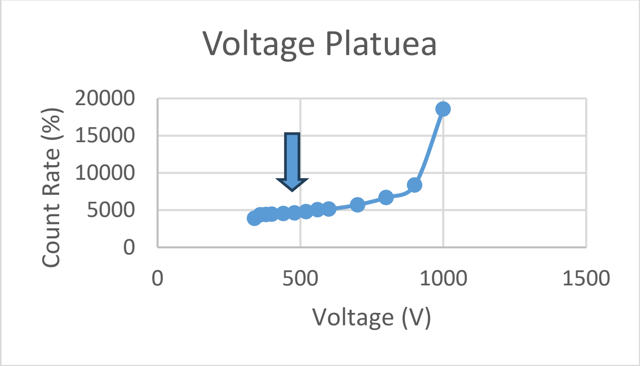


Figure-6. Cs-137 Threshold Voltage and Plateau

At this point the sources were determined to be good for collecting data further and the operating voltage at which to test the rest of the data was determined to be 440 ±10 V for both sources.

The background radiation levels were recorded each day and were subtracted from the recorded data from each source. Each day ranged from around 0-5 counts per minute of background radiation. This ensured that the radiation that was detected by the Geiger counter was based solely on the source and not the surrounding area. To accomplish this nothing was placed underneath the GM-tube and the Geiger counter was allowed to run for 30 seconds. To start taking data on layered graded-Z materials, small rectangular shielding samples of Pb and PE were used. Lead (Pb) was used because it is a high Z material with an atomic number of 82. Polyethylene was used because it is a low Z material made of carbon and hydrogen (CH_2) giving it a mean atomic number of 6.1. Equation (2) of the Bremsstrahlung power equation was used to determine that the Pb samples produced about 548 times as much power. In order to compare the extra x-rays produced by the lead samples, the polyethylene samples were also used. The rectangular samples were later determined to be too small to obtain conclusive data from. Larger circular shielding samples were found to continue with the research. These shielding samples ranged in thickness and were large enough to cover the entire radiation source. Covering the whole radiation source was essential to guarantee that the radiation being detected was only radiation penetrating the shielding and not leaking around it. Both sources were then set beneath the Geiger counter and each shielding sample was placed directly on top of the source and tested individually. This would provide a baseline of how each thickness and material of shielding did on its own. There were 6

PE and 5 Pb shielding samples used. Layering was done in a similar fashion. The shielding samples were layered directly on top of the radiation source. The layering ranged from 0-5 layers thick of varying combinations of Pb and PE. Layering only Pb or PE was also tested. This was done to check if the act of layering the materials had any effect on the radiation recorded.

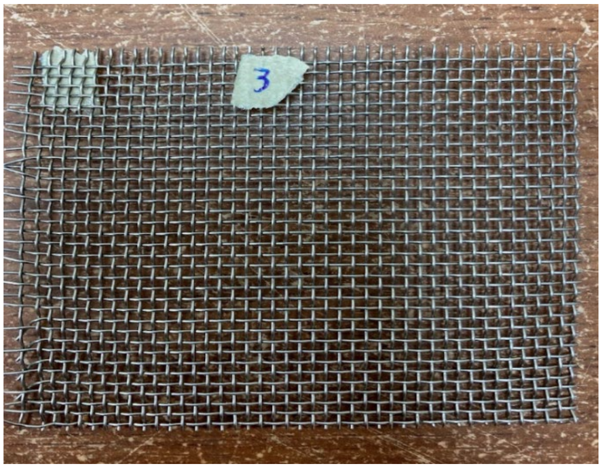


Figure-7. Braided Material Sample 3

The braided materials were tested in a similar fashion. The braided materials were offered in much larger samples as seen in Figure 7. Each braided material was cut to fit the slots in the GM-tube stand. This meant that the shielding samples were not placed directly on top of the radiation source but could be placed on any given slot. This allowed for a few different things to be tested. The first was to determine if the placement of the braided materials increased the shielding ability. It was determined that the closer to the tube the shielding sample was placed the more shielding it offered. Both sources were then tested with each of the braided shielding samples. The braided materials were then layered together and tested almost the same way as the layering of the solid shielding samples. The difference was that since the braided samples could be moved into different slots, when layering the materials each combination was tested layered directly on top of the next or separated into different slots. This was done to determine again if providing empty distance in between the source and different layers made any difference. No significant difference was determined.

The braided shielding samples were then tested against the solid shielding samples. The solid shielding samples were placed directly on top of the radiation source and the braided shielding samples were placed on the slot closest to the source. The radiation source was kept on the same slot for this entire set of testing. This was all done to examine how the braided materials compared with solid materials with no gaps. The braided shielding samples were then layered in various combinations of 1-3 layers thick and again analyzed against single layers of solid shielding samples. Since the braided materials were just scrap materials found for the use of this experiment the type of materials is uncertain. It was determined that the mesh shielding samples were stainless-steel as none were proven to be magnetic. However, once the densities of the mesh samples were calculated they had similar densities to aluminum (2.8 $g * cm^{-3}$). It was then concluded that the mesh materials were made of aluminum (Al) as it is also not magnetic. The thickness in the wire and the tightness of the braiding varied in each sample and no two were the same. The density was calculated for each of the samples, and they were labeled M1-M5.

Results

Table 1 summarizes the results of the data found by comparing the amount shielding blocked from solid shielding samples and the braided shielding samples. This was done for the ^{137}Cs gamma source.

Sample Number	Material	Thickness (mm)	Density ($g * cm^{-3}$)	Counts per minute	Percent of Radiation Blocked
0	NONE	0	0	103±10	0%
1	PE	1.427	0.997	70±8	32±4%
2	PE	3.08	0.954	68±8	34±4%
3	PE	0.714	1.049	87±9	16±4%
4	PE	0.506	1.047	76±9	26±4%
8	PE	6.278	0.943	68±8	34±4%
11	PE	6.19	0.918	77±9	25±4%
7	Pb	0.84	12.302	83±9	19±4%
5	Pb	3.617	11.740	49±7	82±3%
9	Pb	1.662	12.520	88±9	15±4%
10	Pb	0.799	12.333	82±9	20±4%
6	Pb	6.321	11.518	40±6	61±3%
M1	Al	0.144	2.475	85±9	17±4%
M2	Al	0.432	2.610	69±8	33±4%
M3	Al	0.869	1.875	96±10	7±5%
M4	Al	0.332	0.340	95±10	8±5%
M5	Al	0.433	0.983	83±9	19±4%
M1 + M2	Al	0.576	2.576	60±8	42±4%
M1+M3	Al	1.013	1.960	84±9	18±4%
M1+M4	Al	0.476	0.986	84±9	18v4%
M1+M5	Al	0.577	1.355	69±8	33±4%
M2+M3	Al	1.301	2.120	62±8	40±4%
M2+M4	Al	0.764	1.624	81±9	21±4%
M2+M5	Al	0.865	1.796	74±9	28±4%
M3+M4	Al	1.201	1.451	76±9	26±4%
M3+M5	Al	1.302	1.579	73±9	29±4%
M4+M5	Al	0.765	0.704	98±10	5±5%

Table-1. Effectiveness results for braided and solid materials with the ^{137}Cs gamma radiation source.

In this data set the shielding samples made of Pb and PE are solid samples with no layering. The solid samples being a sheet of lead with no holes. The Al samples (M1-M5) are braided materials both single layers and double layered. The solid lead samples were tested in the same format as used before when testing the Pb and PE shielding. Similarly, the same was done with the mesh Al samples. The mesh samples were also layered on top of each other in order to determine the effectiveness of layering mesh samples of different densities. From these data it can be observed that M2 braided material is just as effective as the solid PE samples 1 and 2, but the M2 material is less than half as dense. These results only improve as the braided material is layered with other braided materials for gamma radiation. The layered braided materials even performed as effective at blocking radiation as some of the Pb samples.

Table 2 shows the same data for the ^{90}Sr beta source.

Sample Number	Material	Thickness (mm)	Density ($g * cm^{-3}$)	Counts	Percent Of Radiation Blocked
0	NONE	0	0	745±27	0±4%
1	PE	1.427	0.997	375±19	50±5%
2	PE	3.08	0.954	147±12	80±8%
3	PE	0.714	1.049	500±22	33±4%
4	PE	0.506	1.047	523±23	30±4%
8	PE	6.278	0.943	3±2	99.6±10%
11	PE	6.19	0.918	15±4	98±10%
7	Pb	0.84	12.302	0±0	100±10%
5	Pb	3.617	11.740	4±2	99±10%
9	Pb	1.662	12.520	0±0	100±10%
10	Pb	0.799	12.333	0±0	100±10%
6	Pb	6.321	11.518	0±0	100±10%
M1	Al	0.144	2.475	545±23	27±4%
M2	Al	0.432	2.610	462±21	38±5%
M3	Al	0.869	1.875	387±20	48±5%
M4	Al	0.332	0.340	703±27	6±4%
M5	Al	0.433	0.983	568±24	24±4%
M1 + M2	Al	0.576	2.576	413±20	45±5%
M1+M3	Al	1.013	1.960	300±17	60±6%
M1+M4	Al	0.476	0.986	579±24	22±4%
M1+M5	Al	0.577	1.355	439±21	41±5%
M2+M3	Al	1.301	2.120	190±14	74±7%
M2+M4	Al	0.764	1.624	386±20	48±5%
M2+M5	Al	0.865	1.796	360±19	52±5%
M3+M4	Al	1.201	1.451	362±19	51±5%
M3+M5	Al	1.302	1.579	303±17	59±6%
M4+M5	Al	0.765	0.704	530±23	29±4%

Table-2. Effectiveness results for braided and solid materials with the ^{90}Sr beta radiation source.

As shown here again, M2 performs almost as well as the PE samples 3 and 4 by blocking 30% of the radiation. When layered the braided materials performed as well as some of the PE materials, while still being flexible and easy to work with. However, for the beta radiation the braided Al material was not as effective at blocking radiation as the Pb solid materials. As for the data taken using the gamma source the braided materials performed more uniformly, while braided materials in the beta source data set showed some braided samples performing better than others.

The data for layering different thicknesses of Pb and PE can be seen in figure 7. On this graph 5 sets of data can be distinguished. It is important to first distinguish the plot points that represent single layers of materials rather than layered materials. The layered materials are grouped into three subsets. These subsets are: layers of Pb only, layers of PE only, and layers of both Pb and PE. As can be observed in figure 7, there are combinations of layered PE and Pb materials that, while less in density, shield as effectively from radiation as layers of only Pb. The idea of the layered Pb and PE data points is that they are effectively blocking as much radiation as the just the

Pb data points but are also not emitting as much gamma radiation. The lower green data points between 10000 and 15000 kg $\cdot$ m^{-3} exhibit this behavior.

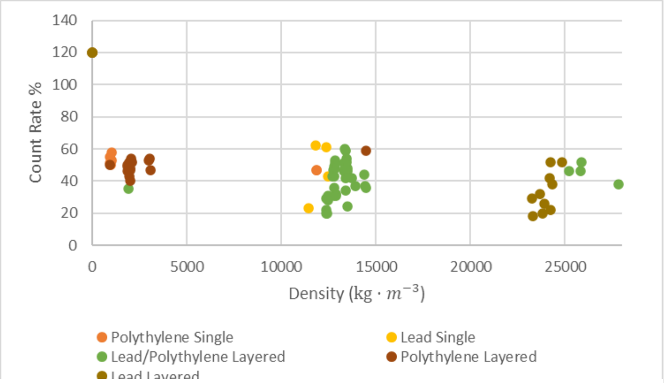


Figure-7. Count rate verses density of single and layered data.

Conclusions and Future Work

This study explored the possibility of more efficient and effective ways of using radiation shielding. This was done by layering high graded materials (Pb) and low graded materials (PE) and comparing the effectiveness of the shielding with non-layered high and low graded materials. The study went a step further to also examine how braided high-Z (Al) materials compared with both high and low Z materials.

The results of this study found that for the layering of Pb and PE there was a sweet spot where the layered samples work as effectively to block radiation as only layers of Pb. This sweet spot was determined to be the combination of a layer of Pb 6.321 mm thick and a layer of PE 6.278 mm thick. The result of this combination compared equally with 2 layers of only Pb with a combined thickness of 7.12 mm, by shielding similar amounts of radiation within the error range. Other similar results were observed. While the layering of Pb and PE does result in a much thicker shield, it does have some benefits. The most important benefit is that the PE shielding reduces the amount of scatter radiation and the number of x-rays emitted. Since x-rays are much harder to shield from than the original beta particles, it is important to lower the risk of creating the x-rays.

This study also found results for using braided high Z materials verses solid high and low Z materials. It was discovered that the braided shielding samples performed just as well as the solid PE shielding samples. This was surprising data as the braided materials are less dense due to the gaps in material. One would expect more radiation to penetrate through the holes in the braided material. However, it was found that a low-Z material, like PE, had a similar outcome to the braided material despite it being completely solid. For the ^{137}Cs (gamma) radiation source data some of the braided samples even performed as well as the Pb shielding samples. This was not the same for the ^{90}Sr (beta) source data. This data is useful for the use of incorporating braided materials into equipment that may be subject to radiation. The flexibility of braided materials rather than a solid material allows for more uses within the manufacturing of equipment. This can be seen with cables and wires. They can easily be wrapped in a high graded-Z material and still perform as a flexible cable would need to. This is also helpful when shielding people as lead vests are heavy, and braided materials will offer more mobility and are lighter to carry.

However, more research will need to be done to ensure that this data continues to follow these trends. Further research should look at the effectiveness of layering solid and braided materials in environments with higher doses of radiation along with longer dose times. This study presents the baseline to take the research to a large scale. Eventually it would be ideal to experiment with the braided high-Z materials with functioning cables in a high radiation environment. It would also be beneficial to run these tests at longer count intervals in order to increase the sensitivity to smaller differences in shielding efficiencies. This would allow more detailed observations to be made between the varying shielding samples.

References

[1] Tran, L. (2019, August 5). How NASA will protect astronauts from space radiation at the Moon. NASA. Retrieved April 24, 2023, from https://www.nasa.gov/feature/goddard/2019/how-nasa-protects-astronauts-from-space-radiation-at-moon-mars-solar-cosmic-rays

[2] Hageman, J. P. (2015, January 26). Radiation Effects- Effects on Materials. HPS: Specialists in Radiation Protection. Retrieved April 24, 2023, from https://hps.org/publicinformation/ate/q11162.html#:~:text=Ionizing%20radiation%20breaks%20down%20the,cause%20shorts%20in%20the%20equipment.

[3] Versant Physics. (2022, April 20). The Basics of Radiation Shielding in Medicine. Versant Medical Physics and Radiation Safety. Retrieved April 24, 2023, from https://www.versantphysics.com/2022/04/20/radiation-shielding-in-medicine/#:~:text=Shielding%20may%20be%20required%20in,in%20the%20adjacent%20areas%2Frooms.

[4] United States Nuclear Regulatory Commission. (2020, March 19). What are the different types of radiation? U.S. NRS. Retrieved April 24, 2023, from https://www.nrc.gov/reading-rm/basic-ref/students/science-101/what-are-different-types-of-radiation.html

[5] Goddard Space Flight Center. (2010, October). X-rays from Free Electrons. NASA. Retrieved April 24, 2023, from https://imagine.gsfc.nasa.gov/science/toolbox/xray_generation_el.html#:~:text=When%20the%20electrons%20collide%20with,that%20occurred%20during%20the%20collision.

[6] United States Nuclear Regulatory Commission. (2020, March 19). What is a Geiger Counter? U.S. NRC. Retrieved April 24, 2023, from https://www.nrc.gov/reading-rm/basic-ref/students/science-101/what-is-a-geiger-counter.html