e-ISSN: 2775-5894

Newton-Maxwell Journal of Physics

Journal Homepage https://www.ejournal.unib.ac.id/index.php/nmj

Evaluation of Cu, Fe, and Pb for Fast Neutron Shielding using Monte Carlo PHITS Simulation

Sitti Yani[1]

[1] Department of Physics, Faculty of Mathematics and Natural Sciences, IPB University, Indonesia

ARTICLE INFO

Article history:
Submitted: March 3, 2024
Revision: April 23, 2024
Accepted: April 24, 2024
Published: April 30, 2024

ABSTRACT

Developing effective neutron shielding materials for applications like muon tomography requires understanding the interaction of neutrons with different materials. This study investigates the effectiveness of heavy metals (Cu, Fe, and Pb) as neutron shields using Monte Carlo PHITS simulations with fast neutrons (0.1, 0.5, and 1 MeV). Simulation results show that the intensity of transmitted neutrons decreases with increasing material thickness and atomic number (Pb > Fe > Cu). How far a particle travels before stopping is determined by two factors: its initial neutron energy and how likely it is to interact with the material it's passing through. These findings provide valuable insights into designing optimal neutron shielding materials for various applications.

Keywords: Neutron shielding, Muon tomography, Monte Carlo simulation, PHITS, Heavy metals

1. INTRODUCTION

Muon tomography, also called muography, is a method for creating 2D or 3D images of large objects. It uses naturally occurring muons, tiny particles from space, and tracks how they bend as they pass through the object. This bending tells us about the object's density and internal structure. For small materials, these muons cannot be directly used due to their large energy. Therefore, in our previous research, the muon energy was reduced to obtain enough energy to image small objects [1-3]. However, the use of materials to reduce muon energy produces contaminant particles in the form of photons and neutrons that must be attenuated [4-5].

Neutrons are uncharged particles that have the ability to penetrate deeper into the material. They are mainly produced by nuclear fission and are not significantly influenced by electrical forces. Scientists categorize neutrons based on their energy levels: thermal (0.025 eV), slow (1 keV - 0.025 eV), moderate-energy (100 keV - 1 keV), fast (100 keV - 10 MeV), and high-energy (above 10 MeV) [6,7]. Materials used for neutron shielding typically have two functions: slowing down fast neutrons (moderation) and absorbing thermal neutrons. This combined effect reduces the number of neutrons passing through (transmission) and keeps radiation levels below safe limits [7-8].

The biggest challenge in creating neutron shielding materials lies in combining various ingredients to achieve optimal protection including heavy elements, light elements, and boron. Each plays a specific role in achieving the desired "synergy" (combined effect) needed to effectively shield against neutrons. The focus is on carefully planning and designing the composition of these materials to achieve optimal neutron protection [9-12]. Malidarre et al. 2018 investigated the ability of Alumino-Boro-Silicate (ABS) glasses to shield against neutrons and gamma rays. They used a combination of MCNPX simulation and theoretical calculations to estimate the material's attenuation characteristics for these types of radiation [13]. Some heavy metals such as Pb, Fe, and W combined with other materials are used as neutron radiation shielding that are studied simulation, theoretically and experimentally [7, 9-12, 14].

In this research, a study of neutron radiation shielding using heavy metals such as Cu, Fe and Pb was conducted through Monte Carlo PHITS simulation. These metals are commonly employed to attenuate radiation. This study uses fast neutrons with energies of 0.1, 0.5, and 1 MeV.

2. METHOD

2.1 PHITS

Particle and Heavy Ion Transport System (PHITS) is a powerful and versatile Monte Carlo simulation code used for modeling the transport of various particles and heavy ions across a wide range of energies. PHITS can be used in the medical, nuclear and space exploration fields. Design effective shielding around particle accelerators and radiotherapy treatment planning can use this PHITS code. This code can be also used to simulate designing protection for astronauts and equipment and exploring the space radiation. PHITS used backend scripting method to design input, proses, and output of simulation so it is friendly to users who do not have a specific programming language background. The creation of PHITS involved a joint effort by JAEA, RIST, KEK, and various other organizations [15].

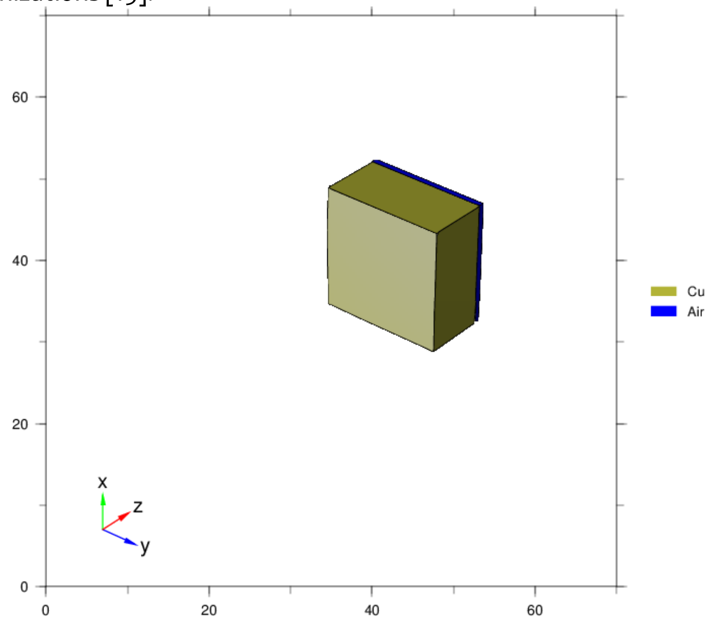

Figure 1. 3D-Show of the simulation geometry

2.2 Simulation Set-up

The sources used are fast neutrons with energies of 0.1, 0.5 and 1 MeV. The source is not set isotropic but directly fired towards the shield which is 10 cm away. Neutron radiation shielding using heavy metal namely Fe (Z=26), Cu (Z=29), and Pb (Z=82) with thickness 10 cm. A 1 cm thick air-filled virtual detector is placed after the shielding material that can record any particles that pass through it (neutrons coming from the source and other secondary particles) and the energy of these particles. Figure 1 above show the 3D-show of shielding material-Cu (camel) and virtual detector (blue). The icntl=11 was applied to show Figure 1 to make sure the geometry and there is no overlapping geometry.

3. RESULTS AND DISCUSSION

3.1 Particle Trajectory

The graphs in Figure 2 depict how the trajectory of a particle is influenced by its energy and the type of particle (neutron vs photon) when traveling through a Cu shielding material. The x-axis represents the distance traveled by the particle in centimeters (cm). The z-axis represents the position of the particle in centimeters (cm). There are two graphs, one for neutrons (left) and one for photons (right). Each graph shows the particle track for three different energy levels (0.1 MeV, 0.5 MeV, and 1 MeV). The neutron tracks appear relatively straight, with minimal deflection regardless of the energy level. This suggests that the neutrons are not significantly interacting with the copper atoms in the shielding material. The photon tracks show more deflection compared to neutrons, particularly at lower energies (0.1 MeV and 0.5 MeV). This indicates that photons are more likely to interact with the copper atoms through processes like Compton scattering or photoelectric absorption. As the energy of the photons increases (1 MeV), the deflection appears less pronounced. The actual distance the particle travels before stopping depends on its energy and interaction cross-section with the material.

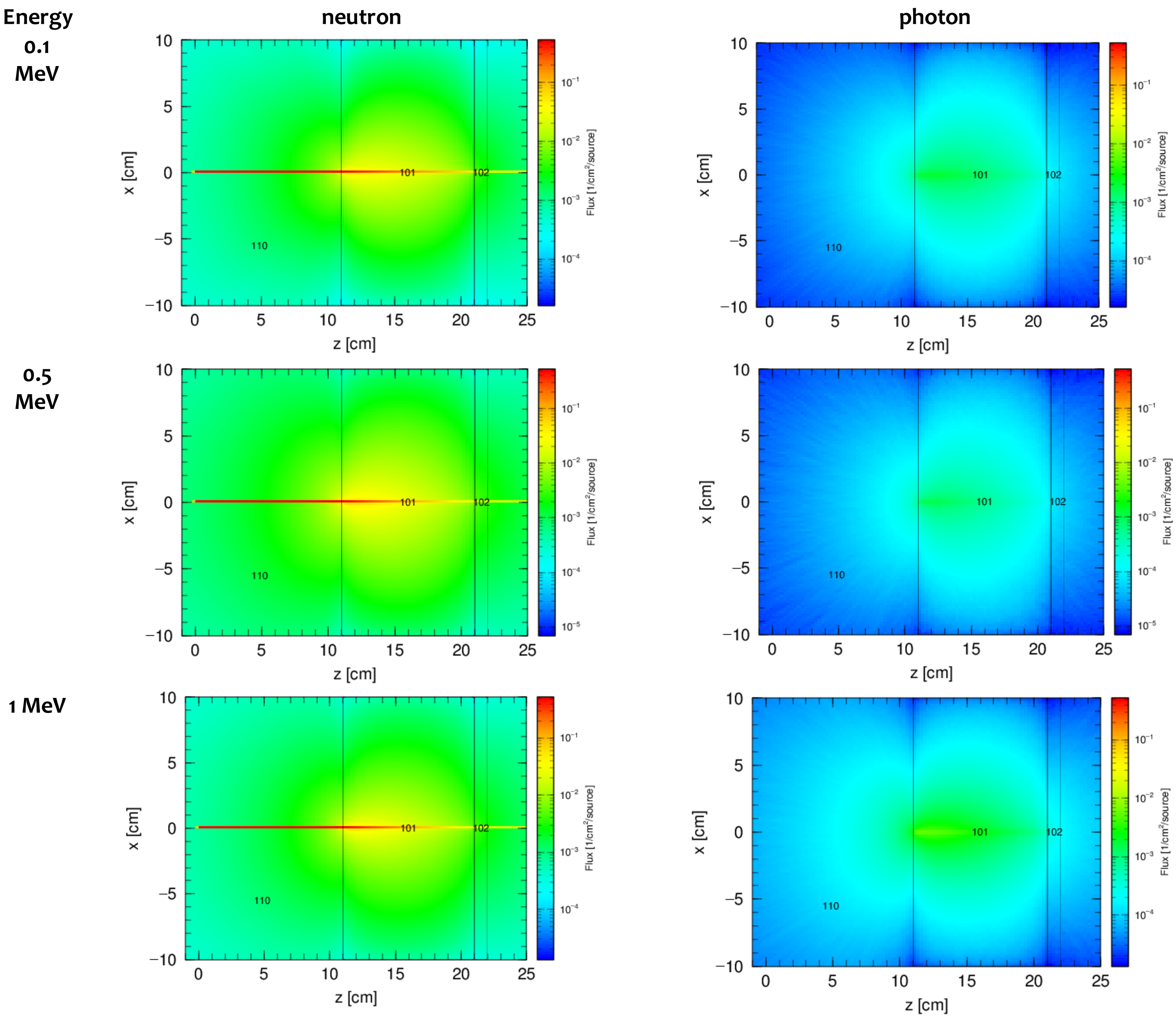

Figure 2. Particle track in Cu shielding material with varied energy

Figure 3 shows the intensity of a neutron source emitting 1 MeV neutrons traveling through different materials: iron (Fe), copper (Cu), and lead (Pb). The y-axis represents the depth (z) in centimeters (cm) the neutrons traveled into the material, and the y-axis represents the relative intensity (arbitrary units) of the neutrons. The graph shows that the intensity of the neutrons decreases as they travel deeper into the material. This is because the neutrons interact with the atoms in the material, and some neutrons are absorbed or scattered in different directions as they travel. The rate of decrease in intensity depends on the material's properties and the energy of the neutrons. For instance, lead (Pb) is a more effective neutron shield than iron (Fe) or copper (Cu) because lead has a higher probability of absorbing neutrons.

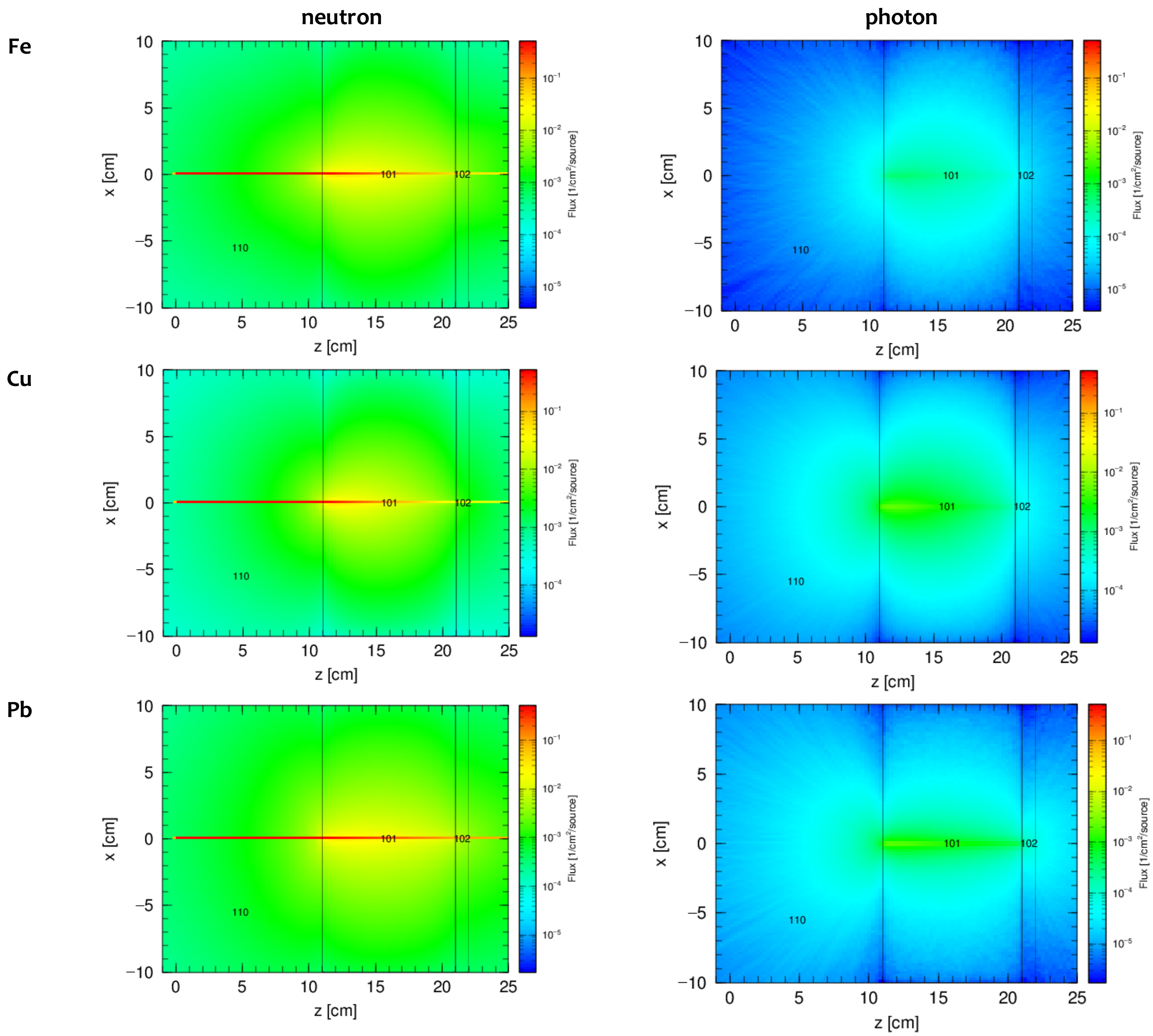

Figure 3. Particle track of 1 MeV neutron source in Fe, Cu, and Pb shielding material

In addition to neutrons, the detector also detects a large number of photon particles, especially at the center of the beam (Figures 2 and 3). These photons are secondary particles resulting from the interaction of neutrons with matter through inelastic scattering and neutron (thermal) capture that can produce photons. The largest photon energy is produced by the secondary neutron interaction with Cu with an initial neutron energy of 1 MeV. This is because the fast neutrons produced by the source are much attenuated and lose their energy into thermal neutrons which results in many thermal neutron interactions.

3.2 Particle Spectrum

The figure 4 is a graph showing the intensity of a neutron flux from a 1 MeV neutron source. The x-axis of the graph shows the energy of the neutrons in MeV. The y-axis shows the intensity of the neutron flux labeled "a.u." refers to "arbitrary units". This means that the actual number of neutrons is not directly indicated on the y-axis, but rather the relative intensity compared to other values in the graph. Neutrons of 1 MeV from the source undergo scattering and absorption which causes neutrons to change direction and energy. However, the neutron flux that reaches the detector is mostly 1 MeV neutrons. This means that these neutrons do not undergo any process when passing through the shielding material. This peak indicates that most neutrons haven't lost energy after being emitted. The intensity decreases on either side of the peak, which suggests that some neutrons lose energy through collisions with other atoms (a process called moderation) while others gain energy through scattering processes. The presence of shielding material: copper (Cu), iron (Fe), and lead (Pb) on the graph indicates that the neutrons are passing through a material composed of these elements. Different elements can affect the neutron flux in various ways, such as by absorbing neutrons or scattering them with different probabilities. This result is confirmed by the Cu, Fe, and Pb cross section data at a neutron energy of 1.0 MeV of 0.007, 0.002, and 0.001 mbarns, respectively (https://www-nds.iaea.org/ngatlas2/). Cu material has the largest cross section data for energy 0.1, 0.5, and 1.0 MeV.

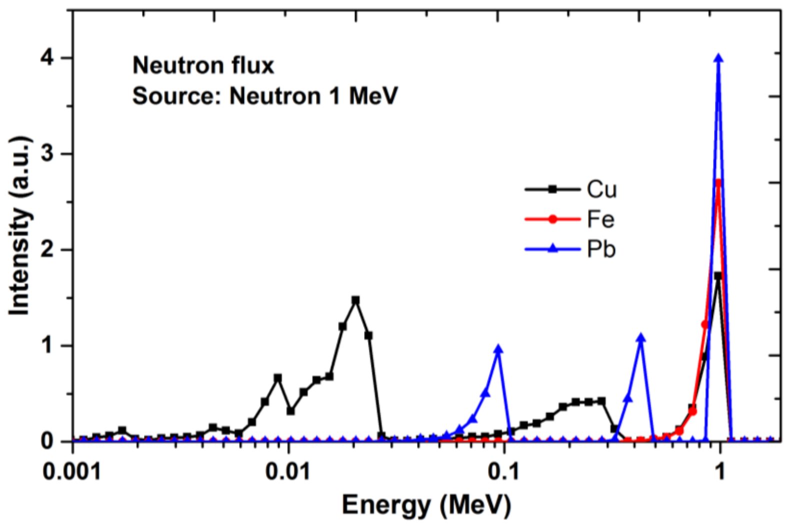

Figure 4. Spectrum of particles crossed the Cu, Fe and Pb shielding material

4. CONCLUSION

This study investigated how particle trajectory and intensity are affected by energy and particle type (neutrons vs photons) in different shielding materials (copper, iron, lead). Neutrons penetrated deeper with minimal deflection, suggesting weak interaction with the materials. Photons interacted more, showing deflection, especially at lower energies. Lead proved most effective at stopping neutrons, while all materials showed a decrease in neutron intensity with depth due to absorption and scattering. Meanwhile, Cu is better at attenuating neutrons than other metals for all simulated neutron types.

5. ACKNOWLEDGEMENT

This study was fully supported by Penelitian Dosen Muda IPB University in 2024.

6. REFERENCES

[1] R. Kaiser, “Muography: overview and future directions,” Phil. Trans. R. Soc. A. 2018 https://doi.org/10.1098/rsta.2018.0049.

[2] L. Oláh, H.K. Tanaka, T. Ohminato, and V. Dezső, V, “High-definition and low-noise muography of the Sakurajima volcano with gaseous tracking detectors,” Scientific Reports, 2018 https://doi.org/10.1038/s41598-018-21423-9.

[3] R. Nishiyama, A. Taketa, S. Miyamoto, and K. Kasahara, “Monte Carlo simulation for background study of geophysical inspection with cosmic-ray muons,” Geophysical Journal International, pp. 1039–1050, 2016 https://doi.org/10.1093/gji/ggw191.

[4] S. Yani, D. Hidayatuloh, and T. Sumaryada, “The Effect of Shielding Material Density in Muography, “ Jurnal Fisika Flux, vol. 20, no. 3, pp. 217-222, 2023 http://dx.doi.org/10.20527/flux.v20i3.16809.

[5] S. Yani, D. Hidayatuloh, and T. Sumaryada, “Analysis of secondary particles produced by muon and water interaction, “ Jurnal Ilmu Fisika, vol. 16, no. 1, pp. 217-222, March 2024 https://doi.org/10.25077/jif.16.1.63-70.2024.

[6] A. A. A. Abuhoza, “Comparison study of reflected and transmitted thermal neutron flux in water and other moderators,” Thesis, King Saud University, Riyadh, Kingdom of Saudi Arabia, 2007.

[7] X. Fu, Z. Ji, W. Lin, Y. Yu, and T. Wu,” The Advancement of Neutron Shielding Materials for the Storage of Spent Nuclear Fuel,” Science and Technology of Nuclear Installations, vol. 2021, 2021 https://doi.org/10.1155/2021/5541047.

[8] E. Mansouri, A. Mesbahi, R. Malekzadeh, A. Ghasemi Janghjoo, and M. Okutan, "A review on neutron shielding performance of nano-composite materials," Int J Radiat Res, vol. 18, no. 4, pp. 611-622, 2020.

[9] D. Zhao, W. Jia, D. Hei, C. Cheng, J. Li, P. Cai, and Y. Chen, "Design of a neutron shielding performance test system base on Am–Be neutron source," Radiation Physics and Chemistry, vol. 193, 2022 https://doi.org/10.1016/j.radphyschem.2021.109954.

[10] K. Wang, L. Ma, C. Yang, Z. Bian, D. Zhang, S. Cui, M. Wang, Z. Chen, and X. Li, "Recent Progress in Gd-Containing Materials for Neutron Shielding Applications: A Review," Materials (Basel), vol.10, no. 16(12), p. 4305, 2023 June https://doi.org/10.3390/ma16124305.

[11] J. Saenpoowa, C. Ruksakulpiwat, C. Yenchai, and C. Kobdaj, "Fabrication and development of neutron shielding materials based on natural rubber and boron carbide," Journal of Physics: Conference Series, vol. 2431, 2022 https://doi.org/10.1088/1742-6596/2431/1/012079.

[12] C. Jumpee and D. Wongsawaeng, " Innovative neutron shielding materials composed of natural rubber-styrene butadiene rubber blends, boron oxide and iron(III) oxide," Journal of Physics: Conference Series, vol. 611, 2015 https://doi.org/10.1088/1742-6596/611/1/012019.

[13] R. B. Malidarre, I. Akkurt, and T. Kavas, "Monte Carlo simulation on shielding properties of neutron-gamma from $_{252}$Cf source for Alumino-Boro-Silicate glasses," Radiation Physics and Chemistry, vol. 186, 2021 https://doi.org/10.1016/j.radphyschem.2021.109540.

[14] J. S. Alzahrani, Z.A. Alrowaili, C. Eke, Z. M. M. Mahmoud, C. Mutuwong, and M.S. Al-Buriahi, "Nuclear shielding properties of Ni-, Fe-, Pb-, and W-based alloys, Radiation Physics and Chemistry, vol. 195, 2022 https://doi.org/10.1016/j.radphyschem.2022.110090.

[15] K. Niita, T. Sato, H. Iwase, H. Nose, H. Nakashima, and L. Sihver, "PHITS—a particle and heavy ion transport code system," Radiation Measurements, pp. 1080-1090, 2006 https://doi.org/10.1016/j.radmeas.2006.07.013.