



A Novel Layered System to Prevent High-Energy, Ionizing Radioactive Photon Transmissions and Control Particle Behavior with the Utilization of Monte Carlo Transport Modeling via SPENVIS-based Modular Implementation

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ABSTRACT

Today, mass nuclear weapons and reactor plants are becoming more prominent. However, current methods of radiation shielding are not viable due to heavy cost and ineffective means of weakening photon momentum. Therefore, it becomes necessary to design structures resistant to the behavior of radiation from exposing to human life. Specifically, 280 computational experiments were conducted in a SPENVIS environment utilizing Multi-Layered Shielding Simulation (MULASSIS) and Geant4 Radiation Analysis for Space (GRAS) on multiple shielding models. These thirteen models tested against nuclear, artificially-generated incident particles under single and multi-ray analyses with four angular photon distributions in comparison to SHIELDSE, a current standard for cosmic radiation shielding developed by the European Space Agency. These designs using stainless steel, lead, slightly-radioactive bismuth, and lithium-hydride prevented over 99% of particle detection compared to SHIELDSE, which conversely increased the neutron-energy dose by over 700%, and insufficiently reduced high-energy gamma ray penetration. Per kilogram, my model is 144 times cheaper and only a small fraction of the thickness of either SHIELDSE or metal foams. Thus, the potential of enhanced nuclear plants, further space exploration, and an overall safer approach to utilizing or preventing exposure to atomic particles such as with multi-disaster protection buildings can become more readily available, thus saving millions of lives that are in impending danger.

Keywords

Radiation Shielding; Photon Behavior; Monte Carlo Analysis; SPENVIS; GRAS; MULASSIS; SHIELDSE; Nuclear energy

Academic Disciplines

High-Particle Physics; Nuclear Physics

1. THEORY

In contrast to the current methods, my designs surround the idea of utilizing a range of metals and metal compounds to refract or dissipate the movement/energy of the photon ray transmitted, rather than singularly reducing the ionizing dose per layer. Figure 1 below depicts this idea more closely in which a model consisting of lead, bismuth, lithium hydride, and stainless steel. Currently, lead and stainless steel are common materials used in radiation shielding. However, the use of bismuth and lithium hydride is novel. In essence, each photon type encounters a specific set of layers in which it will either refract, dissipate, or form a new particle chain, such as a positron or electron, depending on the original photon. The following will describe how each ionizing ray would be controlled in this model:

1. Alpha particle: The smallest of the radioactive photons, this particle consists of two protons and two neutrons. Although this particle is deadly upon inhalation, it is harmless to the skin at low-energy levels (below 1 MeV), which is why this particle was tested at a mono-energetic energy of 5 MeV. The original consensus was that it would be immediately dissipated in the first layer, and this was supported with my data.

2. Beta particle: This particle is a high-energy electron (beta- decay) that converts a neutron into a proton with the low-energy W^- boson, allowing for the switch from one up quark and two down quarks to two up quarks and one down quark. Because of this behavior, beta rays would have a similar effect to alpha rays except that they would have a greater traversal through the layers and would result in multiple sub-particle formations as weaker beta rays well before the third layer at maximum.
3. Gamma ray: The gamma ray consists of high-energy photons decayed from an atomic nucleus. Like alpha or beta waves, gamma waves ionize atoms, which can increase the energetic movement of particles and cause radical subatomic formations. These rays are usually seen under 100 keV, but can obtain energy up to 10 MeV at an Earth-level scale. The idea behind preventing exposure to this ray would be to use bismuth, which is much more dense than lead, to cause mass refraction within the system via Compton scattering and push low energy photons, if any, through the lithium hydride (Li-H) layer unaltered into the last lead layer, where the low-energy gamma rays would be able to be halted.
4. Neutron radiation: Neutrons have a completely different behavior that allows for the production within the system of "fast neutrons" that have a kinetic energy above 1 MeV. However, neutron radiation can be halted or refracted with the use of low atomic number compounds (such as Li-H), in which ionization would not cause further "fast neutron" development. As supported in my data, the neutrons were able to refract, once in exposure to the Li-H layer (Figure 1).
5. X-ray exposure: Lastly, X-rays, mainly constituting of high-energy electrons, do not usually have a large kinetic energy and thus, in this testing environment, had similar movement within the system as the alpha rays. This is because the movement of X-rays is not ionizing and thus provides a weak response in contact to an atom.

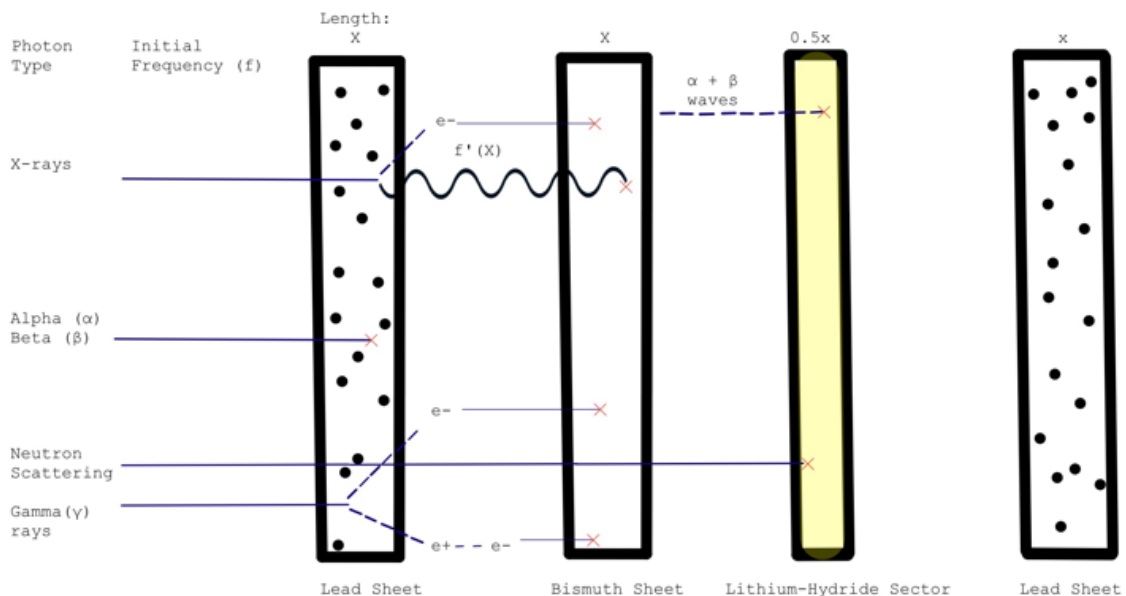


Figure 1: Depicts layer-based photon transmissions

The use of bismuth, being slightly radioactive itself, would need to be contained, which also helped define the usage of Li-H in addition to its use with neutrons as shown in Figure 1. The use of stainless steel (SS) in the model was to keep consistent with the previous year's data showing the strength of stainless steel against external force.



2. OBJECTIVES

The overarching goal in these computational simulations would be to model a novel layered structure that is not only effective against radioactive photon transmissions, but is also inexpensive and will take up a smaller volume than current methods in radiation shielding. In addition, other objectives include:

- Observing the angular distribution of a photon as a constituent of the particle's behavior within the layered system as this idea has been rarely observed in modern-day shielding simulations
- Testing both high and low mono-energetic, particle-based, and Earth-level intensities in order to observe not only particle behavior, but also the increasing or decreasing voltage between layers
- Obtaining at least a 95% mega electron-volt [MeV, equivalent to 1.602×10^{-13} joules] energy reduction over the complete layered system and having a greater MeV reduction than the aluminum-based model used by the European Space Agency
- And lastly, observing consistent and favorable results for all photon types, which would entail the mass decreased dissipation of free particles, a task that has not been achieved as of yet for efficient, multipurpose use

3. CURRENT METHODS

As of today, radiation shielding is a field that is much needed due to the increase in nuclear weaponry and the threat of the collapse of humanity. Currently, there are a few methods that are used to prevent radioactive exposure in humans; however, all of these models are based on singular photon types for only specific situations, not in the event of a major catastrophe, in which the lives of millions if not billions would be at stake. Some of these methods are as follows:

- For human spaceflight, the use of superconducting solenoids creating a large magnetic field around a spaceship to deflect low-energy waves. Still, this method is not compatible at a mass scale for the general public, and it is not completely effective against high-energy neutron or gamma rays.
- Similarly plasma shielding and electrostatic shielding are used in space, but these methods are not shown to be completely safe for humans and have maximum voltage capacities that even Earth-based nuclear radiation could not be prevented.
- On Earth, the usage of thin lead barriers helps in deflecting, but not prevent some radiation, which is not effective alone. Other methods using concrete blocks, for example, can deflect many photon rays, but are still unable to block high-frequency waves completely.
- In addition, the construction of a body suit encapsulating liquid metal has been shown only to prevent exposure to very weak photon rays, making it unsuitable for most applications
- Lastly, one of the most promising methods of radiation shielding is the use of metal foams, which are blocks of metal alloys filled with gas pores, which allows it to become lighter. This method has been shown to prevent most photon rays at low-medium Earth-based levels, but it is rather costly and the procedure to create this material is long and it requires a large thickness of the metal in order for full photon dissipation.

Even with all of these options, there is no method of complete reflection or dissipation of all radioactive photon rays at both high and low voltage energies that is also thin and cheap. Because of this, new and safe containment of energy via nuclear reactors or the possibility of colonization to other planets halts in the further progression of human safety and curiosity.

4. TESTING PROCESS AND RESULTS

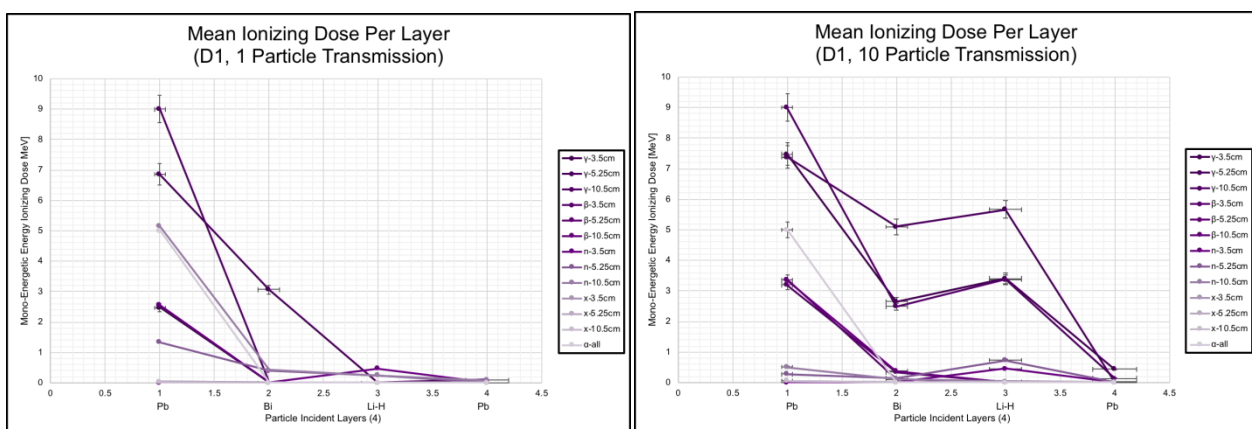
4.1 Photon Transmission Simulations & Discussion

All 280 computational experiments were categorized into 6 graphical models displaying the average ionization of various particles transmitted onto certain thicknesses. Specifically, the design data was split into two subcategories, either 1 or 10 particle transport (Graphs 4-7) in comparison to the default SHIELDOSE aluminum based model (Graphs 8-9). In terms of dosage, there was over a 99% dosage reduction throughout D1, consisting of lead, bismuth, and lithium-hydride, and D2, consisting of lead, bismuth, lithium-hydride, and stainless steel (SS) in order to correlate this data in use toward previous data on the strength and durability of SS in case of external damage. Because of the vast difference in the ionization of atoms along with particle behavior at various photon transmission levels, an increased dosage can be seen in certain layers for all of the combined experiments placed onto one graph. For example, in Graph 5, there is a large atom ionization fluctuation at the 3rd layer, composed of lithium-hydride. This can be justified because over time, the frequency of each photon becomes larger and has a higher probability to ionize an atom. At the 3rd layer, the refraction rate, in which incident photons geometrically changed positional course (up to a 70 degree angular change). This would not only send these photons into backward directions, but it would also increase frequency, and "dissipate" its mono-energetic energy at a faster rate. Therefore, the mean MeV value at the layer would be reasonably higher. This similarly occurs in Graph 6 and Graph 7, however, the higher MeV mean values occur in the lead and bismuth layers. This is mainly in correspondence to the larger wavelength photons, such as gamma rays and neutron intrusion. Because of this, the original theory for the use of bismuth shows to be a valid option that contributes heavily to the mass energy reduction throughout each of the tests.

In contrast to the first two theoretical designs, Graph 8 and Graph 9, serving as comparative models under the same conditions, had vastly different results. To start, although for lower wavelength photons, such as positrons (as beta- decay modulators) and electrons (modified as X-rays). the SHIELDOSE model did serve well in fully decreasing their dosage rates, the model had a few flaws that would prevent its progressive use in situations requiring heavy wave (gamma or neutron for example) prevention. Specifically, the model did was severely unstable against neutrons and gamma rays, as shown by not only the spontaneous variances in peak MeV values, but also the last layer, in which the neutron MeV mean value increased by over 700% in the 1 particle distribution model and over 150% in the 10 particle distribution model. In terms of gamma rays, although both data conglomerates showed a respectable decrease in the layer-based ionization dose, the ending MeV was still well over gamma ray safety precaution on Earth. Especially since these tests were in comparison to high Earth-based radiation photon characteristics, these tests show the lack in viability of SHIELDOSE model from much greater use than space probes at a real-life standpoint.

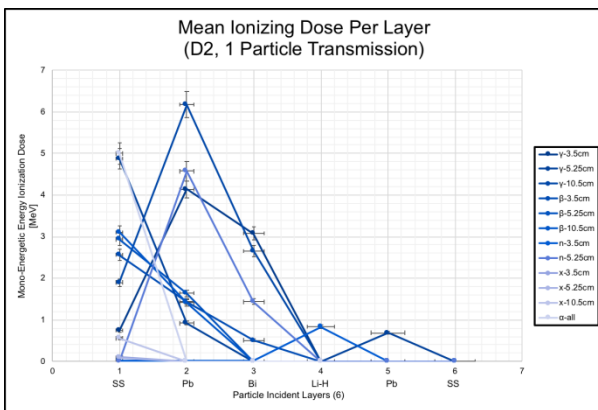
4.1.1 Graph 1.

4.1.2 Graph 2.

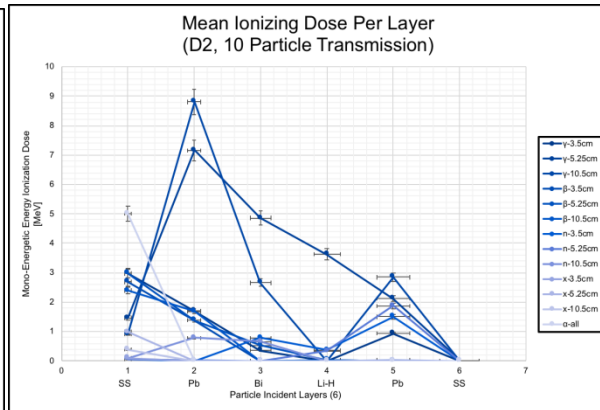


Graphs 1,2: Depicts the average ionizing dose for five particle types on four particle angular distributions and three thicknesses, in which each particle and thickness encompasses one color-coated series

4.1.3 Graph 3.

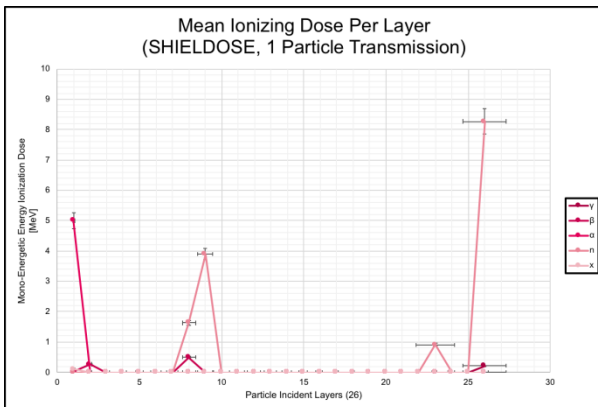


4.1.4 Graph 4.

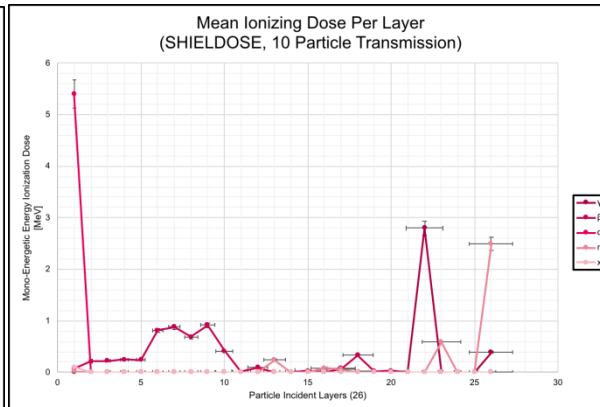


Graphs 3,4: Depicts the average ionizing dose for five particle types on four particle angular distributions and three thicknesses, in which each particle and thickness encompasses one color-coated series (SS = stainless steel)

4.1.5 Graph 5.



4.1.6 Graph 6.



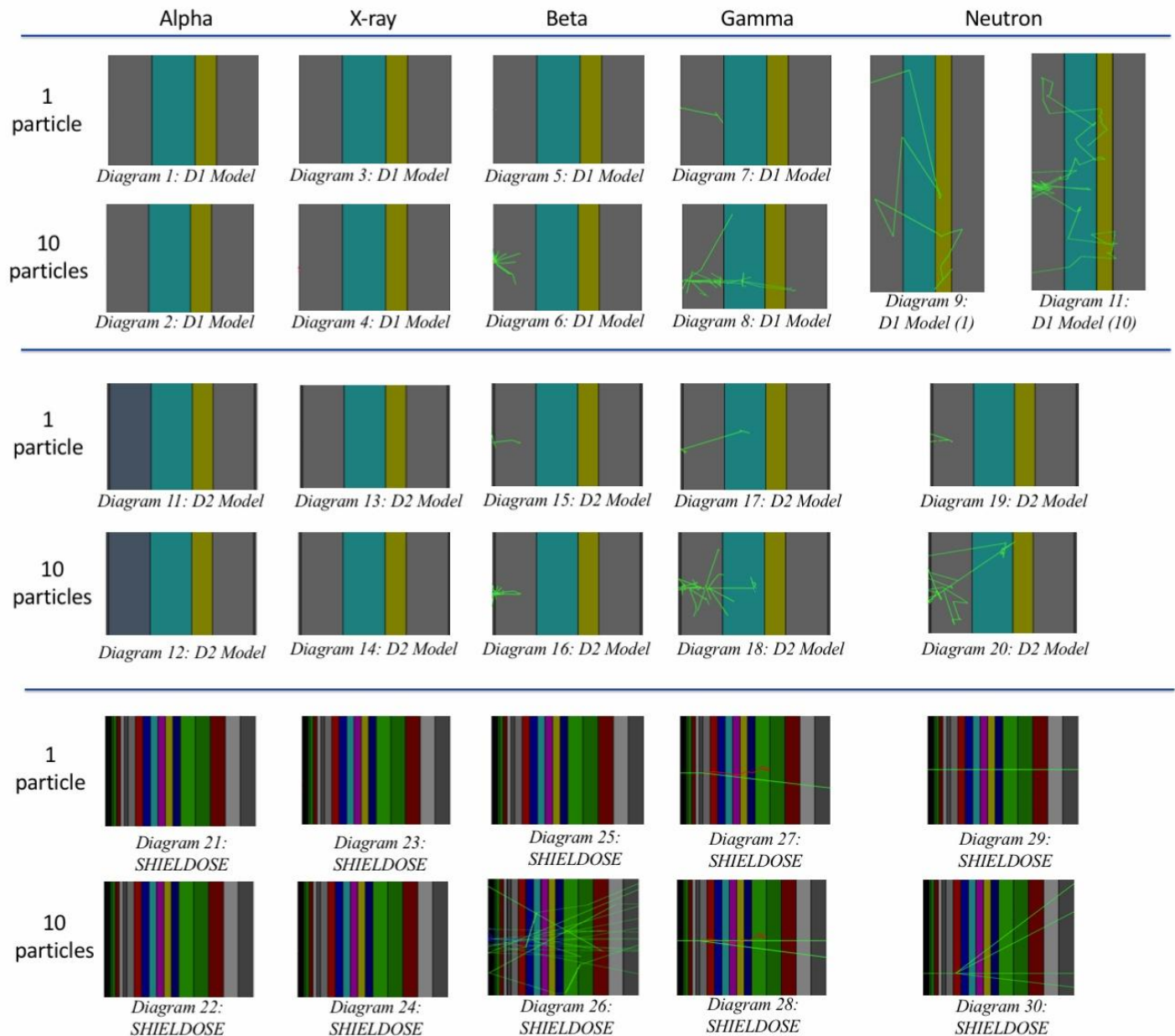
Graphs 5, 6: Depicts the average ionizing dose for five particle types on four particle angular distributions, in which each particle encompasses one color-coated series against the comparative model, SHIELDOSE

4.2 Photon Transmission 2D Diagrams & Discussion

The 30 models portrayed below show the physical movement of the individual photons, along with sub-particle movement when applicable. The first two rows display the 5 particle types of the D1 model at 1 and 10 particle standpoints. The next four show the same standpoints, but for the D2 and SHIELDOSE models, respectively. It is organized from left to right in the following particle order: alpha ray, x-ray, beta ray, gamma ray, neutron insertion. This order is to better demonstrate the gradual increase in particle movement between photon types. For the D1 model, the lead layers are gray, the bismuth layer is cyan, and the lithium-hydride layer is yellow. For the D2 model, these same conditions apply, but with the addition of two stainless steel layers shown to be dark gray. Finally, the last two sets of data show the increasing thickness (from 0.05 mm to 20 mm) of the SHIELDOSE 26 aluminum layers, which is equivalent to around a 23 cm thick model, over twice as thick as the largest depth in the D1 or D2 models. Yet, as shown in the results, the increased thickness in conjunction with the mathematical conformation of the increasing layers was unable to prove as successful to the other tested models. Specifically, as shown, the photon energy dissipated completely, preventing absorption into the photon detection layers. Therefore, even under immense ionizing stress, the thinner layers utilizing the specified materials was able to deflect photon rays immensely. In contrast, the SHIELDOSE model was unable to handle strong beta waves as shown in Diagram 26 with over an 80% photon entry and intensity

onto the last photon detection layer. In addition, in Diagrams 27, 28, 29, and 30, there was little shown photon excitation. This was justified because the model did not have the capability to deflect particle waves throughout the 23cm model as shown by the rapidly increasing neutron and gamma ray mono-energetic energy at many layers of the model. Due to this, the SHIELDOSE model was not able to prevent all photon absorption within the model, as both D1 and D2 had the capability to do

4.2.1 Diagrams 1-30

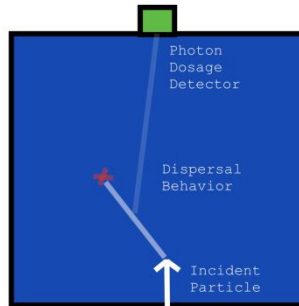


4. SOFTWARE AND PROGRAMMING

The Space Environment Information System, SPENVIS, is an operational software developed by the European Space Agency allowing users to perform analysis to environmental problems including radiation, micro particles, cosmic rays, etc.

From this software, the following Geant4 tools were used to obtain a Monte Carlo photon analysis of computer-generated rays:

- *MULASSIS*: The Multi-Layered Shielding Simulation Software allows for a user-defined one-dimensional shield simulating photon transmission through the geometry. With this software, the structure of the layered system can be modified in terms of thickness and layer type, based upon



atom density and electron configuration.

- *GRAS*: The Geant4 Radiation Analysis for Space is a tool that uses *MULASSIS* geometry to specify multiple factors such as transmitting particle type, number, angular distribution, incident energy spectrum, all to calculate the ionizing dose, entries, path length of photons, and a physical model of the movement of the photons per layer of the user-derived model.
- Lastly, *SHIELDOSE* is a default space radiation model used for both shielding and photon voltage analysis. In this research, *SHIELDOSE* was used as a comparison to my model in terms of testing under the same conditions. The model is made up of 26 aluminum layers that increase in thickness after each layer from 0.05mm to 20mm, which calculates to around a 23cm model in depth, over twice as thick as my largest thickness in all computational experiments.

The movement of major ionizing rays, along with electron and positron movement, within the system can be combined with similar data as a Monte Carlo distribution analysis of the percent ionization, entries, and other results via *GRAS*. With this program, the analysis of photon behavior in conjunction with the layers can be observed with the use of varying voltages and distributions onto the model (Figure 2: Depicts Photon Traversal).

6. VALIDATION

6.1 Ionizing Intensity-Based Thickness Calculations

In order to define specific thicknesses, the Linear Attenuation Shielding Formula is shown below:

$$I_F = I_S * e^{-\mu x}$$

This formula utilizes I_F (the final shielded dose) in comparison to I_S , the initial dose, and the logarithmic correlation of the layer-based linear attenuation coefficients (μ), considered as the fraction of photons interacting with a specific shielding medium, and can be found via online computational physics databanks, and "x", being the thickness. Knowing this, multiple photon energies can be displayed for varying layers with the altered formula below:

$$I_F = I_S(f_1 * e^{-\mu_1 x} + f_2 * e^{-\mu_2 x} \dots + f_z * e^{-\mu_z x})$$

Here, f_z describes the fraction of the initial dose that comes from each photon at the start of the layer which would be mathematically calculated as shown below.



$$f_z = \frac{e^z * n^z}{\sum_z e^z * e^z}$$

Taking this into account, the probability of emission factors for each atomic decay for each energetic level would have to be considered in order for the f_z value to be calculated. Through this, each value excluding x was calculated, and the mean of those thicknesses was rounded to the nearest quarter of a centimeter to provide for the conclusion of 3.5,

6.2 Monte Carlo Coordinate-Based Comparison via SPENVIS Calculations

Below is a modified version of the Boltzmann Transport Equation (BTE) that conveys the phase space, or all possible positions in a 2D area (p) and the momenta of the photon (m).

$$d^2p d^2m = dx dy dp_x dp_y$$

With this, the probability of a certain N molecule is calculated at a specified coordinate not including time as a factor. Specifically, each integral represents the momenta of the photon and a subsequent position.

$$N = \int d^2m \int d^2p f(p, m)$$

Then, since the 2-fold integral sets are defined for momenta and positions, respectively, they can be rewritten as shown below, creating a parameter list based on a 2 coordinate system for each point and 2 subsequent momentum components yielding to a 4D phase space.

$$N = \iiint \iiint f(x, y, m_x, m_y) dx dy dm_x dm_y$$

Within the code of the SPENVIS environment, this modified system, used to describe the statistical behavior of a dynamic kinetic system, such as the MeV value of a photon at the start and end of each layer, is equivalent in geometric perspective to the Boltzmann equation, thus supporting the validity of SPENVIS and Geant4 modular tools.

6.3 Overall Validity of Software

Further validity of SPENVIS and corresponding Geant4 programs:

- The use of the ESA's SHIELDOSE utilizes SPENVIS-based calculations to determine radiation exposure on this detector/shield for real-life ESA space probes.
- A 2015 study compared results between the SPENVIS software and PSTAR databases (officially created by the National Institute of Standards and Technology) by inducing an aluminum slab to a variety of protons ranging from 800 MeV to 1.2 GeV using both programs separately. From these tests, verification of SPENVIS and Geant4 was obtained, thus supporting the conjecture that all 280 computational experiments were valid.



7. CONCLUSION

Overall, the models experimented within this combined two-year research study supported my original objectives and engineering goals. To start, continuing from last year, my unique two-part base isolator, consisting of a laminated rubber bearing and high damping rubber bearing part connected via plastic compression spring shock absorbers, was able to resist over 50% of the inputted gravitational acceleration and decrease at a rapid pace as shown in Graph 1. Similarly, against the 1:50 scaled down Tohoku tsunami-earthquake, my model was able to self-stabilize shock, especially at larger (g) accelerations shown in Graph 3 with the PGA at 1g. Lastly, the model was able to resist all damage externally, including zero water absorption within the base system, and it was concluded that a panel sided conformation was able to better resist the hydrodynamic forces of the impending wave simulations. In regard to radiation testing, I was able to obtain data comparing how the angular distribution of photon waves contributes to the changed behavior of the photon-photon interaction within layered systems. To add, multiple levels of mono-energetic intensity was placed on the five particle types, thus allowing for a varying behavior of the rays within the model. Even with the original projections of the model to obtain at least a 95% energy reduction over the complete layered system or that greater than the SHIELDOSE model, both D1 and D2, according to the data presented in Graphs 4-7, had a combined energy reduction well over 99% from the initial incident particle MeV value. Lastly, this model was able to increase the amplitude of the photon waves through organized deflection throughout the system and subsequently prevented mass photon detection beyond the tested system, thus showing the viability of the model, in total, for a variety of uses (explained in Applications), while exposing the lack of viability of the SHIELDOSE model created by the European Space Agency in higher energy photon transmission experiments. Outside of the objectives, there were many instances of my data justifying my original theories. For example, in Diagrams 9, 11, and 20, the original hypothesis of the use of lithium-hydride, due to its low atomic number element composition, was able to deflect all neutron intrusion back onto the start of the system. In contrast, Diagrams 29 and 30 of the SHIELDOSE model allowed for an unexpected increase in MeV. In addition, SHIELDOSE was unable to stabilize the photon transmission of gamma rays as shown in Diagrams 27 and 28. In sum, both D1 and D2 supported conjectures regarding the usability of the models in comparison to SHIELDOSE, as a cheaper, thinner, and more effective radiation shield.

8. APPLICATIONS AND FUTURE DEVELOPMENT

With these results, this model can be used in a variety of scenarios for many fields where human safety from radiation is necessary as a better alternative to current radiation shielding methods. Specifically, I believe the following are viable future endeavors for this research:

- The construction of a complete disaster safe-house able to resist damage against earthquakes, tsunamis, and radiation exposure, along with more testing against scaled down hurricane and tornado simulations, for example.
- A fully functional body suit that can resist the damage of radiation exposure in more needed situations such as at nuclear reactor sites and in the pursuit toward being able to harness energy by more dangerous means, as exposure to those rays at a higher energy level could be contained.
- Implementation in spaceship hull material to be able to resist low-energy and intensity cosmic rays to further space research progression in total.
- The use of these cheaper materials to homes where radiation-prevention bunkers could be built and used effectively in the case of nuclear war or other means of radiation exposure.
- Protection of agriculture
- Usage in healthcare, specifically containing bismuth, for scanning and body imaging purposes, to allow for greater detail in discovering new methods of disease prevention and detection



In addition to the applications of this novel layered system, these models can be modified to serve other functions that directly correlate with radiation and disaster prevention in general. These include the following:

- Thermoregulation of model to allow for a more viable solution to radiation shielding, while preventing heat related damage to the system or to any living matter within.
- Increased porosity of the model, while keeping the price of the materials constant, which will allow for the following:
 - Decreased weight
 - Increased effectiveness of system in terms of photon shielding
 - Increased strength against external damage

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Student Researcher Mr. Daniel Noon at Brophy College Preparatory in Phoenix, Arizona. His field of interests are in high-energy physics and nuclear physics, and he has previously published work in the fields of applied physics and civil engineering.