Monte Carlo Simulation for Bremsstrahlung Buildup Factor Produced by Absorption of Y-91 Beta Rays

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Abstract

This paper presents the first data for bremsstrahlung buildup factor (BBUF) produced by the complete absorption of Y-91 beta particles in different materials via the Monte Carlo simulation method. The bremsstrahlung buildup factors were computed for different thicknesses of water, concrete, aluminum, tin and lead. A single relation between the bremsstrahlung buildup factor BBUF with both the atomic number Z and thickness X of the shielding material has been suggested.

Keywords

Monte Carlo Simulation, Bremsstrahlung, Buildup Factor.

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محاكاة مونتي كارلو لعامل تراكم اشعة الكبح الناتجه من امتصاص اشعة بيتا لمصدر Y-91

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الخلاصة

في هذا البحث تم استنتاج عامل تراكم اشعة الكبح الناتجه من الامتصاص الكلي لاشعة بيتا في مواد مختلفه باستخدام طريقة مونتي كارلو. حيث تم تصميم برنامج حاسوبي للمحاكاة وذلك لتمثيل حلول مسائل انعكاسات وعبور اشعة الكبح . حيث تم حساب عامل تراكم اشعة الكبح لاسماك مختلفه من مواد التدريع لكل من الماء والكونكريت والالمنيوم والقصدير والحديد والرصاص لمصدر اتريوم Y-91 لانتاج اشعة بيتا بطاقه عظمى مقدارها 1.54 مليون الكترون فولت. وقد تم دراسة عدد من المعاملات المتعلقه بتصميم البرنامج والمسماة بعوامل المحاكاة وكذلك دراسة المعاملات المتعلقه بمادة الدرع والمسماة بالعوامل الفيزيائيه. تم استنتاج معادله رياضيه لعامل تراكم اشعة الكبح نسبة لكل من العدد الذريZ والسمك X لمادة الدرع.

Introduction

Buildup factors are important values in nuclear radiation shielding and absorbed dose calculations. They can be obtained either by experiment, or the solution of the photon transport equation, or using the Monte Carlo simulation method.

The data set of gamma ray buildup factors was first developed by Goldstein and Wilkins [1] based on the method of moments. The comprehensive data set of buildup factors was further developed by the American Nuclear Society in 1991[2]. A detailed historical review on buildup factor calculation and use is given by Harima [3]. The calculations of gamma ray buildup factors considered different gamma sources and different media. Most of these calculation used monoenergetic sources in finite or infinite media with single or multilayer shields, and different penetration depth.

The first attempt to generate bremsstrahlung buildup factors (BBUF) for a continuous energy source was performed by Elias and Ali [4] using Monte Carlo simulation method. They chose a Sr-90/Y-90 beta source of 2.2 MeV maximum energy and a lead target to produce a continuous source of energetic photons. An empirical formula for BBUF with different targets was suggested.

A computer program BBF was written [4,5] to solve the problem of gamma ray reflection and transmission using the BASIC language such that a program “MONTRY” [6] was rewritten and improved in order to include the continuity of energy.

The aim of this paper is to calculate BBUF for Y-91 bremsstrahlung (of 1.54 MeV maximum energy), uniformly incident on an infinite homogeneous slab of different shielding material of variable thickness, and to find a general formula to calculate the bremsstrahlung buildup factor as a function of the material atomic number and its thickness.

Basics and Simulation

Simulation of transport of gamma rays through a medium via Monte Carlo method is described in details elsewhere [7]. In this work, the Y-91 beta source was assumed to be placed beside the lead shield and the bremsstrahlung produced by striking beta particles with the shield at a high speed, then the generated continuous energy photons were uniformly incident with fractional weight, which extracted from the bremsstrahlung spectrum of lead by Pratt et al. theory [8] on the left hand face of an infinite plane of homogeneous slab of shielding material of variable thickness. See Table (1).

Table(1): The fractional weight of bremsstrahlung spectrum of Y-91 source with energy.

Energy (MeV)	0.05	0.1	0.2	0.3	0.4	0.5	0.6
Fractional Weight %	65	12	9	5	3.3	2	1.5
Energy (MeV)	0.7	0.8	0.9	1	1.1	1.2	----
Fractional Weight %	0.9	0.62	0.31	0.23	0.1	0.04	----

The distribution in Table (1) describes the continuous energy spectrum of photons produced by complete absorption of beta rays by lead shield with maximum bremsstrahlung energy 1.54 MeV beta source distributed at 0.1 MeV for each energy interval. This distribution is regarded as the continuous energy source of gamma rays in “BBF” program. The main interaction is Compton scattering thus one does not allow absorption of the photons as such; all collisions forced to be Compton scatterings.

The Compton scattering process is strictly an interaction between a photon and an individual electron. In the interaction, the photon does not disappear. Instead, it is deflected through a scattering angle and part of its energy is transferred to the recoil electron. The energy loss in the process depends on the initial photon energy as well as on the scattering angle. Under the assumption that the electron is free and stationary before collision, the energy change of the incident photon and the scattering angle is related to each other by

$$E=\frac{E_o}{1+\left\{\frac{E_o}{m_oC^2}\right\}(1-\cos\theta)} \qquad (1)$$

where E is the energy of scattered photon, E_0 is the energy of incident photon, m_oc^2 is the rest mass energy of electron, and θ is the scattering angle.

In gamma ray transport calculations it is usually more convenient to use, instead of the energy variable, the wavelength of the photon in Compton units, namely,$\lambda = \frac{0.511}{E}$, where E is the photon energy in MeV. The increase of the photon wavelength associated with a Compton scattering event is

$$\lambda - \lambda o = 1 - \cos\Theta \qquad (2)$$

where λ_0 and λ are the wavelength of the photon before and after scattering respectively.

When the angular dependence of the scattered photon has been removed by integration, in terms of the dimensionless variable x, where x represents λ / λ_0.
The Klein-Nishina differential cross section will take the following compact form [6]

$$d\sigma = k\left(A + \frac{B}{\chi} + \frac{C}{\chi^2} + \frac{D}{\chi^3}\right) d\chi \qquad 1 \le \chi \le 1 + 2\alpha_0$$

where

$$\alpha_0 = \frac{1}{\lambda o} = \frac{E_o}{0.511}$$

$$x = \frac{\lambda}{\lambda o} = \frac{E_o}{E} \qquad (4)$$

and E_0 is the incident photon energy in MeV.

Additionally, the total Compton cross section is obtained by integrating Eq. (3), hence

$$\sigma_c = \int_1^{1+2\alpha_0} d\sigma \qquad (5)$$

$$=K'\left[\frac{4}{\alpha_0} + \left(1 - \frac{1+\beta}{\alpha_0^2}\right)\log_e \beta + \frac{\gamma}{2}\right] \text{ barn/electron} \qquad (6)$$

where

$$K' = K \times 10^{24}$$

$$\beta = 1 + \alpha_0 \quad \text{and} \quad \gamma = 1 - \beta^{-2}$$

It is clear from Eq. (6) that σ_c is only a function of the incident energy of the photon. The corresponding Compton cross section data at each energy interval mesh in cm^2/g, the corresponding total mass attenuation coefficient data in cm^2/g for all materials used in this work, the corresponding total mass attenuation coefficient data for air in cm^2/g are tabulated in Table (2).

The single and multiple scattering are studied by Monte Carlo radiation transport simulation. , in which the life histories of a large number of particles (photons) are followed using random sampling techniques to sample the probability laws that describe the particle's behaviour, and to trace out step by step the particle's random walk through the medium. Bremsstrahlung buildup factor BBF is a computer program which solves the problem of gamma ray reflection and transmission using the basic computer program language.

A computer program "MONTRY" was redesigned and improved in order to include the continuity of energy.

The life history of a particle is built up from knowhedge of its trajectory through the particular system of intrest. The selection techniques for given stochastic variables are used, in MonteCarlo process it is necessary to generate random values of some variable x (e.g., path length) which, from the physics of the particle interaction process, has some distribution f(x); that is, a histogram of a large number of such randomly generated x values should approach f(x) in shape [9].

The Klein-Nishina formula was sampled by the Kahn method, which is the most widly used technique for sampling the probability density function. The double interpolation procedure is used to interpolate the two variable energy E and attenuation absorption coefficient(μ).

The only sophistication employed is the concept of survival weights. Thus one does not allow absorption of the photons as such; all collisions are forced to be Compton scatterings. The effect of absorption is accounted for by modifying the weight of the particle after each collision. That is the particular weight after a collision is the weight before collision multiplied by the survival ratio, $\mu_C(E) /\mu (E)$, which is of course the probability that a collision will be a Compton scattering. It is important to realize that in this, the basic form of the program, the pair production event is regarded as a purely absorptive interaction, the contribution from the resulting annihilation gamma rays is not considered. In this version of the program, the history of each particle is followed until the particle either escapes from the system, or due to successive scatters, its drops below some present minimum; in either event a ‘new’ photon is started with an initial weight (i.e., probability, p) of unity.

Results and Discussion

The obtained bremsstrahlung buildup factors BBUF as a function of thickness and type of the shielding materials for the Y-91 beta source are displayed in Table (3) with its standard deviations. The dependence is shown in Fig. 1. The results showed that the bremsstrahlung buildup factor increases with the increase of thickness for all types of the investigated shields. The increase of buildup factor occurred because the increasing of the bremsstrahlung scattering cross section with the increasing of shield thicknesses.

The calculated bremsstrahlung buildup factors BBUF as function of target atomic number Z is shown in Table (3). The bremsstrahlung buildup factor increases by increasing the atomic number of shielding material.

It is seen that the buildup factor of water is less than that for lead when the shielding material measured in given cm units. This behavior is due to result caused by appreciable the mean free path of Pb is much shorter less than that in water, then the probability of interaction in Pb increased than that in water.

As shown in Fig. (1), the relation between bremsstrahlung buildup factor and shield thickness can be fitted with the potential equation and given as

$$BBUF = 1+ a X^{b} \quad (7)$$

where, a and b are the fitting parameters depends on the shielding material atomic number Z and maximum bremsstrahlung energy, X, the shield thickness in cm. For Y-91 beta source the values of a and b were calculated and given versus the atomic number Z for water, concrete, Al, Sn and Pb shown in Table (4) and Fig. (2).

The results show that the value of these parameters increase with the increase of material atomic number Z.

Fitting these relations with the linear equation Fig. (2) and substituting in Eq. (7), then the bremsstrahlung buildup factor “BBUF” can be expressed as function of both material thickness X and atomic number Z as

$$BBUF = 1 + (a Z + b) X^{(CZ+d)} \qquad (8)$$

where a, b, c, and d are now, new constants depend on the bremsstrahlung energy distribution. For Y-91 beta source these parameters are;

$a = 0.0007$ $b = 0.00007$

$c = 0.0058$ $d = 0.4867$

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Table (2) The mass attenuation coefficient (μ/ρ) and Compton cross section for different materials and air, in cm2/g corresponding to energy interval (in MeV) mesh data. These data were extracted from Hubble [10]

Energy mesh	H_2O		Concrete		Al		Sn		Pb		Air
	$\mu_{Compton}$	μ_{Total}	$\mu_{Compton}$	μ_{Total}	$\mu_{Compton}$	μ_{Total}	$\mu_{Compton}$	μ_{Total}	$\mu_{Compton}$	μ_{Total}	μ_{Total}
15	0.0127	0.0194	0.0116	0.0210	0.0110	0.0219	0.0096	0.0431	0.00902	0.0566	0.018
10	0.0171	0.0222	0.0157	0.0228	0.0148	0.0232	0.013	0.0389	0.0122	0.0497	0.021
8	0.0201	0.0243	0.0184	0.0243	0.0174	0.0244	0.0152	0.0372	0.0143	0.0467	0.022
6	0.0245	0.0277	0.0225	0.0270	0.0213	0.0265	0.0186	0.0358	0.0175	0.0438	0.025
5	0.0278	0.0303	0.0255	0.0291	0.0241	0.0284	0.0211	0.0354	0.0198	0.0426	0.028
4	0.0322	0.0340	0.0295	0.0322	0.0279	0.0311	0.0244	0.0355	0.0229	0.0418	0.031
3	0.0385	0.0397	0.0354	0.0370	0.0335	0.0354	0.0292	0.0367	0.0274	0.0420	0.036
2	0.0490	0.0494	0.0450	0.0455	0.0425	0.0432	0.0371	0.0408	0.0348	0.0453	0.045
1.5	0.0574	0.0575	0.0527	0.0528	0.0498	0.05	0.0435	0.0458	0.0407	0.0509	0.052
1	0.0707	0.0707	0.0648	0.0648	0.0613	0.0613	0.0534	0.0567	0.0499	0.0680	0.064
0.8	0.0786	0.0786	0.0721	0.0721	0.0681	0.0862	0.0593	0.0647	0.0554	0.0841	0.071
0.6	0.0894	0.0894	0.0820	0.0820	0.0775	0.0776	0.0672	0.0777	0.0626	0.117	0.081
0.5	0.0966	0.0966	0.0886	0.0887	0.0837	0.0839	0.0724	0.0888	0.0673	0.150	0.087
0.4	0.106	0.106	0.0969	0.0971	0.0916	0.0919	0.0789	0.108	0.0731	0.215	0.096
0.3	0.118	0.118	0.108	0.109	0.102	0.103	0.0872	0.151	0.0804	0.373	0.107
0.2	0.135	0.136	0.124	0.126	0.117	0.119	0.0982	0.298	0.0897	0.936	0.123
0.15	0.147	0.148	0.134	0.139	0.127	0.132	0.1105	0.561	0.0948	1.91	0.136
0.1	0.163	0.165	0.148	0.164	0.139	0.157	0.112	1.58	0.0989	5.34	0.154
0.08	0.170	0.175	0.154	0.186	0.144	0.182	0.113	2.88	0.0992	2.11	0.166
0.06	0.177	0.192	0.159	0.241	0.148	0.244	0.113	6.33	0.0973	4.53	0.186
0.05	0.180	0.208	0.161	0.306	0.150	0.321	0.111	10.4	0.0948	7.39	0.205
0.04	0.183	0.240	0.162	0.455	0.149	0.5	0.108	19	0.0902	13.4	0.246
0.03	0.183	0.329	0.160	0.880	0.146	1.02	0.101	40.5	0.0823	28.9	0.340
0.02	0.177	0.721	0.152	2.66	0.137	3.24	0.0881	20.2	0.0690	84	0.733
0.015	0.170	1.54	0.143	6.14	0.127	7.64	0.0773	44.9	0.0592	108	1.522
0.01	0.155	5.10	0.125	20.1	0.106	25.7	0.0607	136	0.0454	126	4.910
0.008	0.144	10.1	0.114	38.4	0.0929	49.6	0.0516	247	0.0381	223	9.005
0.006	0.126	24.2	0.0968	83.3	0.0770	114	0.0412	525	0.0297	460	22.154

Table (3) Calculated BBUF for different thicknesses of water, concrete, aluminum, tin and lead shielding materials

Thickness (cm)	Water		Concrete		Aluminum		Tin		Lead	
	Buildup factor	STD in buildup factor	Buildup factor	STD in buildup factor	Buildup factor	STD in buildup factor	Buildup factor	STD in buildup factor	Buildup factor	STD in buildup factor
0.5	1.0036	0.0007	1.0057	0.0008	1.0067	0.0009	1.0195	0.0038	1.0305	0.0062
1	1.0044	0.0008	1.0098	0.0011	1.0099	0.0011	1.0357	0.0049	1.0640	0.0095
2	1.0069	0.0009	1.0134	0.0015	1.0151	0.0017	1.0726	0.0075	1.1118	0.0178
3	1.0097	0.0011	1.0174	0.0020	1.0176	0.0022	1.0852	0.0106	1.1393	0.0298
4	1.0098	0.0013	1.0175	0.0025	1.0179	0.0029	1.1108	0.0145	1.1573	0.0466
5	1.0104	0.0015	1.0229	0.0032	1.0231	0.0035	1.1233	0.0196	1.3881	0.0786

Table (4) The relation between a, b parameter and atomic number Z for Y-91 beta source for water, concrete, Al, Sn and Pb shielding materials

Shield material	Atomic Number Z	a parameter	b parameter
Water	7.89	0.0049	0.5072
Concrete	12.07	0.0090	0.5617
Aluminum	13	0.0098	0.5673
Tin	50	0.0359	0.8100
Lead	82	0.0584	0.9401

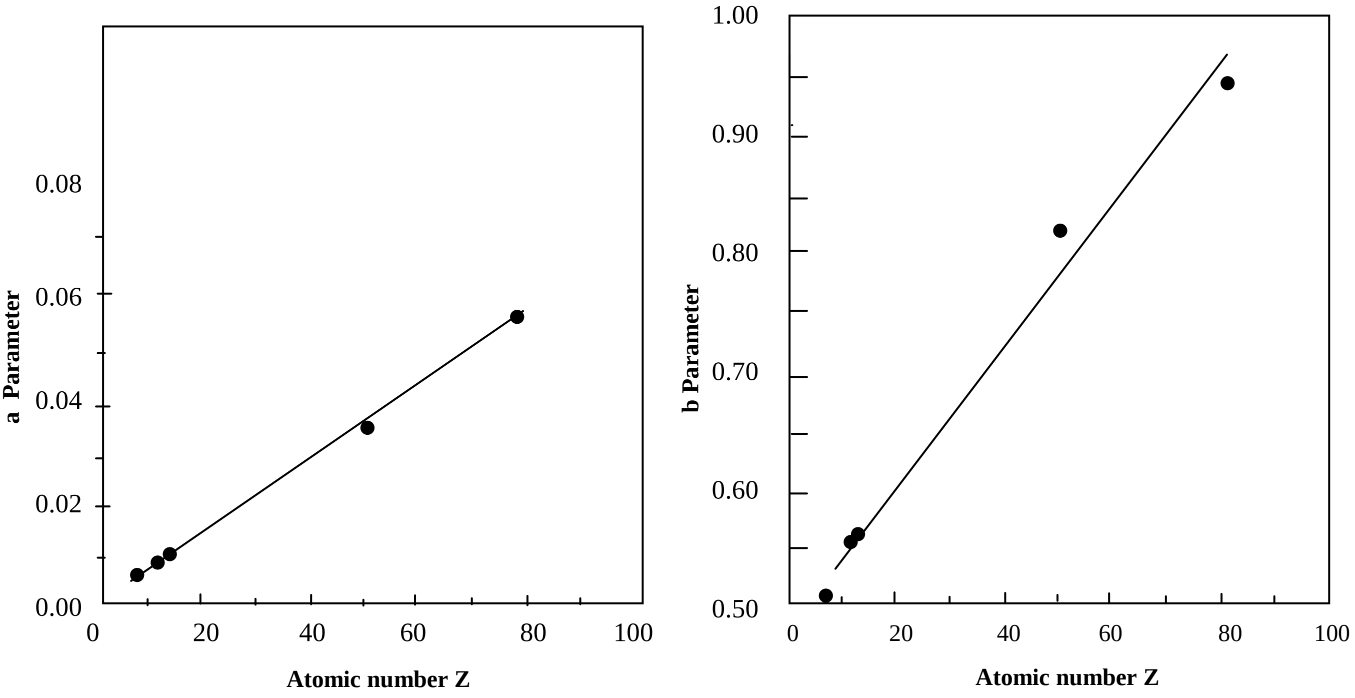

Fig. (2): The relation between the fitting parameters a and b versus the atomic number Z of shield material

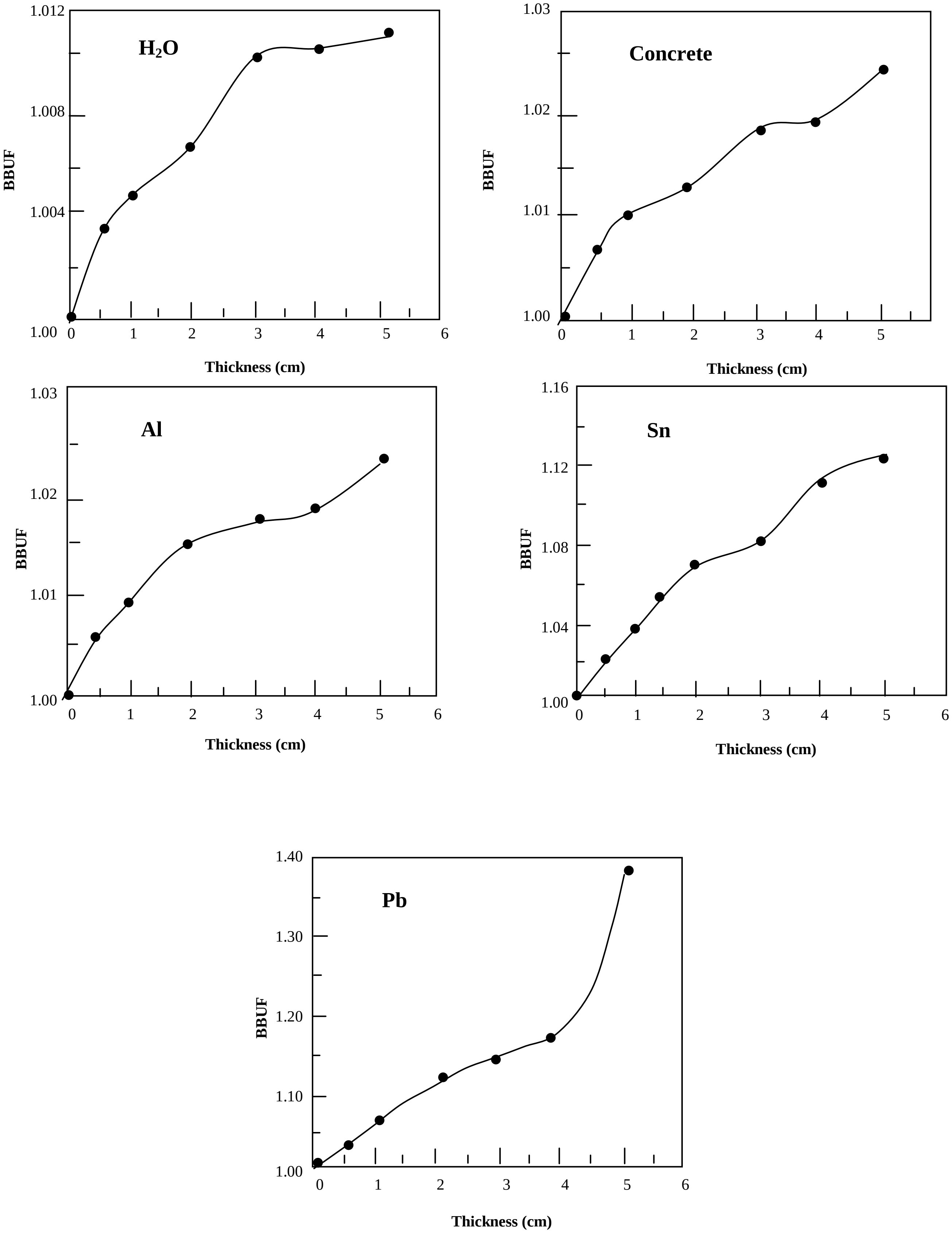

Fig. (1): BBUF for different materials as a function of shield thickness (in cm) for Y-91 beta source.