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Akkuyu Nükleer Reaktörlerinde Kullanılabilecek olan Bazı Kontrol Çubuğu Tiplerinin Radyasyon Koruma Parametrelerinin İncelenmesi

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ÖZET

Kontrol çubukları, nükleer reaktörlerde çekirdekte oluşacak fisyonun kontrol edilmesi için kullanılır. Farklı reaktör tasarımlarında çeşitli enerjilerde bulunabilen nötronlar nedeniyle farklı kontrol çubuğu malzemeleri kullanmalıdır. Nötronları absorbe edebilen B_4C, ZrB_2, TiB_2 veya HfB_2 gibi kimyasal bileşiklerden yapılabilen bu malzemeler, çeşitli enerjilerdeki nötronlar için farklı absorpsiyon özelliklerine sahiptir. Bu çalışmada Akkuyu Nükleer Reaktörlerde kullanılabilecek kontrol çubukları araştırılmıştır. Bu kontrol çubuklarının yapısında B_4C, ZrB_2, TiB_2 veya HfB_2 gibi kimyasal bileşiklerin bulunabileceği ve lineer ve kütle zayıflama katsayıları (LAC, MAC), yarım ve onuncu değer kalınlıkları (HVL, TVL) ve ortalama serbest yol (MFP), atom numarası, elektron yoğunluğu (Zeff, Neff) ve etkin iletkenlik (Ceff) enerji parametreleri Phy-X yazılımı kullanılarak teorik olarak 1 keV ile 20 MeV arasında hesaplanmıştır.

Investigation of Radiation Protection Parameters of Some Control Rod Types that Can Be Used in Akkuyu Nuclear Reactors

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ABSTRACT

Control rods are used in nuclear reactors to control fission in the core. Different reactor designs must use different control rod materials because of the neutrons that can be found at various energies. These materials, which can be made of chemical compounds such as B_4C, ZrB_2, TiB_2 or HfB_2 that can absorb neutrons, have different absorption properties for neutrons of various energies. In this study, control rods that can be used in Akkuyu Nuclear Reactors were investigated. It has been taken into account that chemical compounds such as B_4C, ZrB_2, TiB_2 or HfB_2 may be present in the structure of these control rods, and the linear and mass attenuation coefficients (LAC, MAC), half and tenth value thicknesses (HVL, TVL) and mean free path (MFP), the atomic number, electron density (Zeff, Neff) and effective conductivity (Ceff) energy parameters have been calculated theoretically between 1 keV and 20 MeV using Phy-X software.

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Introduction

Nuclear reactors are facilities where heat energy is produced by using radioactive materials as fuel and electrical energy is produced from this energy (Cox et al., 2020). Unlike other power plants, due to the use of radioactive materials, more stringent security measures need to be taken, and therefore their technology must be continuously improved to include security measures (Lee, 2020).

Without talking about the control of the radioactive particles emerging in the reactor and the reactor control devices, we need to know the physics of the nuclear reactor system and reveal the technologies of these parts. There is a central core in the reactors, where the neutron is created in a controlled manner and the fission chain reactions that occur in the reactor are controlled. The neutrons produced by fragmentation are slowed down in thermal reactors until they decrease to thermal speeds using a moderator in the core. Graphite or heavy water is used for this slowing process. ^{235}U is mostly used in these thermal reactors and ^{235}U, which is a very important fissile material, is more likely to be decomposed by thermal neutrons than fast neutrons (Shultis and Faw, 2010; Lee, 2020; Mohanakrishnan et al., 2021).

The neutrons formed as a result of fission in the reactor core are initiated by the withdrawal of neutron absorbers such as boron or cadmium from the core or by adding another fuel element or using neutron reflectors. Retracting devices called control rods is the most commonly used method here (William Ray, 1963; Cockbame and Gültekin, 1966).

They can be collected in 3 groups as safety bars, closing bars and adjustment bars. Safety bars are located around the ember and provide safety by being placed around the ember during fueling or maintenance. The closing rods are withdrawn at a constant speed when the reactor starts to operate and these rods are held around the core during operation. If the core becomes critical, the safety bars are lowered and reactor operation can be stopped. Adjusting rods are used to bring the reactor to a critical point (Cockbame and Gültekin, 1966.).

Akkuyu Nuclear Power Plant is a VVR1200 type power plant and is a 3rd generation power plant (Fischer and Tiras, 2020). Within the scope of this study, the radiation absorption properties of possible control rod materials that can be used in this power plant were investigated with the Phy-X software (Şakar et al., 2020). For this purpose, linear and mass attenuation coefficients (LAC, MAC), half and tenth value layers (HVL, TVL), mean free path (MFP), effective atomic number and electron density (Z_{eff}, N_{eff}) and effective conductivity (C_{eff}) energy parameters of radiation particles interacting with B_4C, ZrB_2, TiB_2 and HfB_2 materials between 1 keV to 20 MeV energy have been theoretically calculated.

Material and Method

The Phy-X program (Özpolat et al., 2020), which is Photon Protection and Dosimetry (PSD) software available online at https://phy-x.net/PSD, has been developed for the calculation of parameters related to Shielding and dosimetry. By using the program in the range of 1 keV-100 GeV, linear and mass attenuation coefficients (LAC, MAC), half and tenth value layers (HVL, TVL), mean free path (MFP), effective atomic number and electron density (Zeff, Neff), the effective conductivity (Ceff) energy absorption and exposure buildup factors (EABF, EBF) can be calculated. In addition, the energies of some well-known radioactive sources such as 22Na, 55Fe, 60Co, 109Cd, 131I, 133Ba, 137Cs, 152Eu and 241Am and characteristic X-ray energy data of elements such as Cu, Rb, Mo, Ag, Ba and Tb are also available in the program. These energies can be determined by the user and used in calculations (Özpolat et al., 2020). The Beer-Lambert Law (Eskalen et al., 2020) is given in Eq. 1, by using this obtained absorption coefficient (μ), the Mass Attenuation Coefficient (Agar, 2018; Kavun et al., 2019) can be calculated, which defines the probability of interaction between gamma photons and mass per unit area.

$$\mu = \ln\left(\frac{I_0}{I}\right) / (-x) \quad (\mathrm{cm}^{-1}) \tag{1}$$

The Mass Attenuation Coefficient (MAC) (μ_m) is given in Eq.2:

$$\mu_m = \frac{\mu}{\rho} = \sum w_i \left(\frac{\mu}{\rho}\right)_i \quad (\mathrm{cm}^2/\mathrm{g}) \tag{2}$$

Here, I and I_0 are unabsorbed and absorbed photon intensities; $\mu(\mathrm{cm}^{-1})$ and $\mu_m(\mathrm{cm}^2/\mathrm{g})$ are linear and mass attenuation coefficients; x (cm) is the thickness; w_i is the weight fraction and ρ is density (Agar, 2018; Kavun et al., 2021). HVL, TVL, MFP parameters are found using the absorption coefficient (μ) (Özpolat et al., 2020).

Result and Discussion

In the scope of this study, the radiation absorption properties of possible control rod materials that can be used in this power plant were investigated with the Phy-X software. For this purpose, linear and mass attenuation coefficients (LAC, MAC), half and tenth value layers (HVL, TVL), mean free path (MFP), effective atomic number and electron density (Z_{eff}, N_{eff}) and effective conductivity (C_{eff}) energy parameters of radiation particles interacting with B_4C, ZrB_2, TiB_2 and HfB_2 materials between 1 keV to 20 MeV energy have been theoretically calculated.

As seen in Table 1 and Figure 1 for B_4C, the LAC values have been started from 3633.904 cm^{-1} at 1 keV to 0.036 cm^{-1} at 20 MeV. It was observed that the linear attenuation values decreased as the energy increased. Accordingly, there is a similar situation in the MAC values obtained by using the LAC value. In the logarithmic calculated HVL and TVL values, these values increased as the energy increased. But, there is a fluctuation in N_{eff}, C_{eff} and Z_{eff} values as seen in Figure 1.

Table 1. Calculation results of B_4C

Energy *MeV*	**MAC** *cm²/g*	**LAC** *1/cm*	**HVL** *cm*	**TVL** *cm*	**MFP** *cm*	**Neff** *electrons/g*	**Ceff** *S/m*	**Zeff**
0.001	1442.026	3633.904	0.00019	0.00063	0.00028	2.88E+23	5.25E+08	5.29
0.002	447.043	1126.549	0.00062	0.00204	0.00089	2.89E+23	5.26E+08	5.30
0.002	190.770	480.740	0.00144	0.00479	0.00208	2.89E+23	5.26E+08	5.30
0.003	56.163	141.531	0.00490	0.01627	0.00707	2.89E+23	5.26E+08	5.31
0.004	23.290	58.692	0.00019	0.00063	0.00028	2.89E+23	5.27E+08	5.31
0.005	11.732	29.564	0.023	0.078	0.034	2.90E+23	5.27E+08	5.31
0.006	6.714	16.920	0.041	0.136	0.059	2.90E+23	5.27E+08	5.31
0.008	2.831	7.134	0.097	0.323	0.140	2.89E+23	5.27E+08	5.31
0.010	1.498	3.775	0.184	0.610	0.265	2.89E+23	5.26E+08	5.30
0.015	0.553	1.394	0.497	1.652	0.717	2.88E+23	5.23E+08	5.28
0.02	0.332	0.836	0.829	2.753	1.195	2.86E+23	5.21E+08	5.25
0.03	0.217	0.547	1.266	4.207	1.827	2.85E+23	5.18E+08	5.22
0.04	0.186	0.467	1.483	4.926	2.139	2.84E+23	5.17E+08	5.21
0.05	0.171	0.431	1.609	5.344	2.321	2.84E+23	5.16E+08	5.21
0.06	0.162	0.408	1.697	5.639	2.449	2.84E+23	5.16E+08	5.20
0.08	0.150	0.379	1.831	6.082	2.642	2.83E+23	5.16E+08	5.20
0.1	0.142	0.357	1.940	6.445	2.799	2.83E+23	5.16E+08	5.20
0.2	0.127	0.319	2.173	7.218	3.135	2.83E+23	5.16E+08	5.20
0.2	0.116	0.291	2.378	7.901	3.431	2.83E+23	5.16E+08	5.20
0.3	0.100	0.253	2.740	9.103	3.954	2.83E+23	5.16E+08	5.20
0.4	0.090	0.227	3.060	10.164	4.414	2.83E+23	5.16E+08	5.20
0.5	0.082	0.207	3.352	11.134	4.835	2.83E+23	5.16E+08	5.20
0.6	0.076	0.191	3.624	12.037	5.228	2.83E+23	5.16E+08	5.20
0.8	0.067	0.168	4.128	13.712	5.955	2.83E+23	5.16E+08	5.20
1	0.060	0.151	4.590	15.247	6.621	2.83E+23	5.16E+08	5.20
2	0.049	0.123	5.641	18.739	8.138	2.83E+23	5.16E+08	5.20
2	0.042	0.105	6.579	21.854	9.491	2.83E+23	5.16E+08	5.20
3	0.033	0.084	8.224	27.318	11.864	2.83E+23	5.16E+08	5.20
4	0.029	0.072	9.643	32.032	13.911	2.83E+23	5.16E+08	5.20
5	0.025	0.064	10.885	36.159	15.704	2.83E+23	5.16E+08	5.20
6	0.023	0.058	11.979	39.793	17.282	2.84E+23	5.16E+08	5.20
7	0.021	0.054	12.952	43.024	18.685	2.84E+23	5.16E+08	5.20
8	0.020	0.050	13.819	45.906	19.937	2.84E+23	5.16E+08	5.20
9	0.019	0.048	14.590	48.468	21.049	2.84E+23	5.16E+08	5.20
10	0.018	0.045	15.286	50.778	22.053	2.84E+23	5.16E+08	5.21
11	0.017	0.044	15.910	52.852	22.953	2.84E+23	5.16E+08	5.21
12	0.017	0.042	16.478	54.739	23.773	2.84E+23	5.16E+08	5.21
13	0.016	0.041	16.988	56.434	24.509	2.84E+23	5.16E+08	5.21
14	0.016	0.040	17.451	57.969	25.176	2.84E+23	5.16E+08	5.21
15	0.015	0.039	17.870	59.362	25.781	2.84E+23	5.16E+08	5.21
16	0.015	0.038	18.249	60.621	26.327	2.84E+23	5.16E+08	5.21
18	0.015	0.037	18.910	62.818	27.281	2.84E+23	5.16E+08	5.21
20	0.014	0.036	19.464	64.657	28.080	2.84E+23	5.17E+08	5.21

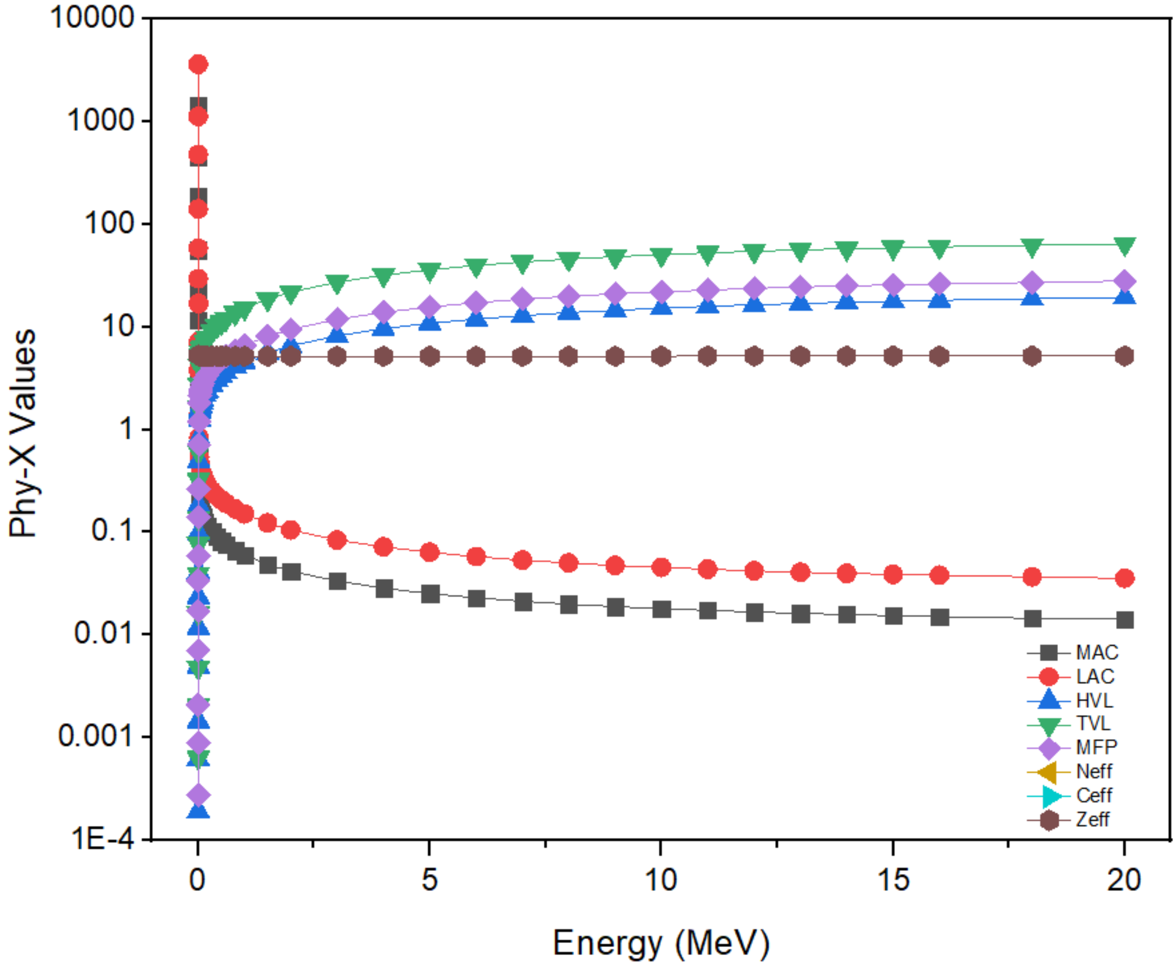

Figure 1. Radiation shielding results of B_4C using Phy-X software

For ZrB_2, the LAC values started from 22140.303 cm^{-1} at 1 keV to 0.219cm^{-1} at 20 MeV as seen in Table 2 and Figure 2. Similarly, The MAC values fluctuated around 3638.505 to 0.036 cm^2/g in these energy ranges. The HVL, TVL and MFP values starts from 0.00003, 0.00010 and 0.00005 cm to 3.169, 10.528 and 4.572, respectively. N_{eff}, C_{eff} and Z_{eff} values have similar behavior as seen in Figure 2. They have taken different values in 1 keV to 20 MeV range.

Table 2. Calculation results of ZrB_2

Energy *MeV*	**MAC** *cm²/g*	**LAC** *1/cm*	**HVL** *cm*	**TVL** *cm*	**MFP** *cm*	**Neff** *electrons/g*	**Ceff** *S/m*	**Zeff**
0.001	3638.505	22140.303	0.00003	0.00010	0.00005	4.41E+23	1.94E+09	27.53
0.002	1391.005	8464.268	0.00008	0.00027	0.00012	4.70E+23	2.06E+09	29.34
0.002	686.829	4179.354	0.00017	0.00055	0.00024	4.88E+23	2.14E+09	30.49
0.003	1441.569	8771.945	0.00008	0.00026	0.00011	6.14E+23	2.70E+09	38.34
0.004	691.345	4206.834	0.00016	0.00055	0.00024	6.17E+23	2.71E+09	38.56
0.005	386.333	2350.837	0.00029	0.00098	0.00043	6.20E+23	2.72E+09	38.70
0.006	238.323	1450.195	0.00048	0.00159	0.00069	6.21E+23	2.73E+09	38.79
0.008	110.111	670.028	0.00103	0.00344	0.00149	6.23E+23	2.74E+09	38.89
0.010	60.203	366.334	0.002	0.006	0.003	6.23E+23	2.74E+09	38.91
0.015	19.997	121.684	0.006	0.019	0.008	6.20E+23	2.72E+09	38.75
0.02	58.570	356.398	0.002	0.006	0.003	6.36E+23	2.79E+09	39.73
0.03	20.130	122.491	0.006	0.019	0.008	6.32E+23	2.78E+09	39.46

0.04	9.240	56.224	0.012	0.041	0.018	6.24E+23	2.74E+09	38.98
0.05	5.023	30.564	0.023	0.075	0.033	6.13E+23	2.69E+09	38.30
0.06	3.057	18.599	0.037	0.124	0.054	5.99E+23	2.63E+09	37.40
0.08	1.420	8.638	0.080	0.267	0.116	5.62E+23	2.47E+09	35.12
0.1	0.807	4.912	0.141	0.469	0.204	5.20E+23	2.29E+09	32.49
0.2	0.330	2.009	0.345	1.146	0.498	4.25E+23	1.87E+09	26.58
0.2	0.203	1.233	0.562	1.868	0.811	3.65E+23	1.61E+09	22.83
0.3	0.125	0.763	0.908	3.017	1.310	3.12E+23	1.37E+09	19.47
0.4	0.099	0.604	1.148	3.812	1.656	2.92E+23	1.28E+09	18.23
0.5	0.086	0.522	1.329	4.414	1.917	2.83E+23	1.24E+09	17.68
0.6	0.077	0.468	1.480	4.915	2.134	2.78E+23	1.22E+09	17.39
0.8	0.066	0.400	1.735	5.762	2.503	2.74E+23	1.20E+09	17.11
1	0.058	0.354	1.955	6.496	2.821	2.72E+23	1.19E+09	16.98
2	0.047	0.287	2.415	8.021	3.484	2.71E+23	1.19E+09	16.93
2	0.041	0.252	2.752	9.142	3.970	2.75E+23	1.21E+09	17.16
3	0.036	0.218	3.186	10.584	4.597	2.87E+23	1.26E+09	17.92
4	0.033	0.202	3.425	11.376	4.941	3.01E+23	1.32E+09	18.79
5	0.032	0.195	3.549	11.789	5.120	3.15E+23	1.38E+09	19.66
6	0.032	0.192	3.607	11.981	5.203	3.28E+23	1.44E+09	20.46
7	0.031	0.191	3.621	12.030	5.224	3.40E+23	1.49E+09	21.21
8	0.032	0.192	3.611	11.995	5.209	3.51E+23	1.54E+09	21.89
9	0.032	0.193	3.585	11.908	5.172	3.60E+23	1.58E+09	22.51
10	0.032	0.195	3.549	11.791	5.121	3.69E+23	1.62E+09	23.07
11	0.032	0.197	3.510	11.660	5.064	3.78E+23	1.66E+09	23.58
12	0.033	0.200	3.468	11.521	5.004	3.85E+23	1.69E+09	24.04
13	0.033	0.202	3.427	11.385	4.945	3.92E+23	1.72E+09	24.46
14	0.034	0.205	3.387	11.252	4.887	3.98E+23	1.75E+09	24.83
15	0.034	0.207	3.348	11.121	4.830	4.03E+23	1.77E+09	25.17
16	0.034	0.209	3.309	10.993	4.774	4.08E+23	1.79E+09	25.48
18	0.035	0.214	3.237	10.752	4.669	4.17E+23	1.83E+09	26.02
20	0.036	0.219	3.169	10.528	4.572	4.24E+23	1.86E+09	26.48

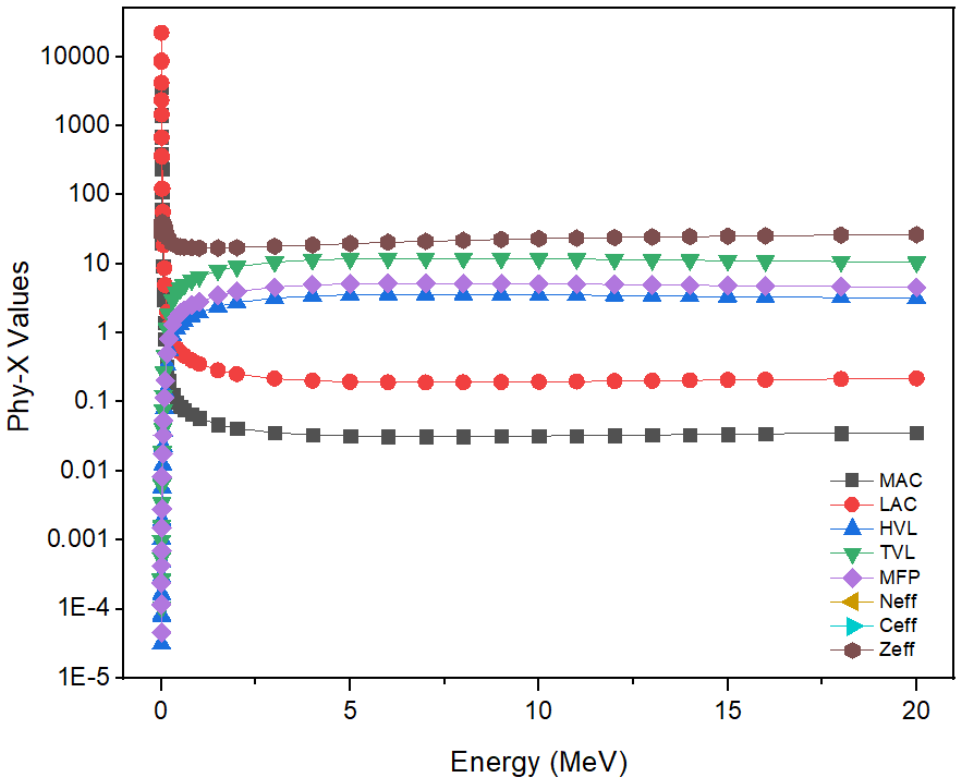

Figure 2. Radiation shielding results of ZrB_2 using Phy-X software.

In Table 3 and Figure 3, TiB_2 calculation results can be seen. The LAC values changed between 20000.205 cm^{-1} to 0.108 cm^{-1} for 1 keV and 20 MeV. These changes affected the MAC values. It was changed between 4424.824 cm^2/g and 0.024 cm^2/g in the same energy range. The HVL, TVL and MFP values started from 0.00003, 0.00012 and 0.00005 cm to 6.430, 21.360 and 9.277 cm, respectively. The fluctuation seen for N_{eff}, C_{eff} and Z_{eff} values in previous calculations is also available here.

Table 3. Calculation results of TiB_2

Energy *MeV*	**MAC** *cm²/g*	**LAC** *1/cm*	**HVL** *cm*	**TVL** *cm*	**MFP** *cm*	**Neff** *electrons/g*	**Ceff** *S/m*	**Zeff**
0.001	4424.824	20000.205	0.00003	0.00012	0.00005	4.42E+23	1.44E+09	17.01
0.002	1561.234	7056.778	0.00010	0.00033	0.00014	4.56E+23	1.49E+09	17.53
0.002	728.936	3294.791	0.00021	0.00070	0.00030	4.64E+23	1.52E+09	17.86
0.003	243.410	1100.213	0.00063	0.00209	0.00091	4.76E+23	1.55E+09	18.29
0.004	110.529	499.591	0.00139	0.00461	0.00200	4.83E+23	1.58E+09	18.57
0.005	474.063	2142.763	0.00032	0.00107	0.00047	5.60E+23	1.83E+09	21.53
0.006	299.572	1354.066	0.00051	0.00170	0.00074	5.61E+23	1.83E+09	21.58
0.008	140.122	633.352	0.001	0.004	0.002	5.62E+23	1.83E+09	21.62
0.010	76.629	346.362	0.002	0.007	0.003	5.62E+23	1.83E+09	21.63
0.015	24.862	112.374	0.006	0.020	0.009	5.60E+23	1.83E+09	21.56
0.02	11.014	49.781	0.014	0.046	0.020	5.56E+23	1.81E+09	21.38
0.03	3.489	15.769	0.044	0.146	0.063	5.38E+23	1.76E+09	20.70
0.04	1.580	7.142	0.097	0.322	0.140	5.11E+23	1.67E+09	19.64
0.05	0.888	4.012	0.173	0.574	0.249	4.77E+23	1.56E+09	18.36
0.06	0.577	2.608	0.266	0.883	0.383	4.43E+23	1.45E+09	17.05
0.08	0.325	1.469	0.472	1.568	0.681	3.87E+23	1.26E+09	14.87
0.1	0.231	1.043	0.665	2.208	0.959	3.49E+23	1.14E+09	13.43
0.2	0.152	0.688	1.007	3.346	1.453	3.07E+23	1.00E+09	11.80
0.2	0.126	0.569	1.218	4.048	1.758	2.93E+23	9.55E+08	11.25
0.3	0.103	0.463	1.496	4.969	2.158	2.83E+23	9.25E+08	10.90
0.4	0.090	0.407	1.703	5.657	2.457	2.81E+23	9.16E+08	10.79
0.5	0.082	0.368	1.881	6.249	2.714	2.79E+23	9.12E+08	10.75
0.6	0.075	0.339	2.042	6.785	2.947	2.79E+23	9.10E+08	10.73
0.8	0.066	0.297	2.336	7.760	3.370	2.78E+23	9.08E+08	10.70
1	0.059	0.266	2.603	8.648	3.756	2.78E+23	9.07E+08	10.69
2	0.048	0.217	3.196	10.617	4.611	2.78E+23	9.08E+08	10.70
2	0.042	0.188	3.689	12.253	5.322	2.80E+23	9.12E+08	10.76
3	0.034	0.156	4.456	14.804	6.429	2.85E+23	9.29E+08	10.95
4	0.031	0.138	5.017	16.668	7.239	2.91E+23	9.48E+08	11.18
5	0.028	0.128	5.429	18.036	7.833	2.97E+23	9.68E+08	11.41
6	0.027	0.121	5.733	19.045	8.271	3.03E+23	9.88E+08	11.65
7	0.026	0.116	5.955	19.782	8.591	3.09E+23	1.01E+09	11.87
8	0.025	0.113	6.119	20.328	8.828	3.14E+23	1.02E+09	12.08
9	0.025	0.111	6.236	20.714	8.996	3.19E+23	1.04E+09	12.28
10	0.024	0.110	6.324	21.009	9.124	3.24E+23	1.06E+09	12.46
11	0.024	0.109	6.384	21.207	9.210	3.28E+23	1.07E+09	12.63
12	0.024	0.108	6.428	21.353	9.274	3.32E+23	1.08E+09	12.79
13	0.024	0.107	6.454	21.440	9.311	3.36E+23	1.10E+09	12.93
14	0.024	0.107	6.472	21.501	9.338	3.40E+23	1.11E+09	13.06
15	0.024	0.107	6.477	21.517	9.345	3.43E+23	1.12E+09	13.19
16	0.024	0.107	6.477	21.516	9.344	3.46E+23	1.13E+09	13.30
18	0.024	0.107	6.462	21.467	9.323	3.51E+23	1.15E+09	13.51
20	0.024	0.108	6.430	21.360	9.277	3.56E+23	1.16E+09	13.69

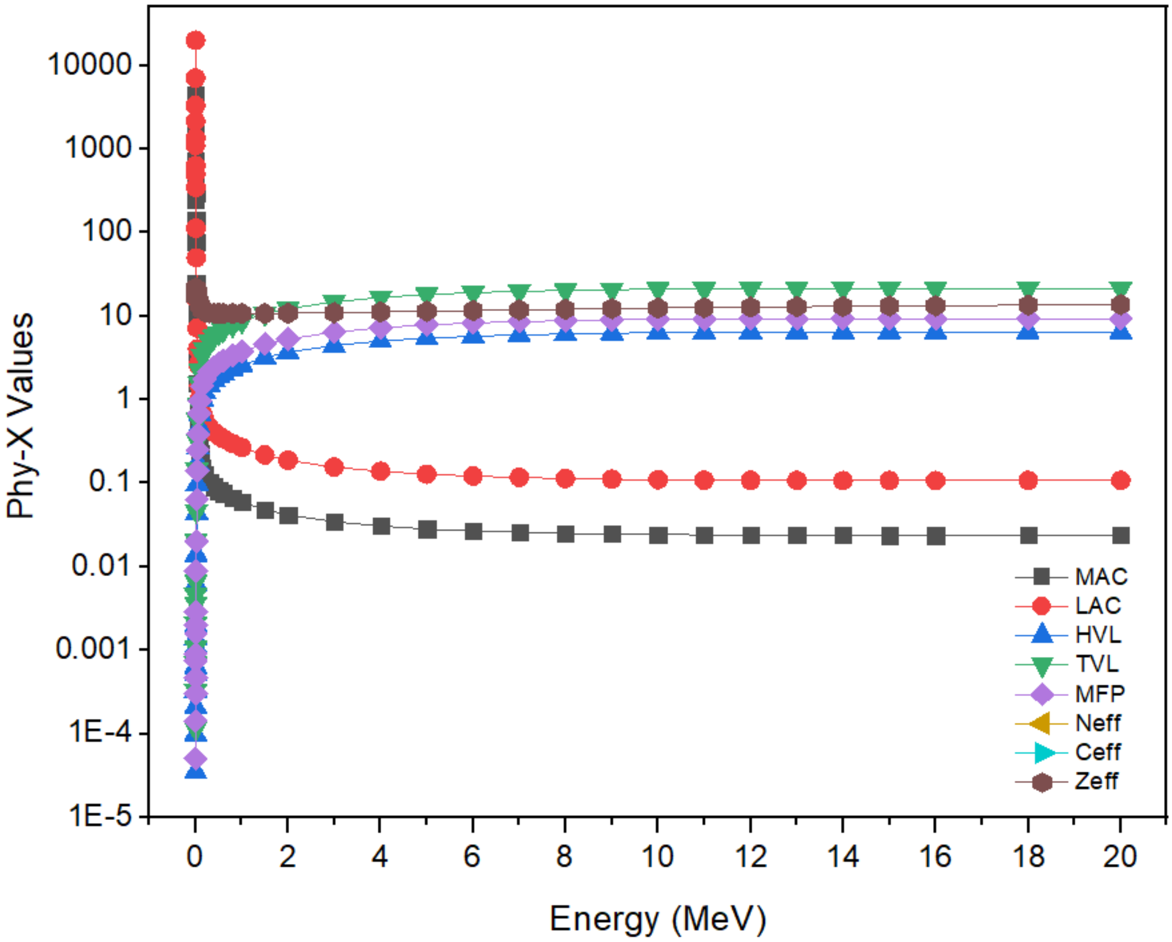

Figure 3. Radiation shielding results of TiB_2 using Phy-X software

Finally, for HfB_2, The LAC values obtained as 32632.138 cm^{-1} and 0.558 cm^{-1} for 1 keV to 20 MeV in Fig.4 and Table 4, respectively. Depending on LAC values, the MAC values have been obtained as 3107.823 and 0.053 cm^2/g. The obtained HVL, TVL and MFP values have been increased as the energy increased. Similar fluctuation in N_{eff}, C_{eff} and Z_{eff} values for this energy range is also available here.

Table 4. Calculation results of HfB_2

Energy *MeV*	**MAC** *cm²/g*	**LAC** *1/cm*	**HVL** *cm*	**TVL** *cm*	**MFP** *cm*	**Neff** *electrons/g*	**Ceff** *S/m*	**Zeff**
0.001	3107.823	32632.138	0.00002	0.00007	0.00003	4.13E+23	3.13E+09	45.79
0.002	1368.924	14373.706	0.00005	0.00016	0.00007	4.65E+23	3.52E+09	51.49
0.002	3225.291	33865.557	0.00002	0.00007	0.00003	6.07E+23	4.60E+09	67.18
0.003	1582.288	16614.024	0.00004	0.00014	0.00006	6.23E+23	4.73E+09	69.05
0.004	792.119	8317.249	0.00008	0.00028	0.00012	6.28E+23	4.76E+09	69.55
0.005	457.167	4800.253	0.00014	0.00048	0.00021	6.31E+23	4.78E+09	69.86
0.006	289.977	3044.757	0.00023	0.00076	0.00033	6.33E+23	4.79E+09	70.06
0.008	140.359	1473.771	0.00047	0.00156	0.00068	6.35E+23	4.81E+09	70.30
0.010	205.395	2156.645	0.00032	0.00107	0.00046	6.44E+23	4.88E+09	71.37
0.015	115.071	1208.246	0.00057	0.00191	0.00083	6.46E+23	4.90E+09	71.57
0.02	54.328	570.441	0.001	0.004	0.002	6.45E+23	4.89E+09	71.43
0.03	18.737	196.743	0.004	0.012	0.005	6.40E+23	4.85E+09	70.87
0.04	8.785	92.238	0.008	0.025	0.011	6.31E+23	4.79E+09	69.93

0.05	4.905	51.498	0.013	0.045	0.019	6.20E+23	4.70E+09	68.63
0.06	3.068	32.210	0.022	0.071	0.031	6.05E+23	4.58E+09	66.99
0.08	6.572	69.008	0.010	0.033	0.014	6.30E+23	4.77E+09	69.74
0.1	3.719	39.051	0.018	0.059	0.026	6.17E+23	4.67E+09	68.30
0.2	1.331	13.976	0.050	0.165	0.072	5.73E+23	4.34E+09	63.42
0.2	0.667	7.001	0.099	0.329	0.143	5.21E+23	3.95E+09	57.75
0.3	0.283	2.973	0.233	0.775	0.336	4.32E+23	3.28E+09	47.86
0.4	0.173	1.818	0.381	1.267	0.550	3.74E+23	2.83E+09	41.40
0.5	0.127	1.332	0.520	1.729	0.751	3.38E+23	2.57E+09	37.48
0.6	0.102	1.076	0.644	2.141	0.930	3.16E+23	2.40E+09	35.04
0.8	0.077	0.812	0.853	2.835	1.231	2.92E+23	2.21E+09	32.35
1	0.064	0.676	1.026	3.407	1.480	2.80E+23	2.12E+09	30.96
2	0.049	0.517	1.340	4.451	1.933	2.70E+23	2.05E+09	29.90
2	0.044	0.458	1.515	5.033	2.186	2.75E+23	2.08E+09	30.44
3	0.039	0.415	1.671	5.553	2.411	2.95E+23	2.24E+09	32.67
4	0.039	0.405	1.710	5.680	2.467	3.17E+23	2.40E+09	35.13
5	0.039	0.408	1.701	5.650	2.454	3.38E+23	2.56E+09	37.43
6	0.039	0.415	1.672	5.553	2.412	3.56E+23	2.70E+09	39.47
7	0.040	0.424	1.634	5.428	2.357	3.73E+23	2.82E+09	41.27
8	0.041	0.435	1.593	5.293	2.299	3.87E+23	2.93E+09	42.86
9	0.043	0.446	1.553	5.158	2.240	4.00E+23	3.03E+09	44.26
10	0.044	0.458	1.513	5.028	2.183	4.11E+23	3.11E+09	45.50
11	0.045	0.470	1.476	4.904	2.130	4.21E+23	3.19E+09	46.59
12	0.046	0.481	1.441	4.786	2.079	4.29E+23	3.26E+09	47.57
13	0.047	0.492	1.408	4.677	2.031	4.37E+23	3.32E+09	48.44
14	0.048	0.503	1.378	4.576	1.987	4.44E+23	3.37E+09	49.22
15	0.049	0.513	1.350	4.485	1.948	4.51E+23	3.42E+09	49.91
16	0.050	0.523	1.325	4.400	1.911	4.56E+23	3.46E+09	50.52
18	0.052	0.541	1.280	4.253	1.847	4.66E+23	3.53E+09	51.58
20	0.053	0.558	1.241	4.124	1.791	4.74E+23	3.59E+09	52.46

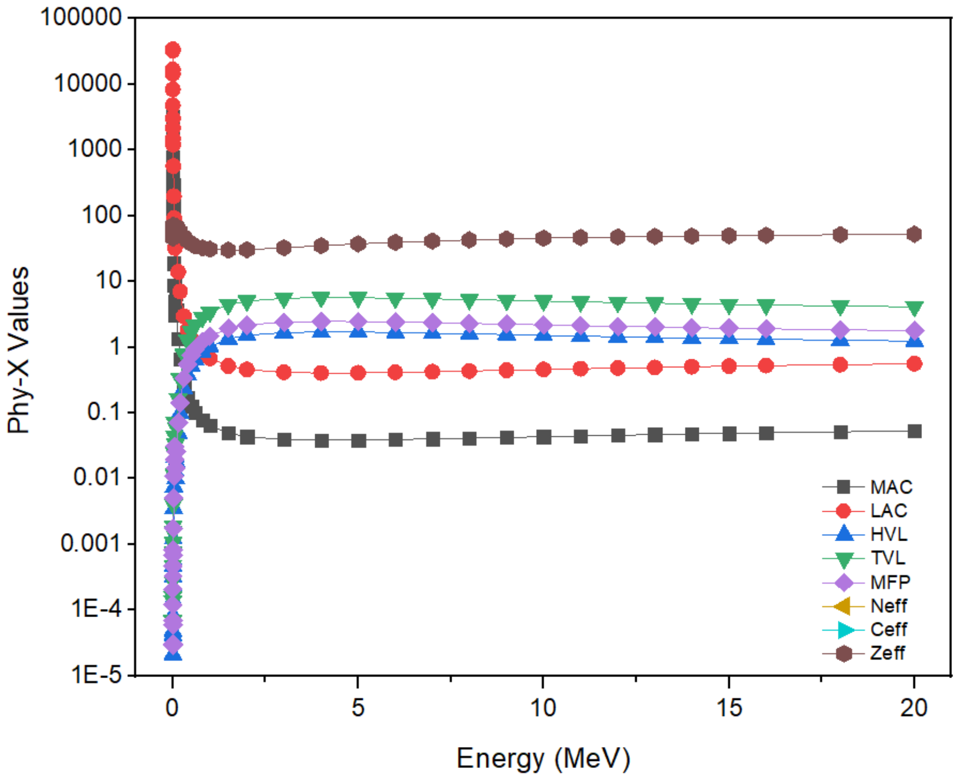

Figure 4. Radiation shielding results of HfB_2 using Phy-X software

Conclusions

The radiation absorption properties of B_4C, ZrB_2, TiB_2 or HfB_2 control rod materials that can be used in this power plant were investigated in this study by using the Phy-X software. To obtain attenuation properties, linear and mass attenuation coefficients (LAC, MAC), half and tenth value layers (HVL, TVL), mean free path (MFP), effective atomic number and electron density (Zeff, Neff) and effective conductivity (Ceff) energy parameters of radiation particles interacting with B_4C, ZrB_2, TiB_2 and HfB_2 materials between 1 keV to 20 MeV energy have been theoretically calculated.

According to the results obtained using the Phy-X software, LAC values decrease as the energy increases. A similar behavior is observed in the MAC values obtained using this LAC value. Here, the effect of energy on mass is clearly seen. HVL, TVL and MFP values increase as the energy increases. There are fluctuations in Neff, Ceff and Zeff values. Thus, the radiation absorption properties of these materials have been demonstrated and it has been theoretically obtained that they have effective absorption properties at low energies.

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Statement of Conflict of Interest

Authors have declared no conflict of interest.

Author’s Contributions

The contribution of the authors is equal.

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