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RESEARCH ARTICLE

NUMERICAL BUILDUP FACTOR CALCULATION OF GAMMA RAYS FOR SINGLE, DUAL, AND MULTI-LAYERS SHIELDS USING LEAD AND ALUMINUM

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ABSTRACT

In this research, Geiger-Muller counter tube detector (Type ABG, hi-energy), have been used together with cobalt-60 radioactive gamma source to calculate buildup factor using lead and aluminum materials.

Effect of material atomic number and thickness of the shield material on buildup factor value of gamma rays has been studied.

Five types of shields were studied as follow:

- Two single-layer shields of both lead and aluminum.
- Two dual-layers shields composed of (Pb-Al) and (Al-Pb)
- Multi-layers shield (Pb-Al) have been used which composed of successive layers of lead and aluminum, respectively, with thickness of (0.5cm) for each layer.

The study showed that the buildup factor value increases with decreasing the atomic number of the shield material. While buildup factor values of the dual-layers shields ((Pb-Al) & (Al-Pb)) and multi-layers shield (Pb-Al) are found to be smaller than the buildup factor values of lead shield. Also it is found that the dual-layers shield (Al-Pb) give the best results in this work where it gives smaller and acceptable buildup factor.

INTRODUCTION

It is important always to develop kind of shielding to attenuate gamma ray especially when gamma source used in some field of technology. Moreover, it is important also to calculate the buildup factor of any shielding design in order to determining the efficiency of the material used for this purpose.

The buildup factor have been studied and calculated by many researchers for a lot of material to determine the possibility of their use as shields against gamma rays emitted by radioactive sources used in a lot of research and industrial fields, among these materials are lead and aluminum.

It is important also to study the possibility of the using of many materials as multilayer shields composition to have best design with good attenuation and small buildup factor.

In 1994, K.H. Al Attiah [1] conducted a study of measure the buildup factor of gamma rays emitted from Cesium-137 and Cobalt-60 using the shields of aluminum, brass, lead, iron, concrete, and copper. The study proved that the buildup factor increases with the shield thickness increasing and decreasing of the atomic number of shield material and decreasing of the radioactive source energy. In 2001 K. Albeity [2] has studied experimentally and theoretically the buildup factor of gamma rays through the shields of single and multi-layers, the experimental study contained measuring of buildup factor of gamma rays emitted from Cs-137 and Co-60. It is found that the buildup factor increases with thickness increasing and decreases with radioactive source energy increasing and decreasing of the atomic number of shield material.

In 2009, H. Alaa [3] submitted a computational studying for gamma rays buildup factor for multi-layers slab shields using Monte Carlo method for Lead and water using Cs-137 and Co-60 radioactive sources, this study has shown that the buildup factor increases with increasing with the increasing of shield thickness.

Theoretical foundation

The gamma ray emitted from a lot of radioactive nuclei is one of the types of electromagnetic radiation. This kind of radiation has short wavelength and interact with the material in several ways. The most important are the

1. photoelectric effect,
2. Compton scattering,
3. Pair production and annihilation.

The diversity of interaction ways of gamma rays with material lead to a dwindling exponential relationship of attenuation:

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$$I = I_o \exp(-\mu x) \qquad (1)$$

Where:

I - gamma rays intensity passing through thickness x of the shield material.
I_o - Incident gamma rays intensity without shield material.
μ - linear gamma attenuation coefficient.
x - thickness of shield.

The above equation is valid only in case of narrow beam and are collimated in a small angle so that the photons reaching the detector is only the non-interactive photons (Figure (1-a)) [4]. But in the case of wide beam setting, as shown in **Figure (1-b)**, both non-interacting and some of the interacting photons may reach the detector again, thereby causing an increase in the counting rate as compared with the results of calculation of **equation 1** shown above. The difference in results between these two types of experimental setting is called buildup factor.

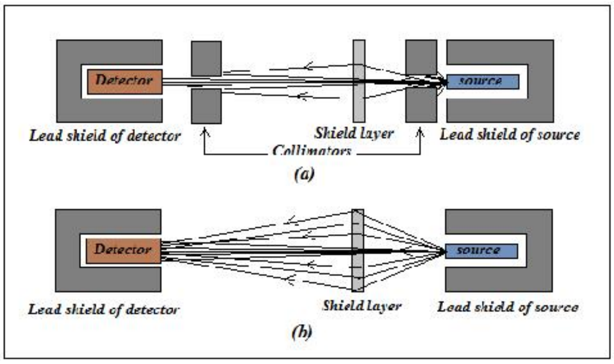

Figure 1 (a) Narrow beam **(**good geometrical arrangement**),**
(b) Wide beam (bad geometrical arrangement**).**

Total beam intensity (**$I_{tot.}$**) that reached to the detector is given by the following **[5]**:

$$I_{tot.} = I_s + I_u \qquad (2)$$

Where:
I_s - Interacting (scattered) beam intensity that reach the detector.
I_u - non interacting (uncollided) beam intensity that reach the detector.

And the total beam intensity can be written as:

$$I_{tot.} = B\, I_u \qquad (3)$$

Where the buildup factor (**B**) represents as described from previous equation as:

$$B = 1 + (I_s / I_u) \qquad (4)$$

The influential quantity may means the number of photons, fallen power, or absorbed dose, in case of number of photons called the numerical buildup factor.

Buildup factor (**B**) may calculated from the following equation **[2]**:

$$B = (I / I_o)_b \,/\, (I / I_o)_g \qquad (5)$$

Where:

$(I / I_o)_b$ - The intensity ratio of the total beam with existence of collimator (good geometrical arrangement).

$(I / I_o)_g$ - The intensity ratio of the total beam without existence of collimator (bad geometrical arrangement). Moreover, equation (5) can be written as follow:

$$\ln B = \ln(I / I_o)_b - \ln(I / I_o)_g \qquad (6)$$

The exponential relationship of equation (1) shows a lack of a specific range of gamma radiation inside the material, so a concept of mean free path is appeared which represents the average distance between two successive photon interactions and is given by the following relation [5]:

$$\lambda(cm) = \frac{\int_0^\infty x e^{-\mu x} dx}{\int_0^\infty e^{-\mu x} dx} = \frac{1}{\mu} \qquad (7)$$

And the material thickness in mfp unites is given by the following relation:

$$x\,(mfp) = \frac{x\,(cm)}{\lambda\,(cm)} = \mu x \qquad (8)$$

The value (**μx**) is also called the penetration depth of the gamma radiation in shielding material.

In addition to that, standard statistical deviation and fractional statistical deviation can be calculation from the follow equation [2]:

$$S.D = B\,[(1/I_g)+(1/I_{ob})]^{1/2} \qquad (9)$$

$$F.S.D = \frac{S.D}{B} \times 100\% \qquad (10)$$

Where:
S.D - standard of statistical deviation.
F.S.D - fractional statistical deviation**.**

Experimental Arrangements

Measurement system

Measurement system consists of

1. Geiger-Muller counter tube detector (type ABG, hi-energy alpha / beta / gamma).
2. Cobalt-60 radioactive gamma source with radioactivity of (0.699μCi) and half-life of (5.27y) emits gamma rays with two energies (1.333MeV) and (1.173MeV), i.e. it emits gamma rays with an average energy of (1.253MeV).

Shields Preparation

Two materials have been used in this work for shielding, namely lead and aluminum, as a single layer, dual-layers, and multi-layers. These layers composed of successive layers of lead and aluminum with thickness of (0.5cm) for each.

The geometric arrangement of the system

To calculate the buildup factor of shields, two collimators were used to obtain the good geometrical arrangement. While the bad geometrical arrangement was obtained by lifting up both collimators. These two collimators made of lead material with dimensions of (5x5x1.5) cm with central hole diameter equal to (1.2cm) to get collimated beam (as shown in figure (1-**a**)), where the distance between detector and radioactive source was (20cm). On the other hands, the distance between the shield and radioactive source was (4cm).

To get the good geometrical arrangement, the first collimator was used in front of the radioactive source at a distance of (0.5cm) while the second collimator was used in front of the detector at a distance of (1.5cm).

RESULTS AND DISCUSSION

Experimental results for both good and bad geometrical arrangement were used to calculate the values of **$(\ln(I/I_o)_g)$** and **$(\ln(I/I_o)_b)$**, these results listed in the table (1), while these values have been shown in figures (**2**) to **(6)**.

Penetration depth (µx) in lead and aluminum can be determine by **equation (8).** [6][5] Experimental results have shown the dependence of buildup factor on the shield thickness (as shown in **table (2)**) and with atomic number as shown in **figure (7)**, which shows a clear reduction in numerical buildup factor values of lead shields as compared with that of aluminum.

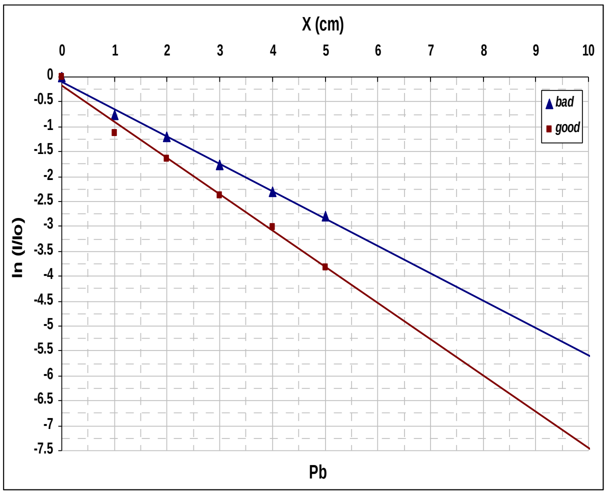

Figure 2 Shows $\ln(I/I_o)$ as a function of absorber thickness (x) for both good and bad geometrical arrangement for (Pb) shield using Co-60.

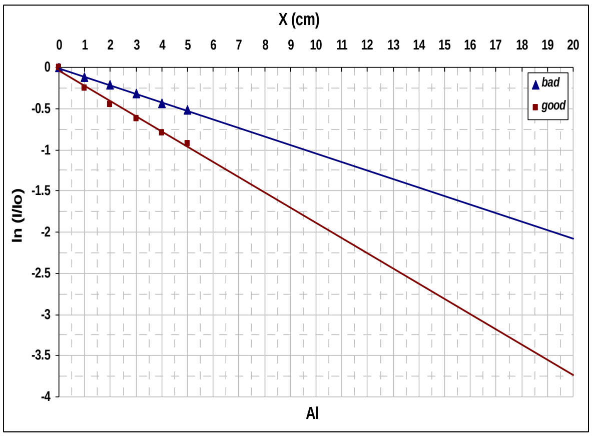

Figure 3 Shows $\ln(I/I_o)$ as a function of absorber thickness (x) for both good and bad geometrical arrangement for (Al) shield using Co-60.

Table 1 I_b, I_g, $\ln(I/I_o)_b$ and $\ln(I/I_o)_g$ values for single, double, and multi layers shields for different thickness (x), using Co-60.

Shield Type	**X(cm)**	**I_b**	**I_g**	**$\ln(I/I_o)_b$**	**$\ln(I/I_o)_g$**
All Shields	0	774	504	0	0
Pb	1	361	162	-0.7627	-1.1350
	2	231	98	-1.2092	-1.6376
	3	134	47	-1.7537	-2.3724
	4	77	25	-2.3078	-3.0037
	5	47	11	-2.8014	-3.8247
Al	1	684	394	-0.1236	-0.2462
	2	626	322	-0.2122	-0.4480
	3	565	270	-0.3147	-0.6242
	4	503	229	-0.4310	-0.7889
	5	459	199	-0.5225	-0.9293
Pb-Al (Dual-layers)	1	475	262	-0.4883	-0.6542
	2	284	126	-1.0026	-1.3863
	3	214	73	-1.2856	-1.9321
	4	159	43	-1.5827	-2.4614
	5	105	22	-1.9976	-3.1315
Al- Pb (Dual-layers)	1	427	248	-0.5948	-0.7091
	2	252	137	-1.1221	-1.3026
	3	147	75	-1.6611	-1.9051
	4	102	49	-2.0266	-2.3308
	5	71	31	-2.3889	-2.7886
Pb-Al (Multi layers)	1	488	274	-0.4613	-0.6094
	2	342	161	-0.8168	-1.1412
	3	218	93	-1.2671	-1.6900
	4	172	64	-1.5041	-2.0637
	5	136	41	-1.7389	-2.5090

This fact shows inverse relationship of buildup factor with atomic number (z), in case of constant gamma rays energy. It is found also that the materials with low atomic numbers, such as aluminum, scatter photons more than the material with higher atomic numbers, such as lead. This fact is due to that the photoelectric effect is a dominant interaction in the case of low gamma ray energies and high atomic numbers. While in the case of the use of aluminum shields slabs the dominant interaction is Compton phenomenon due to the low atomic number and due to the high energy of gamma rays. These results and dissection have been found to be very close with other researches results [6][7][8].

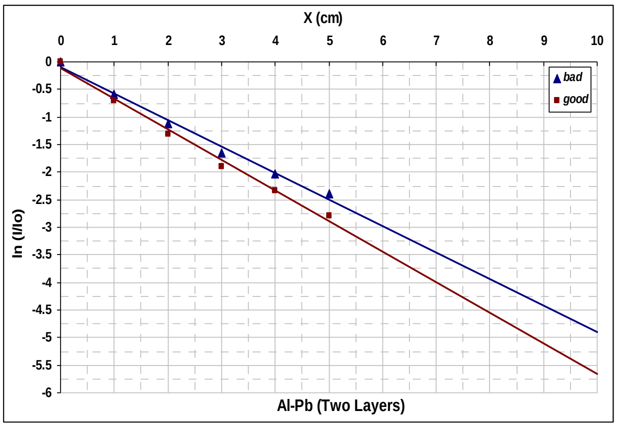

Figure 4 Shows ln(I/I_o) as a function of absorber thickness (x) for both good and bad geometrical arrangement for (Al-Pb) dual-layers shield using Co-60.

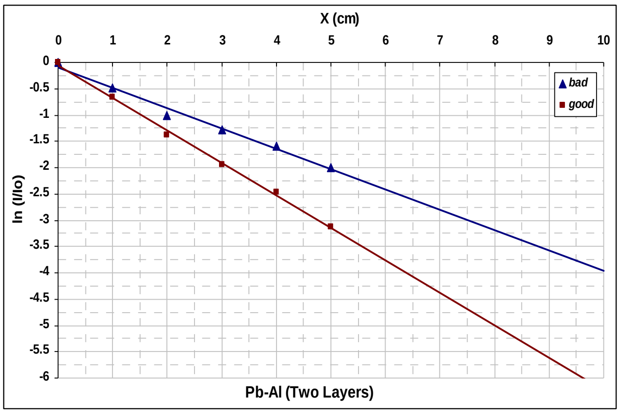

Figure 5 Shows ln(I/I_o) as a function of absorber thickness (x) for both good and bad geometrical arrangement for (Pb-Al) dual-layers shield using Co-60.

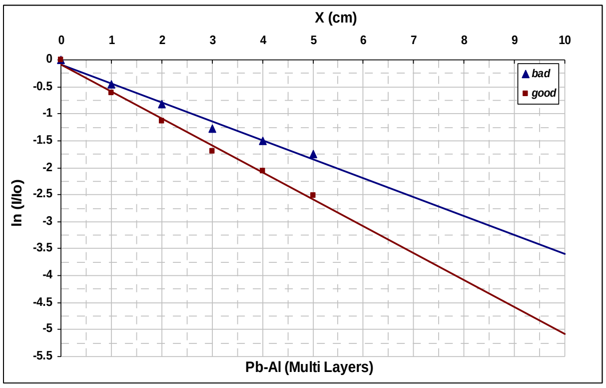

Figure 6 Shows ln(I/I_o) as a function of absorber thickness (x) for both good and bad geometrical arrangement for (Pb-Al) multi layers shield using Co-60.

Moreover, the buildup factors (B) as a function of the values of penetration depth values (μx) in (m.f.p) units have been shown in **figure (7)**. On the other hands, the relationship of (ln(I_o/I)) with thickness (x) for all type of shield composition were listed in **table (3).** While **figure (8)**, Shows ln(I_o/I) as a function of absorber thickness (x) for good geometrical arrangement (narrow beam) for all shield composition using Co-60.

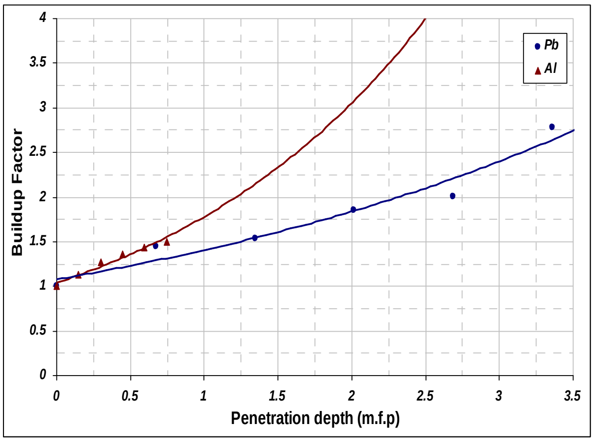

Figure 7 Shows buildup factor (B) as a function of penetration depth (μx) in units of (m.f.p) for (Pb) and (Al) single-layer shield using Co-60.

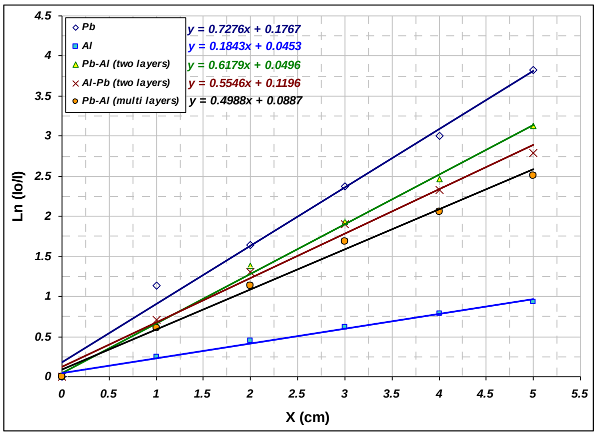

Figure 8 Shows ln(I_o/I) as a function of absorber thickness (x) for good geometrical arrangement (narrow beam) for all shield composition using Co-60.

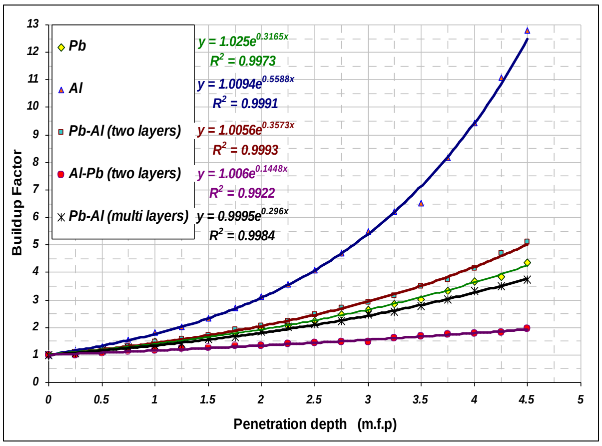

Figure 9 Shows buildup factor (B) as a function of penetration depth (μx) for all kind of shield composition using Co-60.

Results showed that the highest value of the linear attenuation coefficient of gamma rays in lead shield was (0.7276 cm^{-1}), and the lowest value was (0.1843 cm^{-1}) in aluminum shield.

Table 2 Buildup factor (B), Standard of statistical deviation (S.D) and Fractional statistical deviation (F.S.D) values used single, dual, and multi-layers shields for different thickness (x) using Co-60.

Shield Type	X (cm)	Penetration depth (m.f.p)	Buildup Factor (B)	S.D ±	F.S.D %
All Shields	0	0	1	0.0572	5.7237
	1	0.6716	1.4510	0.1254	8.6399
	2	1.3432	1.5349	0.1646	10.7220
Pb	3	2.0147	1.8565	0.2789	15.0228
	4	2.6863	2.0056	0.4075	20.3204
μ =0.67158cm^{-1}[6]	5	3.3579	2.7822	0.8448	30.3646
	1	0.1490	1.1304	0.0700	6.1887
	2	0.2980	1.2659	0.0839	6.6314
Al	3	0.4470	1.3626	0.0963	7.0680
	4	0.5960	1.4303	0.1076	7.5225
μ =0.149cm^{-1}[5]	5	0.7450	1.5019	0.1194	7.9480
	1	0.6179	1.1805	0.0844	7.1475
Pb-Al	2	1.2358	1.4677	0.1410	9.6065
(Dual-layers)	3	1.8537	1.9089	0.2337	12.2436
	4	2.4716	2.4078	0.3772	15.6677
μ =0.6179cm^{-1}	5	3.0895	3.1078	0.6719	21.6209
	1	0.5546	1.1212	0.0818	7.2967
Al- Pb	2	1.1092	1.1978	0.1110	9.2689
(Dual-layers)	3	1.6638	1.2763	0.1543	12.0935
	4	2.2184	1.3555	0.1997	14.7310
μ =0.5546cm^{-1}	5	2.7730	1.4914	0.2732	18.3167
	1	0.4988	1.1597	0.0815	7.0296
Pb-Al	2	0.9976	1.3832	0.1198	8.6620
(Multi layers)	3	1.4964	1.5264	0.1675	10.9748
	4	1.9952	1.7500	0.2276	13.0065
μ=0.4988 cm^{-1}	5	2.4940	2.1600	0.3461	16.0257

Table 3 $\ln(I/I_o)_g$ values for used single, dual and multi-layers shields for different thickness (x) in units (cm) using Co-60.

X (cm)	**$\ln(I_o/I)_g$**				
	Pb	**Al**	**Pb-Al (Dual-layers)**	**Al- Pb (Dual-layers)**	**Pb-Al (Multi layers)**
0	0	0	0	0	0
1	1.1350	0.2462	0.6542	0.7091	0.6094
2	1.6376	0.4480	1.3863	1.3026	1.1412
3	2.3724	0.6242	1.9321	1.9051	1.6900
4	3.0037	0.7889	2.4614	2.3308	2.0637
5	3.8247	0.9293	3.1315	2.7886	2.5090

Buildup factor (B) values for used single, dual, and multi-layers shields are listed in **table (4)** for different penetration depth (μx) in units (m.f.p) and the relationship between them shown in **figure (9)** which shows that the buildup factor values have its lowest value in the case of dual-layers shield (Al-Pb), followed by multi-layers shield (Pb-Al).

A fitting was done for each relation between the measured buildup factors with penetration depth in units (m.f.p) to get a fitting formula which can be use to get the buildup factor at any penetration depth in units of (m.f.p).

Table 4 Buildup factor (B) values for used single, dual, and multi-layers shields composition for different penetration depth (μx) using Co-60.

Penetration depth (m.f.p)	**Buildup Factor (B)**				
	Pb μ =0.67158 cm^{-1}[6]	**Al μ =0.149 cm^{-1}[5]**	**Pb-Al (Dual-layers) μ =0.6179cm^{-1}**	**Al-Pb (Dual-layers) μ =0.5546cm^{-1}**	**Pb-Al (Multi-layers) μ =0.4988cm^{-1}**
0	1	1	1	1	1
0.25	1.1052	1.1618	1.1052	1.0101	1.0513
0.5	1.1618	1.3165	1.1853	1.0736	1.1618
0.75	1.2840	1.5373	1.3165	1.1331	1.2523
1	1.4918	1.8040	1.4623	1.1618	1.3499
1.25	1.5296	2.0238	1.5683	1.2214	1.4191
1.5	1.6905	2.3396	1.7246	1.2523	1.5683
1.75	1.8221	2.7183	1.9155	1.3499	1.6487
2	1.9640	3.1112	2.0544	1.3499	1.8682
2.25	2.0647	3.5787	2.2255	1.4191	2.0136
2.5	2.2255	4.0755	2.4596	1.4550	2.1170
2.75	2.4596	4.7115	2.7183	1.4918	2.2255
3	2.6512	5.4739	2.9008	1.4918	2.4596
3.25	2.8577	6.2028	3.1582	1.6080	2.5857
3.5	3.0042	6.5208	3.4903	1.6905	2.7871
3.75	3.3201	8.1661	3.7434	1.7333	3.0042
4	3.6693	9.4404	4.1579	1.7860	3.3201
4.25	3.8574	11.0784	4.7114	1.8221	3.4903
4.5	4.3710	12.8071	5.1039	1.9542	3.7434

Table 5 Comparison of buildup factor values between present research* and previous researches [6, 9] results for different values of penetration depth (µx) in units (m.f.p) using convergent energies of gamma rays for lead and aluminum materials.

Penetration depth (m.f.p)	Buildup Factor (B)						
	Pb				Al		
	1.253 MeV*	1 MeV [9]	1.5 MeV [9]	1.253 MeV [6]	1.253 MeV*	1 MeV [9]	1.5 MeV [9]
0.5	1.1618	1.46	1.43		1.3165	1.49	1.42
1	1.4918	1.76	1.75		1.8040	2.1	1.93
2	1.9640	2.23	2.29	1.3082	3.1112	3.59	3.09
3	2.6512	2.64	2.82		5.4740	5.35	4.37
4	3.6693	2.99	3.31	2.2020	9.4404	7.37	5.78

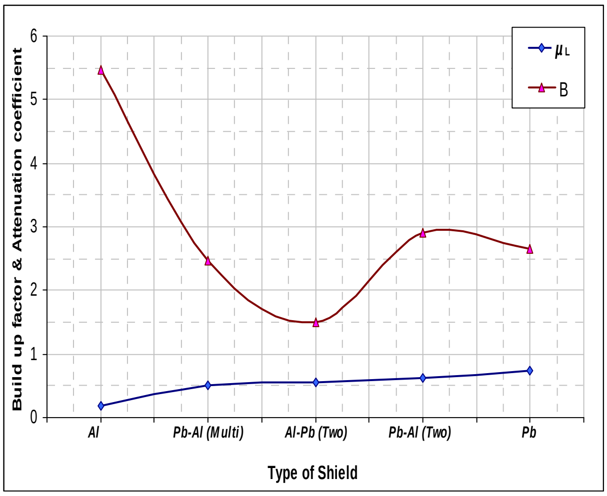

Figure 10 Shows buildup factor (B) and attenuation coefficient as a function of type of shield for all shield using Co-60.

So, in the **figure (9)**, it is possible to see the fitting formula and the correlation coefficient (R^2), where the value of (y) in fitting means "**buildup factors**" and (x) means "**penetration depth**". Good shielding materials and good shielding design for gamma rays need to have materials with buildup factor values are small as possible. That is because small buildup factor mean good absorption. Moreover, the values of the linear attenuation coefficient of shielding materials could be larger at the same time. It is noticed from **figure (9)**, that the values of the linear attenuation coefficient for dual-layers shield (Al-Pb) and multi-layers shield (Pb-Al) are convergent and lower than that for lead shield alone, therefore, the dual-layers shield (Al-Pb) is one of the best shields used in this research because of its smallest buildup factor value which is less than its value of the lead. At the same time, the multi-layers shield (Pb-Al) is better than the shield of lead because the buildup factor value is lower than its value of the lead, as shown in **figure (10)**. The results of this work have been compared with other calculated results of some previous researches [6][10] to the values of buildup factor with convergent energy of gamma rays, as shown in **table (5)**. This comparison to illustrate the convergence of the current search results with the results of previous research.

DISCUSSSION

1. Buildup factor of all type of shield composition (single, dual and multi-layers) increases with the shield thickness increasing.
2. Buildup factor decreases by increasing the atomic number of shielding material.
3. Buildup factor of multi-layers shields consisting of lead with aluminum (Pb-Al), and dual-layers shield composition consist of lead and aluminum in the order of (Al-Pb) is less than the buildup factor of lead single-layer shield.
4. Fitting formulas were done for buildup factor with penetration depth to gate any value of buildup factor at any penetration depth with high accuracy.

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