Calculated-Experimental Model for Multilayer Shield

Maan S. Al-Arif[1] and Diyaree O. Kakil[2]

[1]School of Medicine, Koya University
Danielle Mitterrand Boulevard, Koya KOY45, Kurdistan Region of F.R. Iraq

[2]Department of Physics, Koya University
Danielle Mitterrand Boulevard, Koya KOY45, Kurdistan Region of F.R. Iraq

Abstract—The effective linear attenuation coefficients and build-up factors for single shield of *Al, Fe, Pb*, and for multi-layer shield of *Al-Pb, Al-Fe, Fe-Pb, Al-Fe-Pb* as a function of shield thickness, atomic number, and order of the materials composing the shield are investigated for two photon energies of 0.662 MeV and 1.25 MeV. Two derived practical formulas to calculate the effective attenuation coefficient and build-up factor for multilayer shields are used. It is noticed that changing the order of the materials among the shield has no significant effect on the experimental result. Measurement agrees well with the trend of the suggested formulas for calculating the effective attenuation coefficient and the buildup factor. The linear attenuation coefficient is observed to have a strange dependency with the atomic number and photon energy. For single layer shield, the attenuation coefficient increases with decreasing atomic number at low photon energy and increasing with increasing atomic number at high photon energy.

Index Terms—Attenuation coefficient, build-up factors, multilayer shields, radiation dose.

I. INTRODUCTION

The use of gamma rays in medicine, surgery, industry, research and agriculture, made human subject to dangerous diseases. The lack of knowledge in radiation protection principles among which is the use of proper shielding materials increases this risk. In radiation protection, photon build-up factors, and attenuation coefficient, provide convenient information for calculating dose and exposure response after various shielding configurations. Since gamma rays are very penetrating radiation, selection of shielding materials becomes most important in many cases such as in nuclear accidents, nuclear reactors, research laboratories, in medical institutions, and in high space. People involved in those places may be victims to gamma ray exposure. Moreover, on 2009, NASA has identified the need for developing advanced radiation-shielding materials and structures to protect humans from the hazards of galactic cosmic radiation during lunar missions (NASA, Proposal Number: 09-1X4.01-8309, Sub-topic X4.01, NASA SBIR 2009 Solicitation). NASA proposed to develop lightweight, multi-layered shield with an outer layer of hydrogenous polymeric material. This shield is designed and fabrication of materials tailored to shield against hazardous radiation.

Mathematically methods to solve the problem for multilayer shield may be divided in two groups: the semi-empirical methods based on the use of experimental or theoretical data and method uses low order approximation of the transport equation and Monte Carlo program (Nelson,, Hirayama and Rogers, 1985). However, the relatively accurate solution of the gamma radiation transport equations is realized only for the simple geometrical configurations.

Buildup factor, which is important in calculating radiation shielding and absorbed dose, have been widely studied by various research groups (Shin, and Hirayama, 2001; Alamatsaz, and Shirani, 2002; Saudi, 2013). However, the variation of the buildup factor with penetration distance in multi-layered shield differs from that in homogenous media (Balwinder, et al., 2013). This variation depends on attenuation, buildup factor, and thickness for both penetrated layers.

In this research, experimental measurement for the buildup factor and attenuation coefficient for single and multi-layer shields at *Cs-137* and *Co-60* gamma energies will be carried out. The experimental result will be used to derive a practical formula for calculating the effective buildup factor and attenuation coefficient for multilayer shields. We believe that in practice the design of multi-layer shield for any purposes need a simple method of calculation with good accuracy.

II. THE EXPERIMENTAL MODEL

In practice, broad beam geometry must be considered. The quantity of radiation transmitted through the shield, I, is given by;

$$I = BI_0 e^{-\mu x} \tag{1}$$

Where; I_0 is the incident intensity, exp $(-\mu x)$ is the attenuation factor and B is the buildup factor.

In the present work, three-layer shield geometry will be assumed as in Fig. 1. Photon beam with intensity, I_0, is assumed to be incident perpendicularly on the plane of the shield.

The intensity of the beam entering the second, third layer, and that leaving the third layer of the shield is given by;

$$I_1 = I_0 B_1 e^{-\mu_1 x_1} \tag{2}$$

$$I_2 = I_1 B_2 e^{-\mu_2 x_2} \tag{3}$$

$$I_3 = I_2 B_3 e^{-\mu_3 x_3} \tag{4}$$

Substitute (I_1 and I_2) from (2) and (3) into (4), and rearrange the equation, we get;

$$\therefore \quad I_3 = I_0 \ (B_1 B_2 B_3) \ e^{-(\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3)} \tag{5}$$

If we consider the shield as one unit, we can say;

$$I_3 = I_0 B_{eff} \ e^{-\mu_{eff} \ x_{tot}} \tag{6}$$

From (5) and (6), we get;

$$B_{eff} = B_1 B_2 B_3 \tag{7}$$

and

$$\mu_{eff} = \frac{\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3}{x_{ToT}} \tag{8}$$

The present work aims to verify experimentally the validity of (7) and (8) by measuring μ_1, μ_2, μ_3, B_1, B_2 and B_3. The results obtained will then be used to calculate the effective buildup and attenuation coefficient for different multi-layer shields.

III. MATERIAL AND METHODS

The attenuation coefficient for single and multi-layered shields is carried out by using the narrow beam geometry shown in Fig. 2. The photon beam is directed perpendicular to plane of the shield. Measurements of the attenuation coefficient are carried out for three single elements of *Al, Fe, Pb*, and for four multi-layer shield combinations of *Al-Pb, Al-Fe, Fe-Pb*, and *Al-Fe-Pb* are carried out. The effect of reversing the order of the materials among the shield is also investigated.

The Attenuation coefficients were measured using NaI (TI) scintillation detector connected to a multi-channel analyzer (MCA), having energy resolution of 12.5 % at 662 keV. Plane radioactive sources of Co^{60} and Cs^{137} with activities of $5 \mu Ci$,

$1 \mu Ci$, and effective photon energy of 0.662 MeV, 1.25 MeV are considered for the sources respectively.
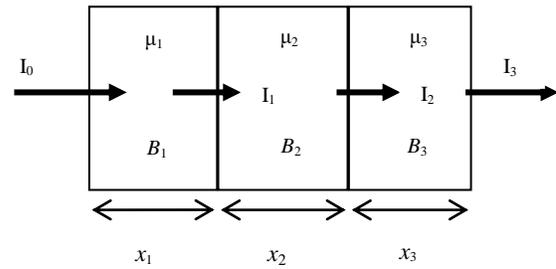
Fig. 1. The multi-layer shield geometry.
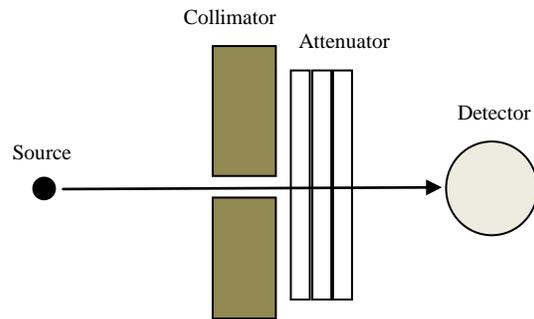
Fig. 2. The irradiation geometry

A broad beam and narrow beam geometries are used in measuring the buildup factor. The broad beam geometry is achieved by removing the collimator in front of the attenuator in Fig. 2. The build-up factor can be deduced experimentally as the ratio of the transmitted beam intensity from a broad beam geometry, $T`$, to that transmitted from a narrow beam geometry, T, and is given by;

$$B = \frac{T`}{T} = \frac{B e^{-\mu x}}{e^{-\mu x}} \tag{9}$$

Measurements for the buildup factor are carried out for three single elements of *Al, Fe, Pb*, and for three multi-layer shield combinations of *Al-Pb, Al-Fe, Fe-Pb* at 0.662 MeV and 1.25 MeV photon energies. The effect of changing the order of the materials among the shield is also investigated in this study.

IV. RESULT AND DISCUSSION

A. The Effective Attenuation Coefficient

Measurement for the linear attenuation coefficient for single element of Al, Fe, and Pb at 0.662 MeV and 1.25 MeV are carried out using narrow beam geometry and the result are shown in Fig. 3 and Fig. 4.

The experimental result for the linear attenuation coefficients for the three single elements and that calculated by (Hubbel and Berger, 1987; Hubbell and Seltzer, 1996) are

shown in Table I. The calculated values appear to be overestimating the experimental results.
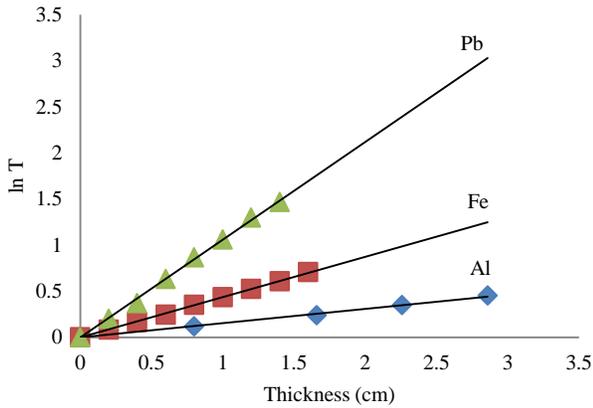
Fig. 3. The attenuation factor for *Al*, *Fe*, and *Pb* as a function shield thickness at 0.662 MeV
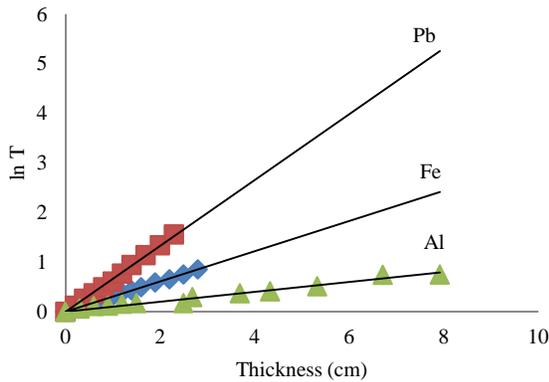
Fig. 4. The attenuation factor for *Al*, *Fe*, and *Pb* as a function shield thickness at 1.25 MeV

The measured attenuation coefficients for three multi-layer shields of Al-Fe, Al-Pb, and Fe-Pb at 0.662 MeV is shown in Fig. 5.
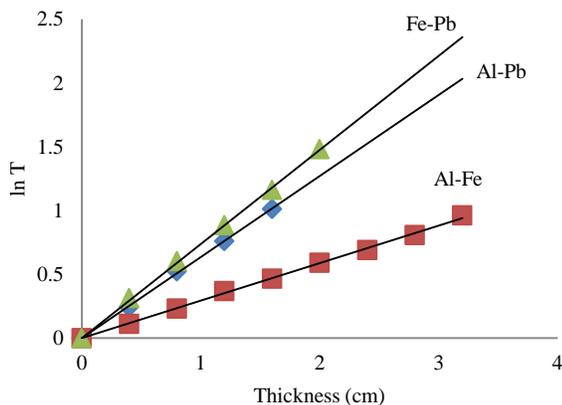
Fig. 5. The attenuation factor for *Al-Fe*, *Fe-Pb*, and *Al-Pb* shields as a function of shield thickness at 0.662 MeV.

The measured linear attenuation coefficients for single layer shields are then used to calculate the effective linear attenuation coefficient for the three multi-layer shield at 0.662 MeV using (8). Table II shows the calculated effective attenuation coefficient and the measured values for different multi-layer shield combinations. A good agreement between them is recorded. No significant effect for changing the order of the material of the shields is observed.

TABLE I
THE EXPERIMENTAL AND CALCULATED LINEAR ATTENUATION COEFFICIENT
(CM^{-1})

| Shield | 0.662 MeV | | 1.25 MeV | |
	Experimental	Calculated	Experimental	Calculated
Al	0.154	0.2003	0.0995	0.1482
Fe	0.437	0.578	0.3046	0.4793
Pb	1.059	1.322	0.6636	0.6418

TABLE II
THE EXPERIMENTAL AND CALCULATED LINEAR ATTENUATION COEFFICIENT
(CM^{-1}) AT 0.662 MEV

Shield	Calculated	Experimental	% error
Al-Pb	0.608	0.635	4.4
Al-Fe	0.296	0.294	0.6
Fe-Pb	0.749	0.737	2.9

The validity of (8) for the multi-layer shield of *Al-Fe-Pb* is also checked at 0.662 MeV and 1.25 MeV photon energies and the result is shown in Fig. 6. It is clear from our result that no significant effect for changing the order of the material of the shield had been seen.
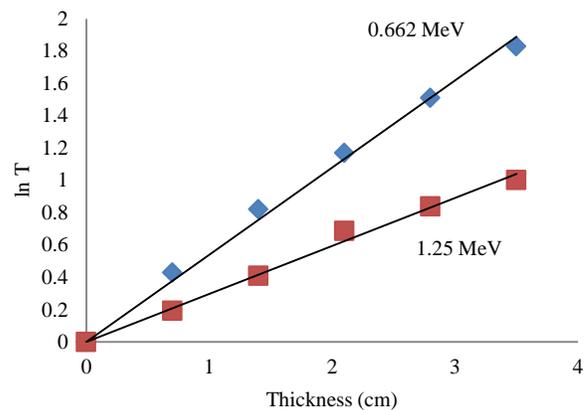
Fig. 6. The attenuation factor for *Al-Fe-Pb* shield as a function of shield thickness at 0.662 MeV and 1.25 MeV.

Table III shows the measured and calculated attenuation coefficient for Al-Fe-Pb shield at 0.662 MeV and 1.25 MeV. The experimental result is in a good agreement with that calculated by using (8).

Shield	0.662 MeV			1.25 MeV		
	Experimental	Calculated	% error	Experimental	Calculated	% error
Al-Fe-Pb	0.5395	0.4947	9	0.2971	0.3192	5.9

B. The Build-up factor

The build-up factors, B, as a function of thickness in units of mean free path (*m.f.p*) for single elements of *Al, Fe*, and *Pb* are measured using a broad and narrow beam geometries at 0.662 MeV and 1.25 MeV, and are shown in Fig. 7 and Fig. 8.
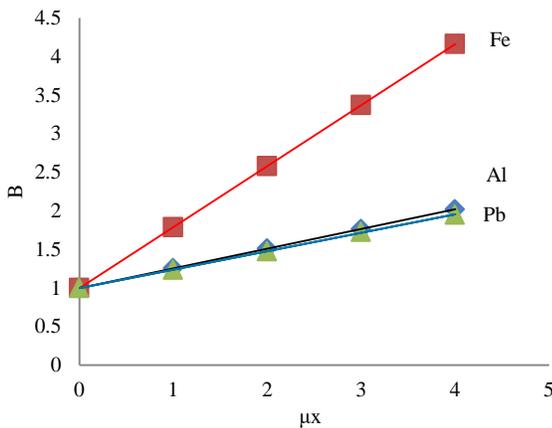
Fig. 7. The build-up factor for single layer shield as a function of shield thickness at 0.662 MeV
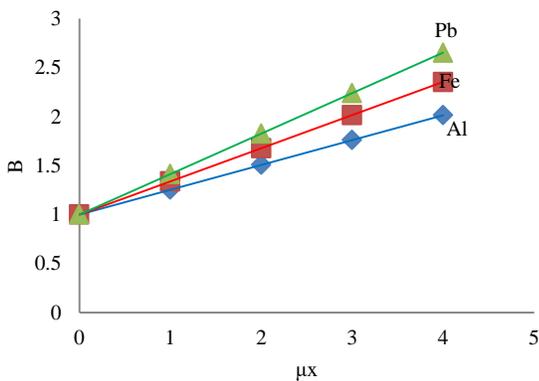
Fig. 8. The build-up factor for single layer shield as a function of shield thickness at 1.25 MeV.

We can see from Fig. 7 and Fig. 8 that the build-up factor at 1.25 MeV increases with shield thickness and with the atomic number of the shield material, while at 0.662 MeV, the build-

up factor for *Al* is lower than that for *Fe* and become very close to that for *Pb*. This agrees well with other findings of some researchers (Abdulfattah, 2010; Al-Baiti, 2010; Jasbir, Barjinderpal and Gurdeep, 2012). They noticed that the build-up factor has a strange dependency with the atomic number and photon energy, increasing as atomic number decreasing at low energy and increasing with increasing atomic number at high energy.

The experimental values of build-up factor for single layer shields are then used to calculate the effective build-up factor for multi-layer shields of *Al-Pb*, *Al-Fe*, and *Fe-Pb*, according to (7) for 0.662 MeV and 1.25 MeV. The calculated and measured values are shown in Table IV. No significant effect for changing the order of the material in the shield is observed with the exception of the case for *Fe-Pb* and *Pb-Fe* shields where the % error increases to about 8 % at 0.662 MeV and 12 % at 1.25 MeV. The experimental measurements are in a good agreement with calculated values.

Shield	Thickness (cm)	0.662 MeV			1.25 MeV		
		Exp	Calculated	% error	Exp	Calculated	% error
Al – Pb	2 – 2	1.465	1.508	2.8	1.734	1.665	4.1
Pb – Al	2 – 2	1.408		6.6	1.678		0.7
Fe – Al	2 – 2	1.489	1.553	4.1	1.387	1.391	0.2
Al – Fe	2 – 2	1.557		0.2	1.455		4.2
Pb – Fe	2 – 2	2.081	2.013	3.3	2.037	2.004	1.6
Fe – Pb	2 – 2	1.847		8.0	1.76		12.1

V. CONCLUSION

It was shown that (7) is in a good agreement with the experimental results for both radiation qualities investigated in this research. It indicates that the effective attenuation coefficient for multi-layer shield is the sum of the fractional thickness multiplied by the attenuation coefficient of the materials composing the shield. No significant effect for changing the order of the materials of the shield on the measured effective attenuation coefficient is recorded.

It was also shown that (8) is in a good agreement with the experimental results for the radiation qualities investigated. It indicates that the effective build-up factor is the product of the build-up factor of the materials consist the shield. No significant effect for changing the order of the material of the shield on the measured build-up factor is observed. A strange dependency of the linear attenuation coefficient on the atomic number and photon energy is observed. It was observed that the attenuation coefficient for single elements increases with decreasing atomic number at low energy and increasing with increasing atomic number at high energy.

This paper concludes that (7) and (8) are simple, having a good accuracy and can be used to design a multi-layer shield of similar geometry used in this research.

REFERENCES

Al-Baiti, K.O., 2010. Calculation of Dose Gamma Ray Buildup Factor up to Thickness of 20 *mfp* using Taylor's Method. *Journal of Kufa University-Physics,* (2)2, pp.33-41.

Alamatsaz, M.H. and Shirani, A., 2002. A study of gamma exposure buildup factors in stratified shields for point isotropic sources, including the effectives of incoherent and coherent scattering. *Journal of science, Islamic republic of Iran,* (3)13, pp.271-279.

Abdulfattah, A.A., 2010. Effect of exposure buildup factors on reactor shielding. *Journal of Al-Nahrain University,* (1)13, pp.78-83.

Balwinder, S., Vipan, K., Sukhwinder, S., Gurdeep, S.S., 2013. Investigations of mass attenuation coefficient and energy absorption buildup factor of some low-Z gamma ray shielding materials. *International Journal of Latest Research in Science and Technology*, (5)2, pp.73-77.

Hubbel, J.H. and Berger, M.J., 1987. Photon cross sections, attenuation coefficients, and energy absorption coefficients from 10 keV to 100 MeV. *National Bureau of Standards report NSRDS-NSB29,* pp.3597-3598.

Hubbell, J.H. and Seltzer, S. M., 1996. Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients from 1 keV to 20 MeV for Elements $Z = 1$ to 92 and 48 Additional Substances of dosimetric interest. *Radiation and Biomolecular Physics Division, PML, NIST.*

Jasbir, S.D., Barjinderpal S. and Gurdeep S.S., 2012. Gamma Ray Photon Energy Absorption Buildup Factor Study In Some Soils. *IOSR Journal of Applied Physics (IOSRJAP), (*6)1, pp.14-21.

Shin, K. and Hirayama, H., 2001. Calculation of gamma-ray buildup factors for two-layered shields made of water, concrete and iron and application of approximating formula. *Radiation Physics and Chemistry,* 61(3), pp.583–584.

Nelson, W.R., Hirayama, H. and Rogers, D.W.O, 1985. "The EGS4 code system" SLAC-265, Stanford Linear Accelerator Center, Stanford, California.

Saudi, H. A., 2013. Lead Phosphate Glass containing Boron and Lithium Oxides as a shielding material for Neutron and Gamma Radiation. *Applied Mathematics and Physics,* (4)1, pp.143-146.