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Comparison Photon Exposure and Energy Absorption Buildup Factors of CR-39 and Trivex Optical Lenses

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Abstract: In the present study, Energy Absorption Buildup Factor (EABF) and Exposure Buildup Factors (EBF) of the CR-39 and Trivex optical lenses are calculated by using the Geometric Progression (GP) fitting method based on ANSI/ANS-6.4.3 database. The study analyses comprehensively for different penetration depths within the energy range of 0.015 - 15 MeV up to 40 mfp. The buildup factors are calculated in the examined materials depending on the photon energy that arrives, the penetration depths, and the chemical composition of the material reach at maximum values in the energy region where inconsistent scattering interaction probabilities are intensive. The results show that the CR-39 optical lens had better radiation shielding performance. The suitability of the results is compared with the powerful software tools (EPICS2017 and Phy-X/PSD), which are preferred frequently in the literature to calculate radiation shielding parameters. It is found that the relative changes between the EPICS2017 and Phy-X/PSD software compared with the results of this study are about 8% and 9% for the CR-39 and Trivex optical lens, respectively. This indicates that the results from the study are in good agreement.

Key words: CR-39, Trivex Optical lenses, Buildup factors, EPICS2017 Library, Phy-X/PSD Software.

CR-39 ve Trivex Optik Lenslerinin Foton Maruz Kalma ve Enerji Soğurma Buildup Faktörlerinin Karşılaştırılması

Öz: Bu çalışmada CR-39 ve Trivex optik lenslerinin enerji absorpsiyon buildup faktörü (EABF) ve maruz kalma buildup faktörleri (EBF), geometrik ilerleme (GP) uydurma yöntemi kullanılarak ve ANSI/ANS-6.4.3 veri tabanı dikkate alınarak hesaplanmıştır. Çalışma 0.015 ila 15 MeV enerji aralığında ve 40 mfp'ye kadar farklı penetrasyon derinliği için kapsamlı bir şekilde analiz edilmiştir. İncelenen materyallerde hesaplanılan her iki buildup faktörünün gelen fotonun enerjisine, penetrasyon derinliklerine ve materyalin kimyasal bileşimine bağımlılık gösterdiği ve tutarsız saçılma etkileşim olasılıklarının baskın olduğu enerji bölgesinde maksimum değerlerine ulaştığı bulundu. Sonuçlar, CR-39 optik lensinin daha iyi radyasyon koruma performansına sahip olduğunu gösterdi. Sonuçların uygunluğu radyasyon koruyucu parametrelerin hesaplanmasında literatürde sıklıkla tercih edilen EPICS2017 ve Phy-X/PSD güçlü yazılım araçları ile karşılaştırıldı. EPICS2017 ve Phy-X/PSD yazılımları ile bu çalışmadan elde edilen sonuçlar arasında nispi değişikliklerin CR-39 ve Trivex Optik lensi için sırasıyla %8, %9 olduğu bulundu. Bu, çalışmadan elde edilen sonuçların iyi bir uyum gösterdiğini belirtmektedir.

Anahtar kelimeler: CR-39, Trivex Optik lensleri, Buildup Faktörü, EPICS2017 Kütüphanesi, Phy-X/PSD Yazılımı.

1. Introduction

CR-39 is a type of plastic in which the optical, mechanical, and physical features of glass are combined. It is used widely in the optical industry with chemical structure and composition for, processing and coatings and it has structure lighter than mineral glasses. CR-39 Resin (Columbia Resin) developed by Pittsburgh Plate Glass Company (PPG) is known also as Allyl Diglycol Carbonate (ADC). The lenses made from CR-39 polymer are resistant against scratches, heat, and household chemicals [1–3]. In addition to their optical use in eyeglass lenses, they are also used in detectors and glass-reinforced fuel tanks for fighter planes to detect radioactive particles such as alpha and protons. The PPG focused on Trivex optical lens is lighter material, in 2001. This lens has excellent impact resistance, and is preferred highly in the optical industry. Trivex lenses are polyurethane, and have optical quality, light weight, and safety features. They are named based on these features [3]. They are also lighter than the CR-39 optical lens [3,4].

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The uses of these lenses are preferred in the optical industry, and especially they increase in eyeglasses, with their importance even more. For this reason, it is important to determine the radiation shielding features of optical lenses.The radiation shielding features differ according to the type of the optical lens used. The World Health Organization (WHO) issued an urgent international public health warning as Public Health Emergency of International Concern (PHEIC) on January 30, 2020, which included recommendations for the use of goggles or face shields to protect against eye contamination of CoV [5]. There are some reports on its effect on the eye in the recent CoVid-19 pandemic [6,7].

The buildup factors for CR-39 and Trivex optical lenses were investigated in the present study by using gamma rays within 0.015-15 MeV energy range. These Gamma rays pass through a medium that interact with the atoms of the substance as a result of which some of them are absorbed or scattered, which creates fluorescence, pair production, and Bremsstrahlung secondary photons. The buildup factors stand for the contribution of secondary photons to the number of photons present at a specific point. It is also defined as the rate of the total amount of photons at a fixed point to the number of photons that arrive at that point without any interaction [8,9]. Buildup factors are evaluated in two classes, which are the Exposure Buildup Factor (EBF) and the Energy Absorption Buildup Factor (EABF). The quantity of interest in EBF is the exposure to incoming photons, and it is the amount of energy stored or absorbed in the material interacting with the photon in EABF [10]. In this study, the database is prepared by the American Nuclear Society (ANS) Standards Committee Work Group ANS-6.4.3 [11] and approved by the American National Standards Institute (ANSI) and then taken as the reference to calculate the buildup factors. The data include a compilation of the Geometric-Progression (G-P) fitting parameters for penetration depths of up to 40mfp (i.e. the mean free path) within the 0.015-15MeV energy range [8,12]. The G-P fitting formula by Harima (1983) and Harima et al. (1986, 1991) is used to determine the buildup factors that took into account multiple scattering. All the results obtained in this study are compared with powerful tools e.g. EPICS2017 [13] and Phy-X/PSD [14] that made radiation shielding parameters, and the results are found as compatible.

2. Materials and Methods

The chemical formula of CR-39 is $(C_{12}H_{18}O_7)_n$, where the elemental compositions of C, H and O contents are 52.6% wt, 6.6% wt and 40.8% wt, respectively. The chemical formula of Trivex is $(C_{11}H_{18}N_2)_n$, with the elemental compositions of C, H and N contents are 74.1% wt, 10.2% wt and 15.7% wt, respectively. Some other features of CR-39 and Trivex optical lenses are given in Table 1 [1,3,4,15–17].

Tablo 1. Some of the physical and optical parameters for lenses

Parameters	**CR-39**	**Trivex**
Refractive index (n)	1.49	1.53
Abbe number	58	43-45
Density (g cm^{-3})	1.32	1.11
Average molecular weight (g/mol)	274.26	178.27
Molar Volume (V_m), (cm^3/mol)	207.77	160.60

It is expected that the polymer structures of the lenses are used commonly in the optical industry, and they have good radiation protection potential. The Equivalent Atomic Number (Z_{eq}), G-P fitting parameters, and EBF and EABF values of the CR-39 and Trivex optical lenses are examined and calculated in this study within the photon energy range of 0.015-15 MeV up to 40 mean free path (mfp) penetration depth. The EBF and EABF values are evaluated by the G-P Fitting method, which is a very convenient and precise approach in calculating EBF and EABF values. The mass attenuation coefficients (MAC) for CR-39 and Trivex optical lenses are obtained theoretically by using the XCOM Web Program [18], which provides convenience to the user with interface that is developed by NIST including a list to describe the material [19,20]. The MAC values of any element, compound or mixture can be assessed with this program for partial photon interactions such as atomic photoelectric effect, incoherent, coherent scattering, and pair production as well as for total photon interaction. MAC is an important parameter for description of how much incoming photon is absorbed, transmitted, and scattered when it interacts with the matter [21]. The amount of photon that is transmitted from a material is calculated by the Beer-Lambert $I = I_0 e^{-\mu x}$ law, which links the absorption of light in optics to the features of the material through which it passes [22–25]. Here I_o is the intensity of the incoming photon, I is the intensity of the transmitted photon, x is the thickness, and μ is the MAC value. Basically, this law applies under three conditions, which are monochromatic beam, thin absorber material, and narrow beam geometry. If one of the conditions is not met, then the law loses its validity. In such a case, it is changed as the Beer-Lambert $I = BI_0 e^{-\mu x}$, Law where B (E, x) is the buildup factor [9,21,26]. The photon buildup factor represents the amount of the secondary photons that are included in the total photon number at a specified point [9]. By using the G-P method with ANSI/ANS-6.4.3 database, the buildup factors take place in three steps after determining the equivalent atomic number (Z_{eq}), G-P fitting coefficients, and EBF/EABF values.

2.1. Computation of the equivalent atomic number (Z_{eq})

The MAC values are obtained for the selected CR-39 and Trivex lenses in the 0.015-15 MeV energy range by using the XCOM program. The Z_{eq} values are determined with the logarithmic interpolation method given in the following equation by using the ratio between the Compton partial mass attenuation coefficient $(\mu_m)_{Compton}$ and the total mass attenuation coefficients $(\mu_m)_{total}$ [27–30]. Z_{eq} is a parameter dependent on the energy of the incoming photon describing the features of a material in terms of equivalent elements in scattering interactions [14,31]. Basically, the accumulation of photons consists of multiple scattering resulting from the Compton scattering process. For this reason, the determination of Z_{eq} is based frequently on the $(\mu_m)_{Compton}$ calculation [30].

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1} \quad (1)$$

Here R's are the $(\mu_m)_{Compton}/(\mu_m)_{total}$ ratio. Z_1 and Z_2 refer to the atomic numbers of the elements corresponding to the ratios of R_1 and R_2, respectively.

2.2. Computation of the G-P fitting coefficients

The geometric-progression (G-P) fitting formula by Harima (1983) [29] and Harima et al (1986, 1991) [32,33] has been used widely to calculate the buildup factors (EABF and EBF) for a wide variety of materials [34]. G-P fitting parameters for the elements are obtained from the database of the American Nuclear Society standard ANSI/ANS 6.4.3 [11]. The ANSI/ANS 6.4.3 standard database has compiled G-P fitting parameters and buildup factor data up to 40 mfp in the photon energy range of 0.015-15 MeV for 23 elements in addition to a compound (water) and two mixtures (air and concrete). Mfp (mean free path) is the path taken by the photon between two interactions. In this study, the Z_{eq} values are calculated for the CR-39 and Trivex optical lenses as in the previous step; the G-P fitting coefficients (a, b, c, d and X_k) are calculated according to the following expression.

$$P = \frac{P_1(\log Z_2 - \log Z_{eq}) + P_2(\log Z_{eq} - \log Z_1)}{\log Z_2 - \log Z_1} \quad (2)$$

where the P's are the G-P fitting coefficients corresponding to the Z atomic numbers at the determined energy.

2.3. Computation of the buildup factors

EBF and EABF values are obtained from the following equations using the G-P fitting parameters for the CR-39 and Trivex optical lenses in the previous step [32]. The buildup factor is expressed as a function of mfp [30].

$$B(E,x) = 1 + (b-1) \times \begin{cases} \dfrac{K^x - 1}{K - 1} & K \neq 1 \\ x & K = 1 \end{cases} \quad (3)$$

$$K(E,x) = cx^a + d\,\frac{\tanh(x/X_k - 2) - \tanh(-2)}{1 - \tanh(-2)} \quad for\ x \leq 40\ mfp \quad (4)$$

Here, E is the photon energy, x is the mfp value, and a, b, c, d and X_k are the G-P fitting coefficients. The b coefficient corresponds to the buildup factor in 1 mfp. The parameter K (E, x) expresses the photon dose multiplier and the change in the shape of the spectrum at 1 mfp.

3. Results and Discussion

The buildup factors are calculated for the CR-39 and Trivex optical lenses using the procedure as described above. It is necessary to know the Z_{eq} and G-P fitting coefficients to calculate the buildup factors according to the G-P fitting method. The MAC values from the XCOM program are used in the photon energy range of 0.015-15 MeV to calculate the Z_{eq} values of the optical lenses that are considered in the study. The G-P fitting coefficients of these optical lenses are evaluated in the photon energy range of 0.015-15 MeV using the ANSI Database. Some results are given in Tables 2-5 for the examined optical lenses that. The dependency of the calculated buildup factors on Z_{eq}, incoming photon energy and mfp is discussed in the following parts. All the results of this study are compared with powerful software such as EPICS2017 and Phy-X/PSD. EPICS2017 calculates the photon attenuation and accumulation factors for the energy absorption and exposure. The data library is formed by interpolation of the relevant photon energies in the ENDF-6 [35] data format on IAEA-NDS website. Phy-X/PSD is an online software that is developed to calculate various radiation shielding parameters. The WinXCOM software is useful to generate the data library. The deviation percentages (Dev.%) between the buildup factors are obtained from the EPICS2017 and Phy-X/PSD software according to Equation 5, and some of the buildup factors are given in Tables 4 and 5. The maximum EBF deviations are between Phy-X/PSD and EPICS2017 software as 7.889 for CR-39 and 9.322 for Trivex. The maximum deviations are 4.230 for CR-39, 6.351 for Trivex for the EABF values, which indicates that the results are compatible.

$$Dev. = \left|\left(\frac{(EBF)_{EPICS2017} - (EBF)_{XCOM}}{(EBF)_{XCOM}}\right)\right| \times 100 \qquad (5)$$

Tablo 2. G-P fitting parameters (exposure and absorption) calculated in this work for CR-39

Energy (MeV)	Z_{eq}	EBF					EABF				
		a	b	c	d	X_k	a	b	c	d	X_k
0.015	6.7447	0.1648	1.2729	0.4906	-0.0824	14.2911	0.1611	1.2738	0.4940	-0.0782	14.5319
0.02	6.7589	0.1178	1.6236	0.6199	-0.0578	15.4035	0.1207	1.6345	0.6150	-0.0593	15.2654
0.03	6.7702	0.0357	2.8229	0.9092	-0.0293	15.0661	0.0350	2.9259	0.9098	-0.0274	15.2930
0.04	6.7770	-0.0690	4.2368	1.3787	0.0271	13.6567	-0.0672	4.2241	1.3677	0.0251	13.8412
0.05	6.7815	-0.1244	5.4041	1.7374	0.0539	13.9562	-0.1214	5.0296	1.7240	0.0518	14.0599
0.06	6.7861	-0.1624	5.8791	2.0269	0.0746	13.8894	-0.1578	5.1888	1.9914	0.0708	13.9971
0.08	6.7939	-0.2005	5.7148	2.3614	0.0912	13.5291	-0.1894	4.9021	2.2699	0.0822	13.6942
0.1	6.7986	-0.2008	5.3312	2.4111	0.0871	14.3662	-0.1886	4.5921	2.3117	0.0786	14.5252
0.15	6.8023	-0.2152	4.0590	2.5292	0.0966	14.1348	-0.1912	3.7035	2.3325	0.0768	14.5800
0.2	6.8049	-0.2117	3.4714	2.4601	0.0919	13.6414	-0.1819	3.3289	2.2243	0.0760	14.7911
0.3	6.8112	-0.1856	3.0048	2.1921	0.0789	14.1872	-0.1687	2.8364	2.0662	0.0669	14.4223
0.4	6.8132	-0.1686	2.7329	2.0169	0.0707	13.8948	-0.1506	2.6271	1.8985	0.0606	14.3832
0.5	6.8140	-0.1509	2.5647	1.8677	0.0646	14.1585	-0.1379	2.4627	1.7841	0.0566	14.3938
0.6	6.8149	-0.1365	2.4408	1.7567	0.0577	13.9871	-0.1232	2.3745	1.6713	0.0492	14.3736
0.8	6.8148	-0.1157	2.2542	1.6017	0.0514	13.9916	-0.1055	2.2026	1.5460	0.0437	14.1934
1	6.8161	-0.0984	2.1401	1.4863	0.0444	13.9690	-0.0871	2.1011	1.4383	0.0364	14.6302
1.5	6.1870	-0.0669	2.0007	1.3029	0.0315	13.8816	-0.0599	1.9397	1.2748	0.0264	14.3027
2	6.1626	-0.0433	1.8960	1.1893	0.0200	14.0267	-0.0373	1.8420	1.1680	0.0148	14.4658
3	6.1560	-0.0140	1.7468	1.0584	0.0058	12.2964	-0.0113	1.7141	1.0508	0.0029	14.1578
4	6.1526	0.0040	1.6498	0.9865	-0.0074	24.0742	0.0037	1.6262	0.9888	-0.0028	13.0639

5	6.1516	0.0172	1.5730	0.9392	-0.0112	14.3983	0.0151	1.5641	0.9451	-0.0081	14.8325
6	6.1503	0.0266	1.5236	0.9071	-0.0155	14.0908	0.0281	1.5161	0.9039	-0.0181	13.1077
8	6.1475	0.0373	1.4376	0.8709	-0.0320	16.2444	0.0341	1.4295	0.8828	-0.0170	12.1088
10	6.1458	0.0414	1.3713	0.8577	-0.0211	12.5927	0.0398	1.3759	0.8604	-0.0221	14.3094
15	6.1449	0.0463	1.2752	0.8410	-0.0303	15.2397	0.0472	1.2812	0.8384	-0.0328	15.7840

Tablo 3. G-P fitting parameters (exposure and absorption) calculated in this work for Trivex

Energy (MeV)	Z_{eq}	EBF					EABF				
		a	b	c	d	X_k	a	b	c	d	X_k
0.015	5.8161	0.1379	1.4398	0.5616	-0.0677	14.4122	0.1435	1.4538	0.5490	-0.0725	14.5000
0.02	5.8315	0.0698	1.9858	0.7662	-0.0359	16.1229	0.0673	2.0145	0.7720	-0.0344	16.3288
0.03	5.8421	-0.0402	3.6807	1.2242	0.0147	13.0577	-0.0393	3.8743	1.2231	0.0139	12.8917
0.04	5.8453	-0.1373	5.4860	1.8151	0.0602	14.0005	-0.1353	5.1513	1.8033	0.0586	14.1345
0.05	5.8528	-0.1775	6.9258	2.1829	0.0769	14.3679	-0.1700	5.6279	2.1257	0.0714	14.5246
0.06	5.8564	-0.2046	7.4053	2.4571	0.0905	14.5334	-0.1905	5.4220	2.3387	0.0802	14.7032
0.08	5.8633	-0.2315	6.9387	2.7520	0.1014	14.4911	-0.2068	4.8291	2.5267	0.0835	14.8626
0.1	5.8643	-0.2401	6.1882	2.8500	0.1035	14.5727	-0.2112	4.2682	2.5798	0.0834	14.9422
0.15	5.8506	-0.2470	4.5611	2.8895	0.1073	14.2674	-0.2042	3.5238	2.4950	0.0765	15.2121
0.2	5.8712	-0.2381	3.7759	2.7568	0.1080	15.0281	-0.1951	3.1764	2.3653	0.0744	15.0837
0.3	5.8737	-0.2170	3.1521	2.4693	0.0980	14.3763	-0.1759	2.7888	2.1387	0.0697	14.9957
0.4	5.8752	-0.1978	2.8481	2.2436	0.0837	13.3713	-0.1544	2.6200	1.9354	0.0634	14.8063
0.5	5.8758	-0.1764	2.6618	2.0498	0.0823	14.0470	-0.1390	2.4534	1.8070	0.0618	15.9483
0.6	5.8764	-0.1559	2.5465	1.8831	0.0657	13.5971	-0.1198	2.3959	1.6680	0.0461	14.9729
0.8	5.8768	-0.1367	2.3180	1.7127	0.0669	13.7550	-0.1095	2.1968	1.5658	0.0464	14.0932
1	5.8764	-0.1127	2.1998	1.5579	0.0553	13.7519	-0.0934	2.0864	1.4631	0.0408	14.1655
1.5	5.2502	-0.0791	2.0563	1.3541	0.0433	13.7533	-0.0612	1.9388	1.2808	0.0275	14.3136
2	5.2328	-0.0483	1.9396	1.2075	0.0261	14.2773	-0.0407	1.8379	1.1757	0.0180	14.1990
3	5.2296	-0.0171	1.7777	1.0645	0.0095	12.5315	-0.0125	1.7160	1.0515	0.0047	13.2708
4	5.2250	0.0055	1.6759	0.9805	-0.0053	19.1483	0.0038	1.6281	0.9890	-0.0031	14.4484
5	5.2246	0.0177	1.5921	0.9351	-0.0101	14.9222	0.0162	1.5680	0.9437	-0.0092	14.1768
6	5.2246	0.0260	1.5363	0.9065	-0.0144	14.7317	0.0276	1.5264	0.9033	-0.0154	12.9421
8	5.2238	0.0357	1.4470	0.8683	-0.0237	14.8066	0.0404	1.4463	0.8625	-0.0212	11.3814
10	5.2236	0.0412	1.3811	0.8510	-0.0186	13.1120	0.0401	1.3871	0.8555	-0.0212	14.4388
15	5.2215	0.0475	1.2831	0.8340	-0.0256	14.2945	0.0470	1.2923	0.8353	-0.0279	14.5319

Tablo 4. Comparison of buildup factors from Phy-X/PSD, EPICS2017 and this work for CR-39

Energy (MeV)	EBF for 1 mfp			EBF for 5 mfp			EBF for 10 mfp			EBF for 40 mfp		
	Phy-X/ PSD	EPICS 2017	This work	Phy-X/ PSD	EPICS 2017	This work	Phy-X/ PSD	EPICS 2017	This work	Phy-X/ PSD	EPICS 2017	This work
0.015	1.2708	1.2705	1.2729	1.6691	1.6683	1.6744	1.9108	1.9096	1.9180	2.6201	2.6177	2.6317
0.1	5.3381	5.3365	5.3312	89.6972	89.5769	89.5267	551.7521	550.5560	548.7464	60337.2317	60070.6000	58189.1673

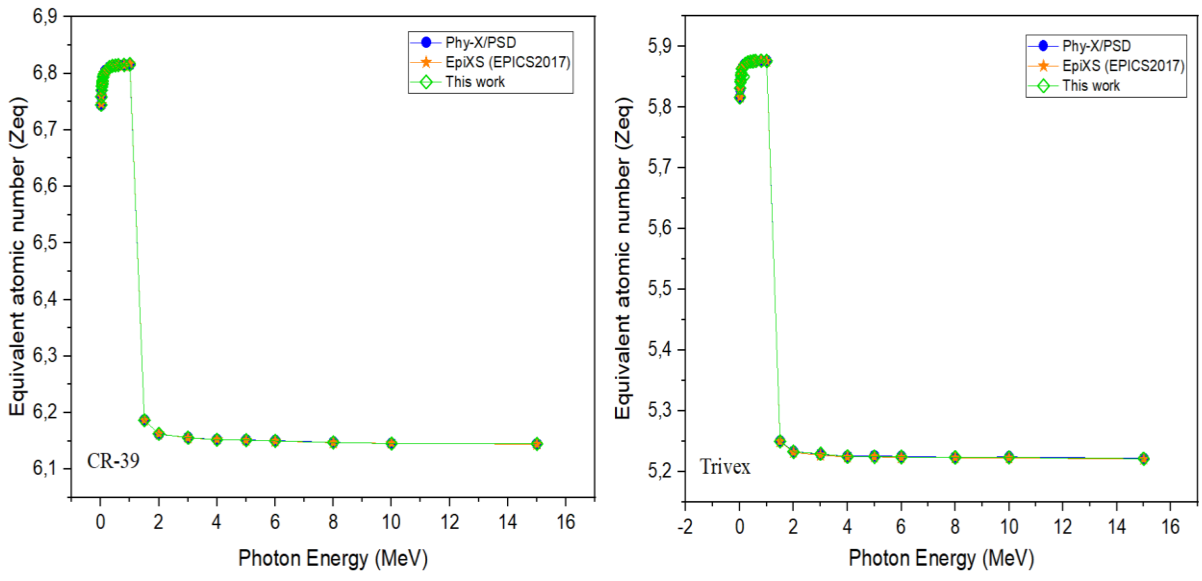
0.2	3.4601	3.4601	3.4714	51.5413	51.5400	51.9123	298.7471	298.7350	303.3430	19721.7098	19720.1000	21410.9834
1.5	2.0024	2.0025	2.0007	8.0396	8.0400	8.0266	18.4882	18.4891	18.4502	108.2787	108.2820	107.8566
3	1.7463	1.7464	1.7468	5.0025	5.0026	5.0040	9.3736	9.3738	9.3738	37.9086	37.9092	37.8260
15	1.2752	1.2752	1.2752	2.1397	2.1397	2.1395	3.0653	3.0653	3.0652	7.9250	7.9248	7.9268
Energy (MeV)	EABF for 1 mfp			EABF for 5 mfp			EABF for 10 mfp			EABF for 40 mfp		
0.015	1.4443	1.4442	1.4398	2.2362	2.2357	2.2196	2.7882	2.7875	2.7607	4.6767	4.6749	4.5985
0.1	6.1872	6.1882	6.1882	146.0108	146.0500	146.7632	1152.5615	1152.9800	1159.4548	208977.6072	209124.0000	204136.5642
0.2	3.7711	3.7711	3.7759	72.0774	72.0744	72.0285	502.3245	502.2900	501.0687	48246.3886	48240.4000	47726.6145
1.5	2.0578	2.0579	2.0563	8.7816	8.7823	8.7531	20.6700	20.6721	20.5497	126.1588	126.1770	123.8823
3	1.7769	1.7770	1.7777	5.1885	5.1890	5.1775	9.7418	9.7426	9.6777	39.0314	39.0337	37.6838
15	1.2836	1.2836	1.2831	2.1576	2.1577	2.1589	3.0696	3.0696	3.0790	7.7658	7.7657	7.9264

Tablo 5. Comparison of buildup factors from Phy-X/PSD, EPICS2017 and this work for Trivex

Energy (MeV)	EBF for 1 mfp			EBF for 5 mfp			EBF for 10 mfp			EBF for 40 mfp		
	Phy-X/ PSD	EPICS 2017	This work	Phy-X/ PSD	EPICS 2017	This work	Phy-X/ PSD	EPICS 2017	This work	Phy-X/ PSD	EPICS 2017	This work
0.015	1.4443	1.4442	1.4398	2.2362	2.2357	2.2196	2.7882	2.7875	2.7607	4.6767	4.6749	4.5985
0.1	6.1872	6.1882	6.1882	146.0108	146.0500	146.7632	1152.5615	1152.9800	1159.4548	208977.6072	209124.0000	204136.5642
0.2	3.7711	3.7711	3.7759	72.0774	72.0744	72.0285	502.3245	502.2900	501.0687	48246.3886	48240.4000	47726.6145
1.5	2.0578	2.0579	2.0563	8.7816	8.7823	8.7531	20.6700	20.6721	20.5497	126.1588	126.1770	123.8823
3	1.7769	1.7770	1.7777	5.1885	5.1890	5.1775	9.7418	9.7426	9.6777	39.0314	39.0337	37.6838
15	1.2836	1.2836	1.2831	2.1576	2.1577	2.1589	3.0696	3.0696	3.0790	7.7658	7.7657	7.9264
Energy (MeV)	EABF for 1 mfp			EABF for 5 mfp			EABF for 10 mfp			EABF for 40 mfp		
0.015	1.4584	1.4582	1.4538	2.2567	2.2563	2.2357	2.8122	2.8115	2.7706	4.7291	4.7272	4.5525
0.1	4.2714	4.2713	4.2682	78.8384	78.8426	78.8725	567.7329	567.8160	568.1815	97565.4832	97608.1000	97158.0623
0.2	3.1825	3.1825	3.1764	44.1534	44.1532	44.1546	263.0272	263.0240	263.2623	21207.7910	21206.9000	21144.1716
1.5	1.9366	1.9366	1.9388	7.4671	7.4671	7.4704	17.0071	17.0072	16.9911	101.1113	101.1130	100.5558
3	1.7150	1.7150	1.7160	4.8122	4.8122	4.8064	8.9519	8.9518	8.9104	35.7384	35.7372	34.8036
15	1.2921	1.2922	1.2923	2.1965	2.1966	2.1979	3.1442	3.1443	3.1482	7.8822	7.8822	7.9302

3.1. The depence of buildup factors on Z_{eq}

The Z_{eq} values for CR-39 and Trivex optical lenses are given in Tables 2, 3 and they indicate that Trivex had lower values than CR-39. Although Z_{eq} depends on the incoming photon energy it differed for all materials, because of the differences in the materials chemical structure. It is seen in Figure 2. (a-d) that the buildup factors depend on the chemical composition. The fact that the Trivex had higher buildup factor values than CR-39 may be associated with Trivex's lower Z-element polymer structure. The size of the accumulation factors and their dependence on Z_{eq} vary depending on the energy region in question. Although the Z_{eq} values for both optical lens materials had small values in the low and high energy regions, they have high values in the medium energy region, which can be explained by the dominance of the photon interaction process. Z_{eq} has the maximum value in the region dominated by Compton scattering as there is a strong dependence on Z_{eq} in this energy region. Low Z_{eq} values occur because of the dominance of photoelectric interactions in the low energy region and pair production interactions in the high energy region. It is seen from Figure 3 (a-d) that the buildup factors at 0.015 and 0.15 MeV are inversely proportional to Z_{eq} for all determined mfps. The buildup factors of the lens materials at 1.5 and 15 MeV are nearly constant for all mfps, which indicates that the buildup factors are independent of Z_{eq} and of the chemical structure of the material.

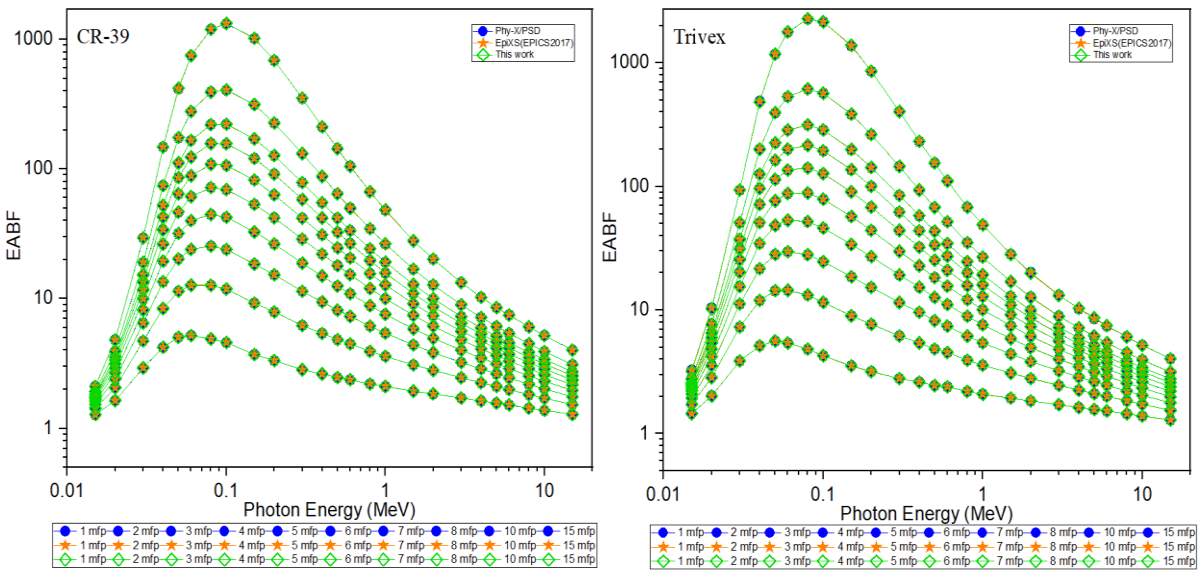


(a) (b)

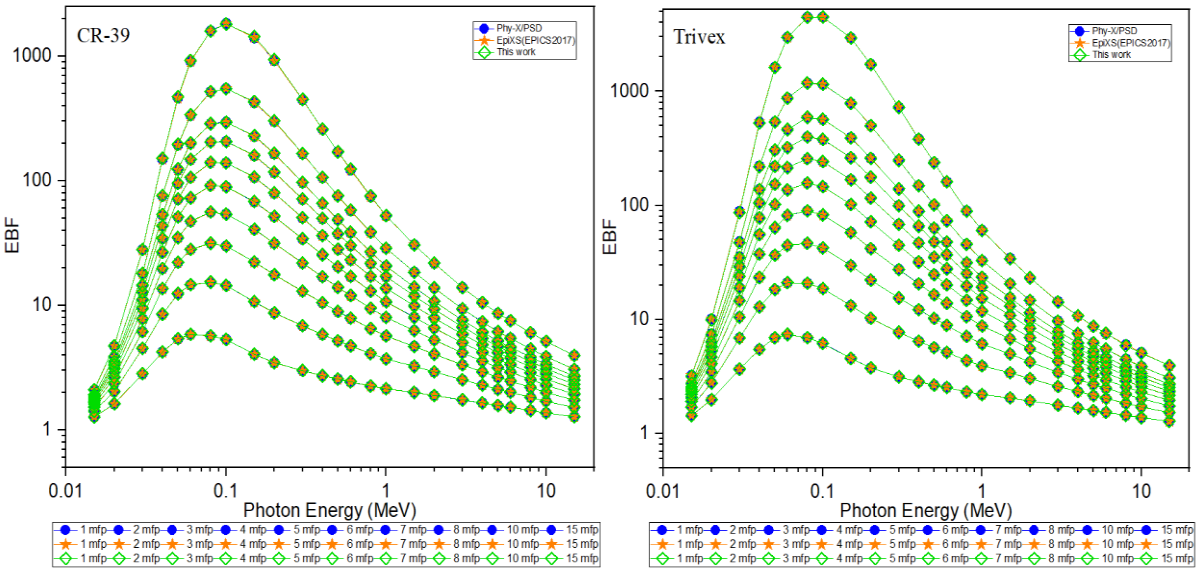
Figure 1. (a–b) Equivalent atomic numbers of the CR-39 and Trivex optical lenses with photon energy.

3.2. The depence of buildup factors on incident photon energy

It is seen that the EBF and EABF changes calculated for the CR-39 and Trivex optical lenses and given in Table 2 and 3 are similar. In the low energy range, photoelectric is dominant, and in the high energy range, the absorption of photons is more because the pair production is dominant. Thus, the lifetime of photons in optical materials is short. This is Figure 2. When (a-d) is examined, it can be explained as the reason for the formation of less buildup factor in low and high energy regions. In the intermediate energy region, since Compton scattering is dominant, only the energies of the photons change and their lifetimes in the material are longer. This causes more buildup factor in the material. Maximum buildup occurs in the intermediate energy range where scattering increases [9]. Maximum buildup factor values for CR-39 and Trivex optical lens materials were approximately 58189 and 204136, respectively. In the intermediate energy values where Compton scattering is dominant, the buildup factor values are independent of the chemical composition.



(a) (b)

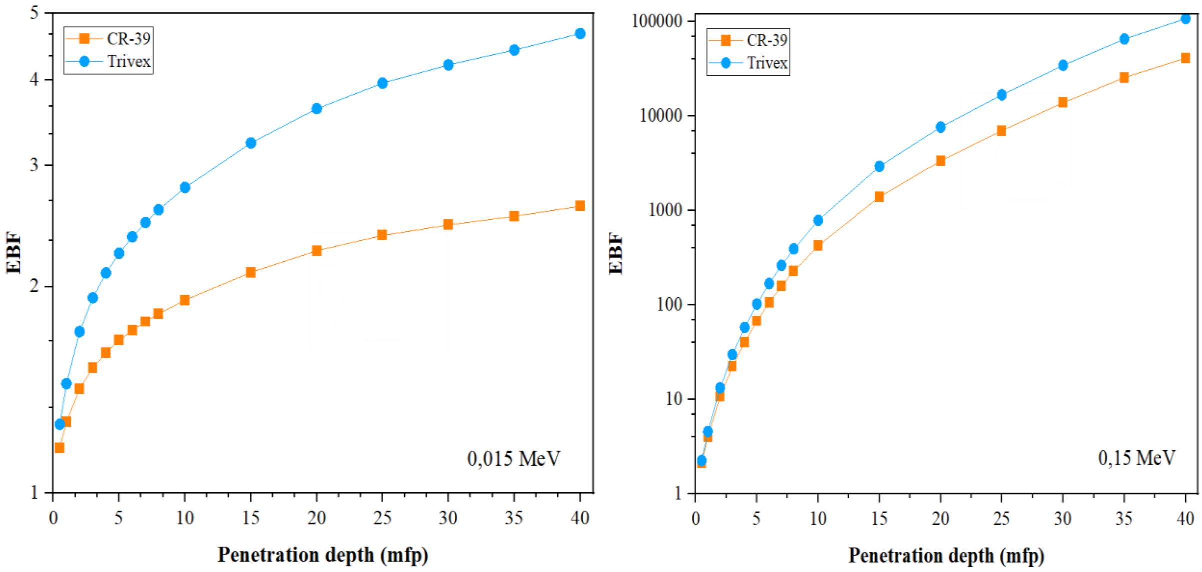


(c) (d)

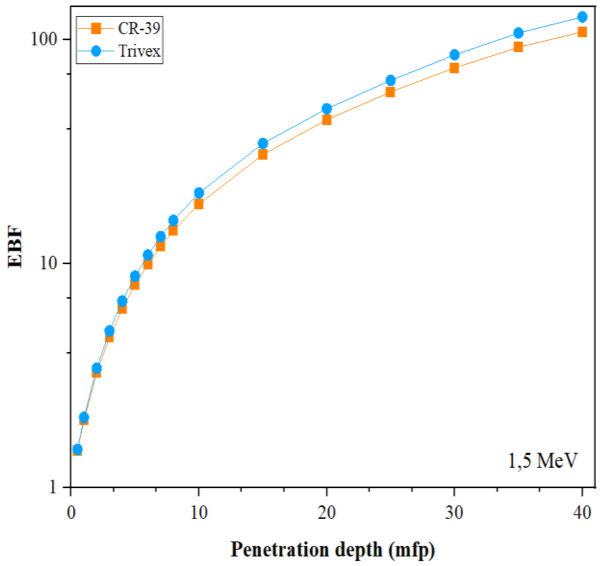
Figure 2. (a–d) The buildup factors in the energy region 0.015–15 MeV at the 1–15 mfp for CR-39 and Trivex optical lenses.

3.3. The depence of buildup factors on penetration depth

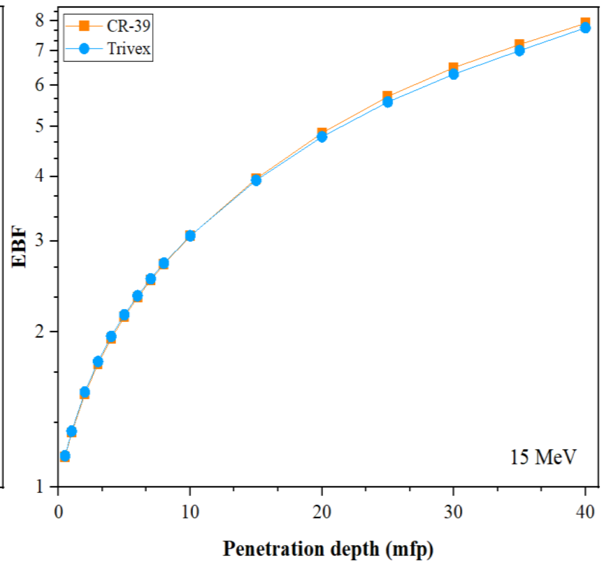
The variation of mfp for CR-39 and Trivex optical lenses at some specific photon energies such as 0.015, 0.15, 1.5 and 15 MeV is given in Figure 3 (a–d) and Figure 4 (a–d). In general, an increase in buildup factors is valid as increasing mfp values. This observation arises from the fact that the big mfp is proportional to the photon scattering. Maximum buildup factors for the optical materials study range are from 41833-58189 to 99626-204136 for CR-39 and Trivex, respectively. The buildup factor results reveal that the EBF effect should be considered at high penetration depths.



(a) (b)

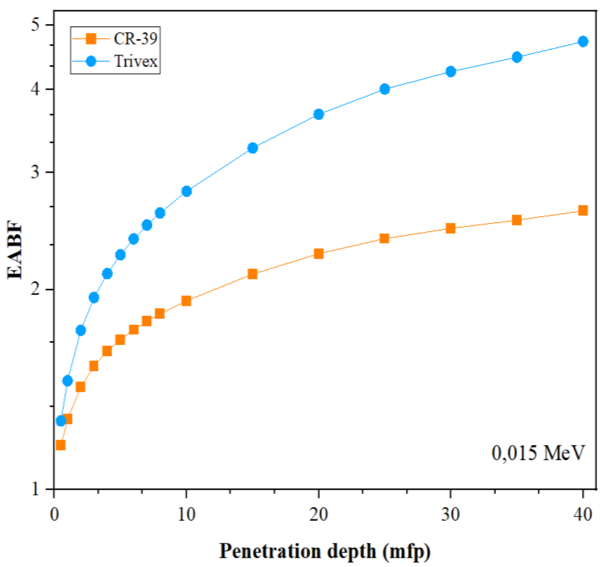


(c)

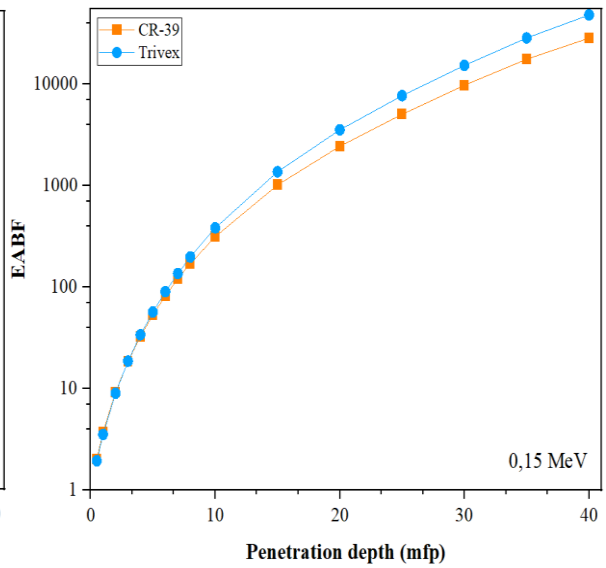


(d)

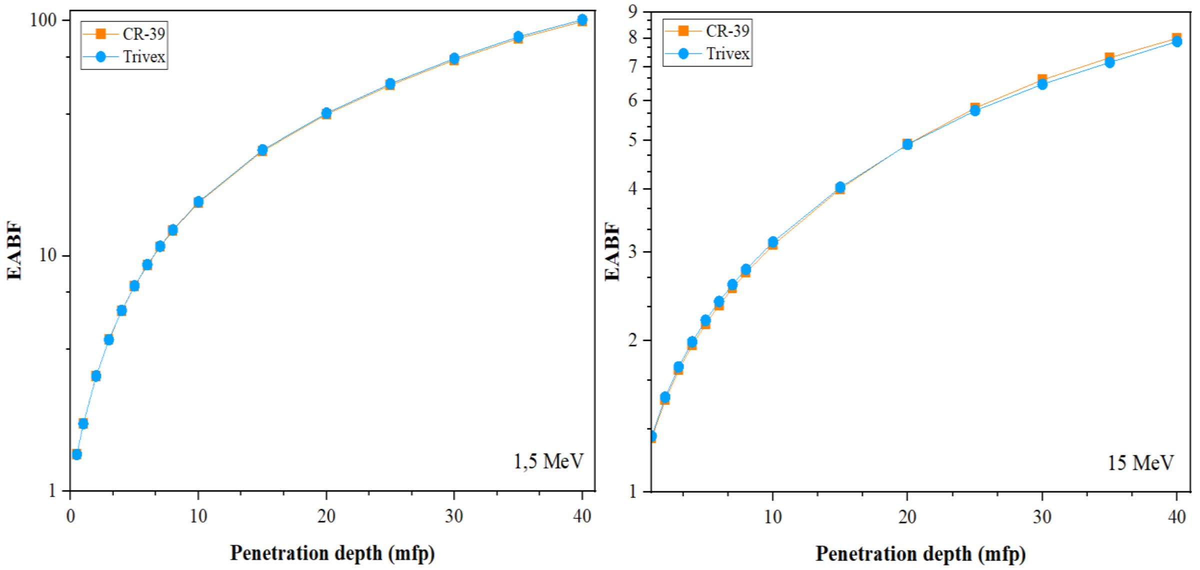
Figure 3. (a–d) The exposure buildup factors in the energies 0.015,0.15,1.5 and 15 MeV at the 1–40 mfp for CR-39 and Trivex optical lenses.



(a)



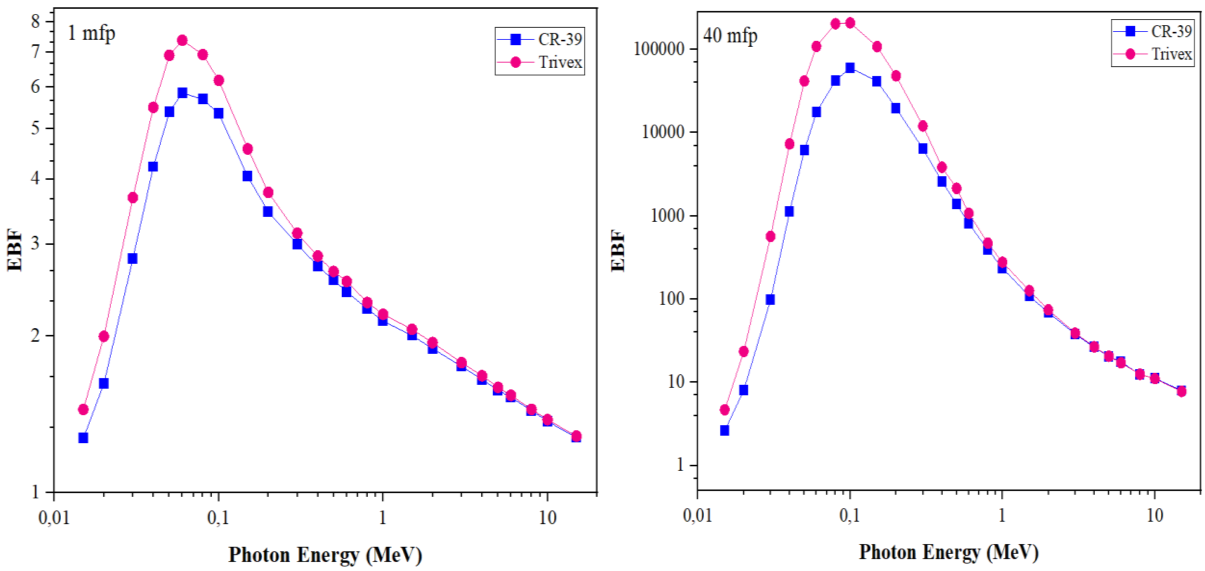
(b)



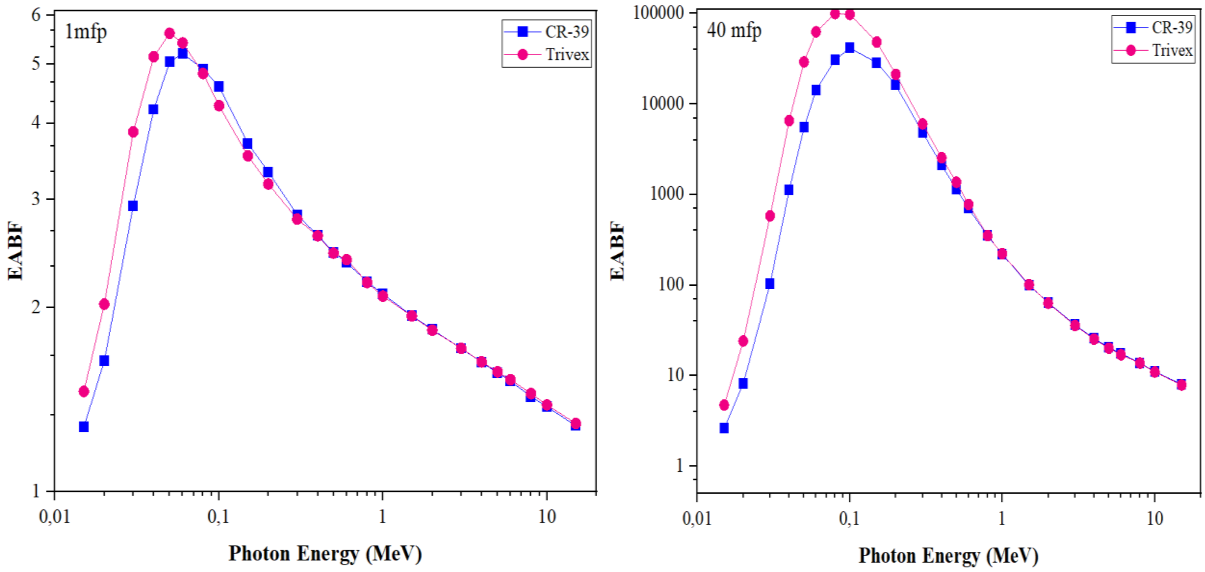
(c) (d)

Figure 4. (a–d) The energy absorption buildup factors in the energies 0.015,0.15,1.5 and 15 MeV at the 1–40 mfp for CR-39 and Trivex optical lenses

The variation of the accumulation factors at 1 and 40 mfp for CR-39 and Trivex optical glasses is given in Figure 5 (a-d). It is seen that the maximum EABF values are 5.196-41833 and 5.627-99626, respectively for CR-39 and Trivex optical glasses at 1 and 40 mfp, and the maximum EBF values are 5.879-58189 and 7.405-204136, respectively. Furthermore, CR-39 had lower buildup values, which indicate that CR-39 had a greater absorption effect than scattering. Like the explanations given above, it is obvious that the accumulation effects are much higher in the intermediate energy region, where Compton scattering is dominant and tended to decrease in the high energy region at dominant pair production. The chemical composition of the investigated materials had no impact on the accumulation factor values in the high-energy region.



(a) (b)



(c) (d)

Figure 5. (a–d) The energy absorption buildup factors in the energy region 0.015–15 MeV at 1 and 40 mfp for CR-39 and Trivex optical lenses

4. Conclusion

In the present study, the compatibility of the results is analysed by the buildup factor values that are obtained from the XCOM and the EPICS2017 library and Phy-X/PSD software, which are frequently preferred in the literature to determine radiation shielding features. It is found that the relative changes between the EPICS2017 and Phy-X/PSD software and the results obtained in this study are 8% and 9%, respectively for the CR-39 and Trivex optical lens, which indicate good agreement. Buildup factors (EBF and EABF) are important and required for radiation shielding in healthcare physics, nuclear laboratories, and optics. Good radiation shielding performance of the materials requires that the buildup factor values are small. In this respect, it is seen that the radiation shielding performance of CR-39 had better shield features among the examined optical lens materials. This is also a result of the CR-39 with higher Z_{eq} values. Figure 2 (a-d) indicates that the changes against the photon energy and mfp values are similar. There is a significant difference between the values, because the energy absorbed in the material is taken into account in the interaction of the material with the photon in EABF, and the absorption in the air in EBF. Although there are similar variations in the graphs in terms of the dependence of the buildup factors on incoming photon energy, namely mfp and Z_{eq}, it is discussed in the text that different photon interaction events are intense in the low, moderate, and high-energy regions of the buildup factors. Especially, Figure 2 (a-d), presents that both buildup factors reach maximum values in the moderate-energy region, where Compton scattering is dominant, and hence, supports the occurrence of multiple scattering in this region. It is important to note that the buildup factor increases in the energy region that has the Compton Scattering, and photon absorption is higher in the energy regions where photoelectric and pair production are dominant, and this causes the buildup factor to have lower values. In addition, it was observed that the differences between increasing energy and buildup factor values in CR-39 and Trivex optical lenses decreased significantly at 1.5 MeV (Figure 3c and Figure 4c). This can be explained by the fact that the variation of the buildup factors with the depth of penetration in this energy region is independent of the chemical composition of the material. After 1.5 MeV, it was observed that the order of the buildup factor changed (Figure 3d and Figure 4d). This is a consequence of the reduced probability of multiple scattering at higher penetration depths and the increased probability of the absorption effect. Because the pair production event with an initial energy of 1.02 MeV becomes more dominant with increasing energy.

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