IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 11, Issue 2 Ser. I (Mar. – Apr. 2019), PP 68-74
www.iosrjournals.org

Radiation Shielding Properties and Exposure Buildup Factor of TI-Al-Nb Alloy Materials

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Abstract: *This work, gamma ray shielding properties of TAN1 and TAN2 alloys were studied by computation of mass attenuation coefficient, effective atomic number, effective electron density, half value layer at photon energy 1 keV-100 MeV and the exposure buildup factor (EBF) of these alloys were computed by GP fitting method for photon energy 0.015–15 MeV up to 40 mfp penetration depth. Gamma shielding effectiveness for energy 1 keV-100 MeV, TAN1 was found to be better than TAN2 for shielding material at this energy range. The EBF values of TAN1 are found lower TAN2 in low-to-intermediate energy (<3 MeV), thus it has better gamma ray shielding properties. These results indicated that it can develop for gamma rays shielding materials.*

Keywords: *mass attenuation coefficient, half value layer, exposure buildup factor, alloy*

Date of Submission: 01-03-2019 Date of acceptance: 18-03-2019

I. Introduction

Present, alloy materials are found in many fields such as in nuclear reactors, petro-chemical industries, engineering materials, biomedical implants and irradiation [1-4]. In the field of radiation physics and dosimetry, the physical parameter for gamma ray interaction with alloys such as mass attenuation coefficients, effective atomic number, electron densities and half value layer are important which regarding the design of materials for radiation shielding [5-6].

Exposure buildup factors (EBF), the various codes for buildup factors were collected and reported by American Nuclear Society (ANSI/ANS-6.4.3, 1991) in ANSI/ANS-6.4.3-1991 and this report covers energy range 0.015–15 MeV up to penetration depth of 40 mean free path (mfp). It was developed a fitting formula by Harima, called Geometrical Progression (GP). This method is used for computation of the exposure buildup factors for gamma ray buildup factors in different materials such as concretes, fly-ash materials and alloy which known to be accurate within the computed uncertainty (<5%) [1]. The buildup factor can be divided into two types: (1) the absorbed or deposited energy in the interacting medium and detector response function is that of absorption in the interacting medium; (b) the exposure buildup factor (EBF) in which quality of interest is the exposure and detector response function is that of absorption in air [7-8].

In this context, the mass attenuation coefficients, effective atomic number, effective electron density, half value layer has been computed by WinXCom software at energy range 1 keV-100 MeV and the exposure buildup factor (EBF) for gamma rays of alloys have been computed for photon energy 0.015–15 MeV up to 40 mfp penetration depth by GP fitting formula.

II. Theoretical formulation

Mass attenuation coefficient and half value layer

The probability of interactions of photon with medium can investigate by mass attenuation coefficient (μ_m) in (cm^2/g). It is important probability interaction used to receive other photon interaction parameters. In the event of mixture of elements, μ_m can be determined by [8-9]:

$$\mu_m = \sum_i w_i (\mu_m)_i \tag{1}$$

where w_i and $(\mu_m)_i$ are weight fraction and mass attenuation coefficient of element i, respectively. For alloys, μ_m has been determined by using WinXcom software at energy from 1 keV to 100 Gev.

The total atomic cross section ($\sigma_{t,a}$) in (barns/atom) can be computed from total mass attenuation coefficient, by relation [10-11]:

$$\sigma_{t,a} = \frac{(\mu_m)_{alloy}}{N_A \sum_i^n (w_i / A_i)} \tag{2}$$

where N_A is Avogadro's number, A_i is atomic weight of an element in the alloy.

The total electric cross section ($\sigma_{t,el}$) is given by relation [10]:

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i^n \frac{f_i A_i}{Z_i} (\mu_m)_i \tag{3}$$

where $f_i = n_i / \sum_i^n n_i$ is the mole fraction, Z_i is the atomic number of constituent element, n_i is the total number of atoms of the constituent element in the molecule, and $\sum_i^n n_i$ is the total number of all atoms in the molecule. The n_i and A_i, are the total number of atoms and the atomic weight of the i^{th} element in the molecule, respective.

The number of electron which interacted with photon per atom is the effective atomic number (Z_{eff}). It can be computed as the ratio of total atomic effective cross section to total electronic cross section [8,10]:

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \tag{4}$$

The number of electron which interacted with photon per unit mass is the effective electron density (N_{el}). It can be calculated as the ratio of the total mass attenuation coefficient to the total electronic cross section [8,10]:

$$N_{el} = \frac{\mu_m}{\sigma_{t,el}} \tag{5}$$

The half value layer (HVL) is thickness of material which reduces photon intensity to 50% of incident intensity (I_0), and computed by using formula [9]:

$$HVL = \frac{0.693}{\mu} \tag{6}$$

where μ is linear attenuation coefficient.

Exposure buildup factor (EBF)

The exposure buildup factors (EBF) and G–P fitting parameters of alloys were computed from equivalent atomic number (Z_{eq}) by logarithmic interpolation method. The calculation has been operated in three steps:

1. Computation of equivalent atomic number (Z_{eq});
2. Computation of G–P fitting parameter using interpolation method;
3. Computation of exposure buildup factors (EBF).

Z_{eq} is a single parameter which explains properties of alloys in terms of equivalent elements and has been computed from ratio of Compton partial mass attenuation coefficient (μ_m) Compton associate with the total mass attenuation coefficient (μ_m) Total at same photon energy, using formula [12,13]:

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1} \tag{7}$$

where Z_1 and Z_2 are atomic numbers of elements according to ratios R_1 and R_2 respectively. R is ratio (μ_m) Compton/(μ_m) Total for alloys at same energy. The parameters of G–P fitting are computed by logarithmic interpolation method for Z_{eq}. The parameters of G–P fitting for elements were taken report by the standard reference database, the American Nuclear Society ANSI/ANS-6.4.3. For alloys was using formula [12,13]:

$$P = \frac{P_1(\log Z_2 - \log Z_{eq}) + P_2(\log Z_{eq} - \log Z_1)}{\log Z_2 - \log Z_1} \tag{8}$$

where P_1 and P_2 are value of G–P fitting parameters according to atomic numbers of Z_1 and Z_2, respectively at same energy. The parameters of G–P fitting of glasses were used to compute exposure buildup factor (EBF) as determined by [12,13]:

$$B(E,X) = 1 + \frac{b-1}{K-1}(K^x - 1) \text{ for } K \neq 1 \tag{9}$$

$$B(K,X) = 1 + (b-1)x \text{ for } K=1 \tag{10}$$

and

$$K(E,x) = cx^a + d\,\frac{\tanh\left(\frac{x}{X_K} - 2\right) - \tanh(-2)}{1 - \tanh(-2)} \text{ for } x \leq 40 \text{ mfp} \tag{11}$$

where E and x are incident photon energy and penetration depth in terms of mean free path (mfp), respectively., a, b, c, d and X_K are G–P fitting parameters. K parameter with deep penetration indicates photon dose multiplication and adjusts in configuration of spectrum.

III. Results and discussion

The radiation shielding properties of alloys were computed and discussed on mass attenuation coefficient, effective atomic number, effective electron density, half value layer and exposure buildup factor.

Table 1 The different chemical compositions (at%) and density (ρ) of Ti-Al-Nb alloys

Code	Fraction by Weight			ρ_{mix} (g/cm^3)
	Ti	Al	Nb	
TAN1	0.514	0.153	0.333	5.63
TAN2	0.507	0.206	0.287	5.35

Density, ρ_{mix}, of alloys in Table 1 was computed by the rule of mixture (ROM) [14]:

$$\rho_{mix} = \frac{\sum_{i=1}^{n} c_i A_i}{\sum_{i=1}^{n} \frac{c_i A_i}{\rho_i}} \tag{12}$$

here ρ_i, c_i, and A_i are density, atomic fraction and atomic weight of element i, respectively.

Mass attenuation coefficient

The mass attenuation coefficients (μ_m) of alloys from WinXCom software are shown in Fig. 1. It is shown that, μ_m values of alloys are shown the same trend and it has very high at lower photon energy range which photoelectric absorption is major interaction mechanism. After that, it reduces gradually and become lowest at intermediate energy range which Compton scattering is major interaction mechanism. At the end, it begins increasing and become nearly constant at high energy range, around 100 MeV which pair production is major interaction mechanism. Coefficient value peaks were observed for all alloys in photoelectric absorption region, it can be discussed by photon energy and Z dependency of the interaction cross section of elements as occurred from absorption edge of titanium (K 4.97×10^{-3} MeV), aluminum (K 1.56×10^{-3} MeV) and niobium (L3 2.37×10^{-3}, L2 $2.47\ 10^{-3}$, L1 $2.70\ 10^{-3}$ and K $1.90\ 10^{-3}$ MeV).

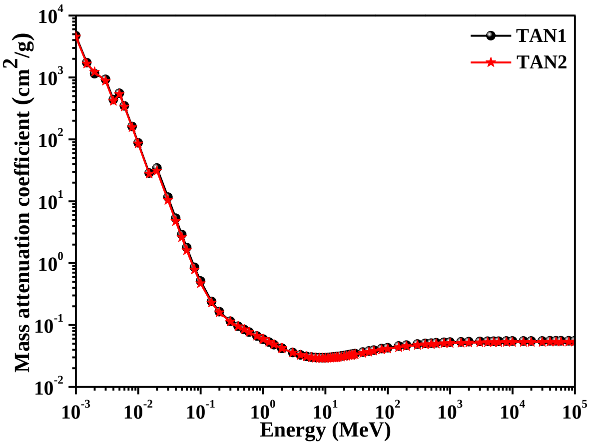


Fig. 1. Variation in mass attenuation coefficient of Alloys with photon energy

Effective atomic number and Effective electron density

The effective atomic number (Z_{eff}) of both alloys has peaks, as shown in Fig. 2, which shows the same trend and correspond to the x-ray absorption edge of titanium. The number drops to value of 20 for TAN1 and 19 for TAN2, which corresponds to the atomic number of titanium (Z=22). The effective atomic number of TAN1 alloy is higher than that of TAN2. The reason is that Ti in TAN1 alloy has fraction by weight higher than that of TAN2. As in Fig. 3, the effective electron density (N_{el}) of both alloys shows the same trend and similar values in range 2.43×10^{23} to 4.04×10^{23} electron/gram for TAN1 and 2.42×10^{23} to 4.18×10^{23} electron/gram for TAN2. Also they show the peaks that accords to titanium x-ray absorption edge.

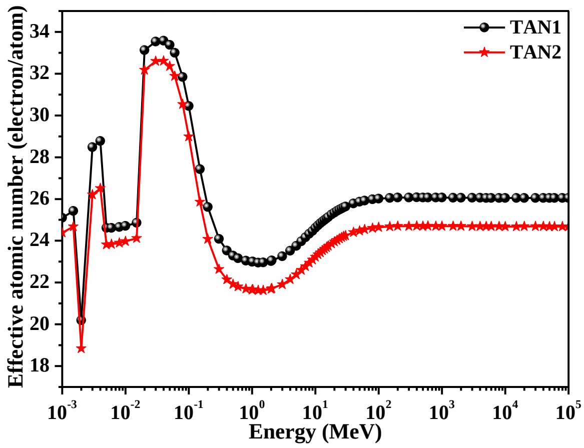


Fig. 2. Variation in effective atomic number of Alloys with photon energy

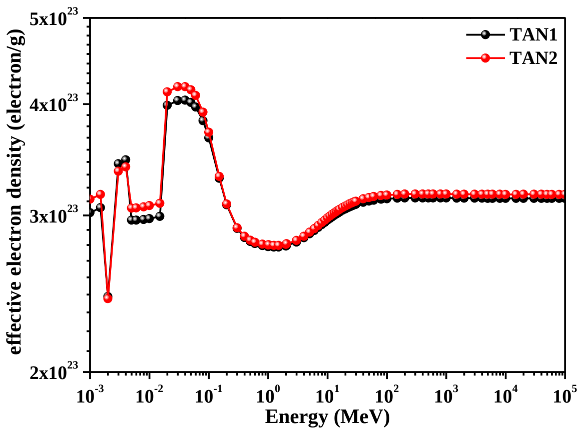


Fig. 3. Variation in effective electron density of Alloys with photon energy

Half value layer

The variation of half value layer (HVL) with gamma energy of alloys is shown in Fig. 4. It found that HVL values were low in photoelectric absorption range. And then it gradually becomes independent of photon energy in Compton scattering and pair production range. It is worth noting that TAN1 alloy requires less than thickness compared with TAN2 alloy in the interesting energy range. The TAN1 alloy shows lower HVL, so it can be inferred TAN1 is the better shielding among the TAN2 alloy.

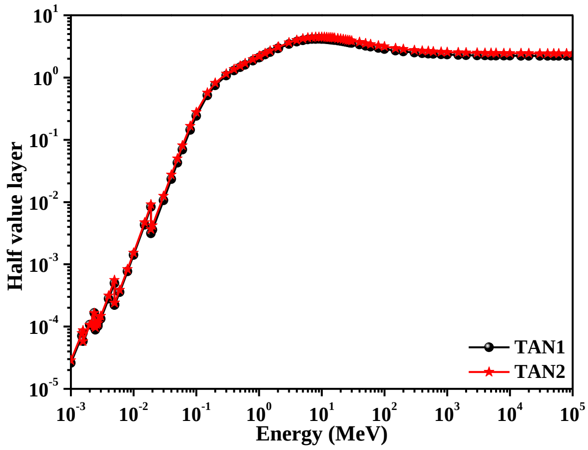


Fig. 4. Variation in half value layer of Alloys with photon energy

Exposure buildup factors

The variation in equivalent atomic numbers (Z_{eq}) as shown in Fig. 5, it is found that Z_{eq} of both alloys have the same trend and TAN1 alloy is higher TAN2 alloy. It is because TAN1 contains fraction by weight of Ti more than TAN2. The pair production is proportional to Z^2, so low Z_{eq} shows small in high energy (>1 MeV).

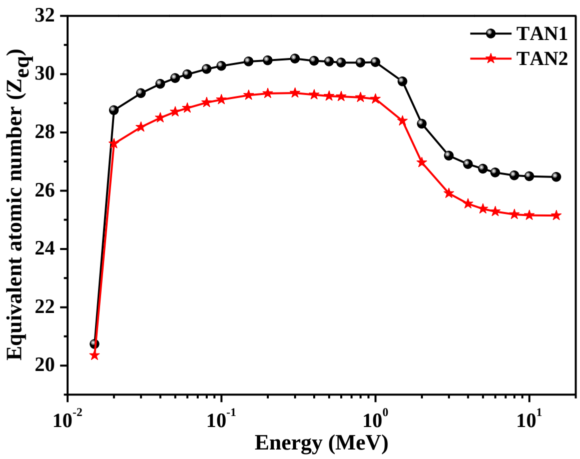


Fig. 5. Variation in equivalent atomic numbers of Alloys with photon energy

Table2 G-P fitting parameters of exposure buildup factor for TAN1 and TAN2

	TAN1					TAN2				
Energy (MeV)	b	c	a	X_k	d	b	c	a	X_k	d
0.015	1.007	0.729	-0.058	6.832	0.160	1.007	0.660	-0.017	6.936	0.144
0.02	1.009	0.105	0.753	10.827	-1.027	1.010	0.115	0.699	11.054	-0.862
0.03	1.102	0.382	0.202	12.767	-0.059	1.022	0.363	0.201	16.546	-0.046
0.04	1.213	0.331	0.227	15.420	-0.096	1.045	0.331	0.240	14.003	-0.100
0.05	1.223	0.328	0.206	13.179	-0.126	1.074	0.354	0.242	12.995	-0.140
0.06	1.101	0.381	0.227	13.606	-0.127	1.111	0.366	0.236	13.572	-0.134
0.08	1.176	0.435	0.201	13.884	-0.117	1.189	0.446	0.192	13.968	-0.110
0.1	1.266	0.491	0.175	13.786	-0.101	1.285	0.505	0.166	13.879	-0.093
0.15	1.482	0.647	0.112	13.858	-0.063	1.511	0.670	0.102	13.964	-0.057
0.2	1.647	0.801	0.063	13.755	-0.041	1.684	0.827	0.055	13.652	-0.038
0.3	1.819	0.983	0.016	12.780	-0.025	1.854	1.014	0.008	12.573	-0.021
0.4	1.874	1.098	-0.009	11.814	-0.017	1.901	1.127	-0.016	11.532	-0.014
0.5	1.884	1.157	-0.022	10.490	-0.013	1.905	1.183	-0.028	10.019	-0.011

0.6	1.871	1.188	-0.029	9.242	-0.011	1.886	1.211	-0.034	8.651	-0.009
0.8	1.836	1.201	-0.032	7.894	-0.012	1.845	1.222	-0.036	7.156	-0.012
1	1.807	1.186	-0.030	8.266	-0.012	1.815	1.202	-0.034	7.557	-0.011
1.5	1.727	1.180	-0.036	17.953	0.010	1.736	1.187	-0.038	17.883	0.011
2	1.699	1.121	-0.021	8.690	-0.005	1.706	1.122	-0.021	8.280	-0.005
3	1.623	1.059	-0.005	12.081	-0.014	1.627	1.059	-0.005	12.008	-0.013
4	1.551	1.025	0.006	12.927	-0.021	1.554	1.025	0.005	12.872	-0.019
5	1.482	1.009	0.013	13.156	-0.027	1.485	1.007	0.012	13.128	-0.026
6	1.439	0.983	0.023	13.340	-0.036	1.444	0.978	0.023	13.351	-0.035
8	1.354	0.971	0.031	13.623	-0.045	1.357	0.970	0.029	13.634	-0.042
10	1.296	0.951	0.042	13.960	-0.056	1.299	0.947	0.041	13.923	-0.054
15	1.198	0.959	0.049	14.388	-0.060	1.202	0.952	0.049	14.311	-0.059

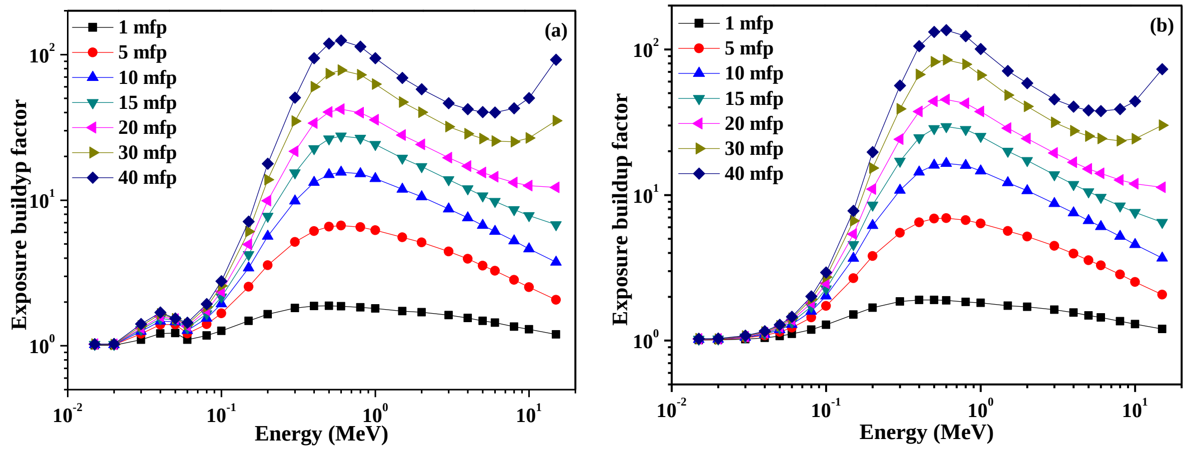
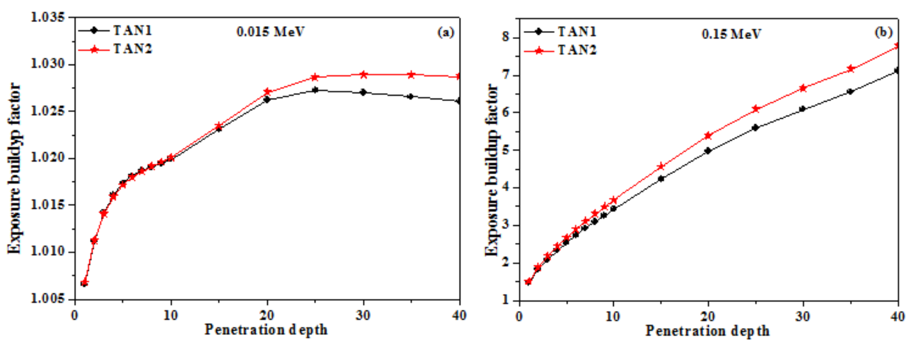


Fig. 6. (a-b) Variation of EBF of TAN1 and TAN2 alloys with photon energy

The differentiation of exposure buildup factors (EBFs) of both alloys with photon energy are shown in Fig. 6 (a–b). The EBFs of both alloys are small in low photon energy range and maximum peak at 0.6 MeV in intermediate energy range. The differentiation of EBFs can be discusses by Z of elements and interaction cross section dependency upon photon energy. The Z_{eq} of mixture have similar roles with Z of an element. The EBF values of both alloys are low in low energy range because photoelectric absorption is major process as the interaction cross section is directly proportional to Z^{4-5}/E^{3-4}. In intermediate energy range which Compton scattering dominates, EBF values increase with increasing in photon energy because of multiple scattering linearly to Z. In high energy range, pair production is dominant process because of dependency on Z^2 and log (E) [7].

For 30 and 40 mfp penetration depth, at high photon energy range (>8 MeV), the EBFs were increased for both alloys. The reason for such variation is chemical composition dependency of alloys same as concretes [1].



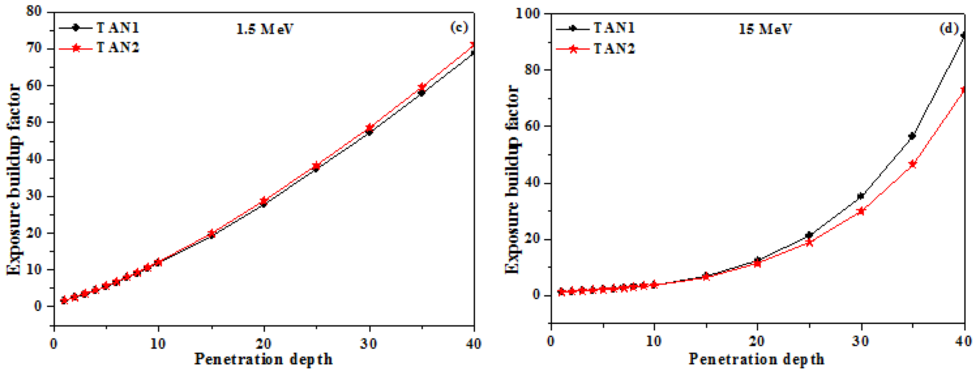


Fig. 7. (a-d) Variation of EBF of Alloys with penetration depth

Figure 7 (a–d) shows the EBFs of both alloys with penetration depth at photon energies 0.015, 1.5, 5, and 15MeV. It found that the EBF values of both alloys increased with increasing photon energy and penetration depth. The EBF values of TAN1 alloy is found lower than TAN2 at photon energies 0.15, 0.15, and 1.5MeV up to 40 mfp. When photon energy increases, EBF values saturate in higher penetration depths. At photon energy 15 MeV, EBF of TAN2 showed lower than TAN1. It is because of pair/triplet production in alloy which produces electron/positron pair. The remaining positron is destroyed by electrons to produce secondary photon of 0.511 MeV. In low penetration depth, these photons may escape from alloy thickness whereas multiple scattering will happen in large penetration depths.

IV. Conclusions

In this context, the mass attenuation coefficients, effective atomic number, effective electron density, half value layer has been computed by WinXCom software at energy range 1 keV-100 MeV. TAN1 was found to be better than TAN2 for shielding material at energy 1 keV-100 MeV. The exposure buildup factor (EBF) for gamma rays of alloys have been computed for photon energy 0.015–15 MeV up to 40 mfp penetration depth. It found that EBF of alloys have maximum values at intermediate energy range which Compton scattering is major photon interaction process. That indicated EBF values depend on fraction by weight of alloy in lower energy range and slight dependence in the region, higher energy. The EBF values of TAN1 are found lower TAN2 in low-to-intermediate energy (<3 MeV), thus it has better gamma ray shielding properties. These results indicated that it can develop for gamma rays

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Dr. R.K. Chanana " Radiation Shielding Properties and Exposure Buildup Factor of TI-Al-Nb Alloy Materials." IOSR Journal of Applied Physics (IOSR-JAP) , vol. 11, no. 2, 2019, pp. 68-74.