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Geant4 calculations for space radiation shielding material Al_2O_3

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Abstract. Aluminium Oxide, Al_2O_3 is the most widely used material in the engineering applications. It is significant aluminium metal, because of its hardness and as a refractory material owing to its high melting point. This material has several engineering applications in diverse fields such as, ballistic armour systems, wear components, electrical and electronic substrates, automotive parts, components for electric industry and aero-engine. As well, it is used as a dosimeter for radiation protection and therapy applications for its optically stimulated luminescence properties. In this study, stopping powers and penetrating distances have been calculated for the alpha, proton, electron and gamma particles in space radiation shielding material Al_2O_3 for incident energies 1 keV – 1 GeV using GEANT4 calculation code.

1 Introduction

Aluminium Oxide, Al_2O_3 is the most widely used material in the engineering applications. It is significant aluminium metal, because of its hardness and as a refractory material owing to its high melting point. It is one of the most important materials due to its interesting characteristics such as easy availability, low cost, low environmental impact, ease of synthesis, good optical transparency, high refractive index, high melting point, hydrophobicity, mechanical strength, dielectric behaviour, electrical insulating property, thermal, and chemical stability [1].

NASA has always had a major emphasis on developing technologies that can be used for manned space flight, space station and satellite. Clearly, any sort of manned space requires extraordinary design considerations and extremely effective technology, because there are innumerable hazards associated with manned space flight [2]. Among these, radiation damage and heat and cold thermal efficient are very major concern. Currently, NASA uses aluminium for radiation shielding [3].

This material is marginally effective at radiation shielding, since it has a low electron density. Therefore, researchers have been looking for other materials, which have higher hydrogen content than aluminium, to use as radiation shielding material. It would then re-enter the atmosphere of the Earth and glide back down to the ground. In order to withstand the high temperatures associated with re-entry, NASA created the Space Shuttle Orbiter Thermal Protection System (TPS) [4].

2 Methods

GEANT4 is a free simulation and calculation code that can be used to investigation of high-energy physics, medical physics, space, and radiation physics. GEANT4 is an abundant set of physics models to handle the interactions of particles with matter across a large energy range. Data and expertise have been drawn from many sources around the world and in this respect, GEANT4 acts as a repository that incorporates a large part of all that is known about particle interactions [5].

Energy lost by α-particle in a single collision is very small. However the energy gained by the orbiting electron is often more than the binding energy of the atom and is therefore removed from the atom. The interacting atom is said to be ionized due to this α-particle electron collision. The physical quantity that describes the slowing down of charged particles in mater is the stopping power dE/dx where dE is the energy lost in the distance dx. The Bohr relation for stopping power of heavy particle is given by

$$-\frac{dE}{dx}=\frac{4\pi z^2 k_0^2 e^4}{mv^2} ln\left(\frac{2mv^2}{I}\right) \tag{1}$$

n = number of electrons per unit volume,
m = electron rest mass,
v = velocity of the particle,
Z= charge of the particle,
e = electron charge
$k_o = 1/4\pi\varepsilon_o$,
I = mean excitation energy of the medium [6].

This was modified by taking into account the quantum effects by Bethe, and the relativistic effects by Bloch, and finally the well-known Bethe–Bloch expression for the stopping power was given as [7]:

$$-\frac{dE}{dx}=\frac{4\pi z^2 k_0^2 e^4}{mv^2}\left[ln\left(\frac{2mv^2}{I}\right)-ln\left(1-\frac{v^2}{c^2}\right)-\frac{v^2}{c^2}\right] \tag{2}$$

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The stopping power given in the above equation takes into account only collisions with electrons. Events with nuclei are not considered in this formula. There is one important drawback of this formula. It was derived using the perturbation theory and the first Born approximation [8].

3 Results

The penetrating distance and stopping power calculations of alpha, electron, proton and gamma particles for Al_2O_3 shielding material have been given in Figs. 1 and 2. The calculated stopping power values of alpha, proton and electron projectile particles in Al_2O_3 target for incident energies of 1 keV – 1 GeV have been exhibited in Fig. 1. Based on an approximate theory i.e. the Thomas Fermi model of atom, Bohr suggested that for high energies above 100 keV region, the stopping power decreases as the particle velocity approaches the velocity of light. When the velocity of the particle is comparable with speed of light, the normal spherical field becomes distorted in the direction of motion of the particle expanding laterally and in the perpendicular direction shrinking. Bethe Bloch suggested that for high energies above approximately 1 MeV region, the stopping power decreases as the incident particle's energy.

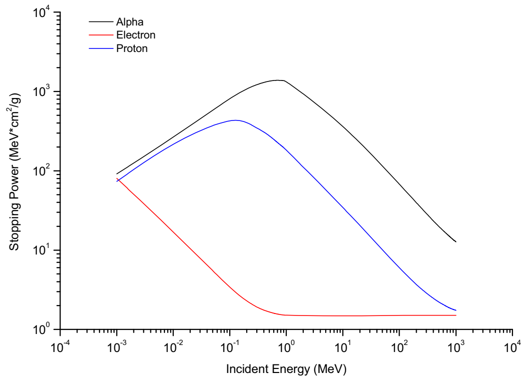

Figure 1. The stopping power calculations of proton, electron and alpha particles in the incident energy range of 1 keV – 1 GeV for Al_2O_3.

The penetrating distance calculations of alpha, electron, proton and gamma particles for Al_2O_3 shielding material have been given in Figs. 2 and 3. According to calculated penetrating results, the penetrating distance of alpha particles are the poorest. So this particles cannot be managed to enter into Al_2O_3. On the contrary alpha particles, gamma has the most penetrating in the Al_2O_3 target.

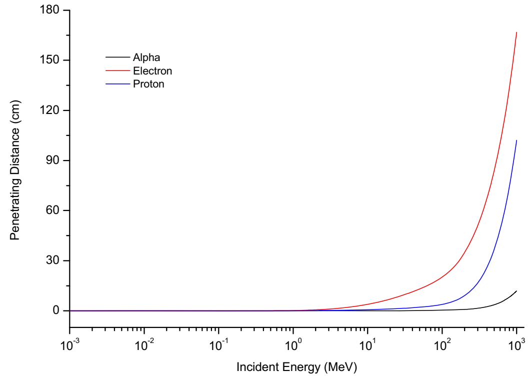

Figure 2. The penetrating distance calculations of proton, electron and alpha particles in the incident energy range of 1 keV – 1 GeV for Al_2O_3.

In the incident gamma energy range of 1 keV – 0,9 MeV, required stopping thickness of Al_2O_3 could be approximately 1,7 cm.

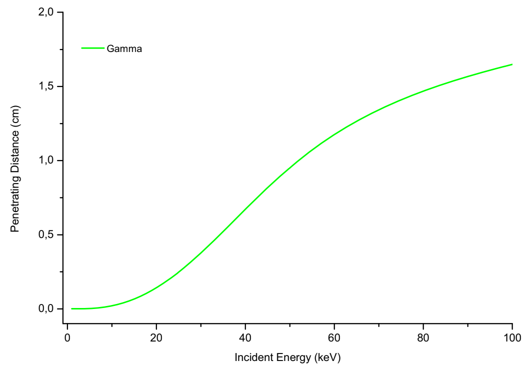

Figure 3. The penetrating distance calculations of gamma in the incident energy range of 1 keV – 100 keV for Al_2O_3.

All calculated stopping power and penetrating distance results used by GEANT4 have been given in Tables 1, 2 and 3.

Table 1. The Geant4 penetrating calculations results of proton, electron and alpha particles for Al_2O_3.

Energy (MeV)	Alpha Penetrating Distance (cm)	Electron Penetrating Distance (cm)	Proton Penetrating Distance (cm)
0.001	1.76E-05	2.29E-05	6.85E-05
0.01	2.30E-04	4.98E-04	2.17E-04
0.1	4.30E-04	0.00453	7.84E-04
0.2	6.80E-04	0.01409	0.00135
0.3	8.42E-04	0.02632	0.00201
0.4	9.81E-04	0.04012	0.00277
0.5	0.00111	0.0549	0.00363
0.6	0.00168	0.07033	0.00459
0.7	0.00193	0.08622	0.00565
0.8	0.0021	0.10246	0.0068
0.9	0.00234	0.11895	0.00805

1	0.0024	0.13561	0.00938
10	0.05271	1.68422	0.40925
100	0.20755	16.8012	2.42436
200	0.71304	33.4877	8.0816
300	1.46686	50.159	15.9504
400	2.43978	66.8267	25.4686
500	3.60954	83.4936	36.2854
600	4.95783	100.16	48.1289
700	6.46885	116.27	60.7857
800	8.12877	133.494	74.0742
900	9.92531	150.16	87.8831
1000	11.8485	166.827	102.132

Table 2. The Geant4 stopping power calculations results of proton, electron and alpha particles for Al_2O_3.

Energy (MeV)	Alpha Stopping Power (MeV*cm2/g)	Electron Stopping Power (MeV*cm2/g)	Proton Stopping Power (MeV*cm2/g)
0.001	91.7138	80.3267	73.51
0.01	260.744	17.3191	232.5
0.1	828.899	3.30542	470
0.2	1083.77	2.26224	412.7
0.3	1222.91	1.91587	345.5
0.4	1306.44	1.7528	310.6
0.5	1355.2	1.66384	276.5
0.6	1379.95	1.60608	249.4
0.7	1386.82	1.56534	227.9
0.8	1382.69	1.53815	210.2
0.9	1371.6	1.519	195.7
1	1353.52	1.50706	183.2
10	394.568	1.47181	35.309
100	68.2801	1.507	5.895
200	39.6243	1.51054	3.659
300	29.0284	1.51115	2.877
400	23.4376	1.5113	2.464
500	19.9658	1.51133	2.214
600	17.5955	1.51133	2.051
700	15.8731	1.51133	1.938
800	14.565	1.51133	1.855
900	13.5382	1.51133	1.793
1000	12.7116	1.51133	1.745

Table 3. The Geant4 stopping power calculations results of gamma particles for Al_2O_3.

Energy (MeV)	Gamma Penetrating Distance (cm)
0.001	8.92E-04
0.01	0.00158
0.1	0.12273
0.2	0.36485
0.3	0.67607
0.4	0.96181
0.5	1.18423
0.6	1.34936
0.7	1.4734
0.8	1.57004
0.9	1.64883

Composite materials that contain the highest hydrogen and oxygen are very good shielding materials whereas aluminium and same materials are not a good shielding material due to its low electron density [5]. Therefore, Al_2O_3 is better than aluminium for radiation shielding. In the incident alpha, electron and proton energy range of 1 keV–1 GeV, required stopping thickness of Al_2O_3 could be approximately 12, 167, 103 cm. respectively. The obtained Al_2O_3 stopping power results for the projectile charged particles can be used in several applications such as space engineering, radiation therapy and protection.

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