Effect of aluminum shield on deposition parameters of Teflon irradiated by high energy electrons

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Abstract. To study the influence of aluminum shield on deposition parameters of typical insulating medium Teflon irradiated by high energy electrons, a calculation model of aluminum shield and Teflon irradiated by high energy electrons was established. Monte Carlo method was used to simulate the effects of the energy of irradiated electrons, the thickness of aluminum shield and the electron irradiation current density on the distribution of parameters such as injection current density, charge deposition rate, radiation dose rate and radiation induced conductivity. The results show that the larger the energy of irradiated electrons, the stronger the ability of electrons to penetrate aluminum shield and Teflon. The higher the injection current density in Teflon is, the deeper the position of Bragg peak is, and the lower the height of the peak is. The thicker the aluminum shield, the shallower the peak position of charge deposition rate and electron radiation dose rate is, the smaller the absolute value of charge deposition rate peak is, and the lower the peak of radiation dose rate is.

1. Introduction
The energy of electrons in space can reach 100 keV or even several MeVs. High energy electrons will deposit inside the dielectric materials used in satellites or spacecrafts when it is irradiated by high energy electrons, and this will not only affect the insulating physical properties of the dielectric materials, but also seriously threaten the operation safety of satellites or spacecrafts due to the internal charging and discharging effect [1-2]. High energy electrons in space need to penetrate the shield before they can charge and discharge the insulating dielectrics, because satellites or spacecrafts usually have a shell or metal structure [2-3]. When calculating the charging electric field in dielectric materials, not only the energy and irradiation electrons, as well as the characteristic parameters of dielectric materials, but also the influence of metal shield on charging effect should be considered.

A lot of numerical simulations have been carried out to study the charging effect of high energy electrons in dielectric materials after the electrons penetrate the shield layer. Zhou Qing et al. simulated the effect of aluminum shield with different thickness and different energy electrons on the maximum electric field in epoxy resin by MCNP program. The results show that when the thickness of the medium is constant, the maximum electric field in the medium increases first and then decreases with the increase of the thickness of the shielding layer [4]. Huang Jianguo et al. have shown that for epoxy resin medium with thickness of 0.1 cm, the maximum electric field in the medium decreases rapidly with the thickness of aluminum shield. When the thickness of shielding layer exceeds a certain thickness, the effect of increasing the thickness of shielding layer on reducing the maximum electric
field is very limited [5]. Through Geant4 program, Qin Xiaogang simulated the charging process of electrons with energy of 1MeV passing through an aluminum shield with thickness of 1.5mm and then irradiating Teflon dielectrics [6-7]. Tian Tian calculated the interaction of high energy protons with metal shield and insulating dielectrics by Geant4 program. The transmission and deposition process of protons in polyethylene was simulated. The research shows that the ability of electron to penetrate the shielding layer is stronger than that of proton [8]. Based on Geant4, Gao Bingrong simulated and studied the relationships between the maximum electric field strength in polyethylene and the parameters of high energy electron energy, thickness of aluminum shield [9].

In this paper, the influence of the thickness of aluminum shield layer, the electron energy and the irradiation current density on the deposition parameters of the irradiated electrons in Teflon dielectrics was simulated and studied based on the MCNP program. The results of this study can provide a reference to the charge-discharge safety analysis of satellites or spacecrafts irradiated by high energy electrons.

2. Physical model and method

The geometric model shown in Figure 1 is established, and the whole geometric model is in vacuum. The sectional dimension of Teflon is 20 mm*20 mm, the thickness is \(d = 6\) mm, and the density of Teflon is 2.2 g/cm\(^3\). The aluminum shield is located in front of the medium and parallel to Teflon dielectrics. The vertical distance between aluminum and Teflon dielectrics is 2 mm, and the cross-section size of the aluminum shield is 28 mm*28 mm. According to the results of literature [10], the model that the radius of electron beam is larger than that of medium is more reasonable. The electron beam is a 30 mm*30 mm area source, and the irradiation direction is perpendicular to the aluminum shield. The electron beam intensity is 1pA/cm\(^2\) and the electron energy range is 0.8MeV-10MeV. The thickness of aluminum shield \(d_{Al}\) varies from 0 mm, 0.4 mm, 0.8 mm, 1 mm, 1.2 mm, 1.6 mm and 2 mm. When the thickness of aluminum shield is 0, it is equivalent to no aluminum shield.

![Figure 1. Schematic diagram of the geometric model.](image)

The general Monte Carlo simulation program MCNP4 is used for simulation calculation [11]. The Teflon dielectric is divided into 100 layers, each with a thickness of 0.006 cm. The simulated number of electrons \(N_0 = 10^7\) can make the statistical error of the simulated results less than 5%. The surface current \(F_1(x)\) of each layer is recorded by F1 card, the energy deposition \(D_M(x)\) of each layer is recorded by *F8 card, and the charge deposition \(F_8(x)\) of each layer is recorded by +F8 card. The parameters calculated by MC are converted to injection current density \(J(x)\), charge density deposition rate \(\rho_\xi(x)\) and dose rate \(D_\xi(x)\).

\[
J(x) = \frac{F_1(x)e}{dt \cdot A_0} \\
D_\xi(x) = \frac{D_M(x)}{dt \cdot m} = \frac{D_M(x) \times 10^6 \times e}{dt \cdot \rho \cdot A_0 \cdot \Delta x} 
\]

(1) (2)
In the formula, \( e \) is the charge of electron; \( \Delta t \) is the unit time; \( m \) is the mass of each Teflon layer; \( \rho \) is the density of Teflon material; \( \Delta x = 0.006 \text{cm} \) is the thickness of each medium layer in simulation model; \( A_0 \) is the area of medium irradiated by electron beam, that is, the cross-sectional area of medium material. \( A_0 = \pi \times 2 \times 2 \text{cm}^2 \).

After being irradiated by high energy electrons, the radiation induced conductivity of insulating medium will be produced. The radiation induced conductivity of Teflon is

\[
\sigma(x) = \sigma_0(x) + k_p D_e(x)^\Delta
\]

In the formula, the intrinsic conductivity is \( 1.0 \times 10^{-16} \text{S/m} \), \( D_e \) is the radiation dose rate in unit of \( \text{rad/s} \), and \( k_p \) and \( \Delta \) are coefficients related to Teflon dielectric materials. In this paper, \( k_p = 1.2 \times 10^{-14} \text{(S/m)/(rad/s)} \), and \( \Delta = 0.7 \).

3. Results and discussion

3.1. Effect of electron energy on deposition parameters

The thickness of the aluminum shield is \( d_{Al} = 1 \text{ mm} \), and the irradiation current density is set to \( J_0 = 1 \text{ pA/cm}^2 \), that is, the number of electrons emitted per unit area per unit time is \( 6.25 \times 10^6 \text{cm}^{-2}\text{s}^{-1} \). The distribution of deposition parameters of Teflon dielectrics irradiated by electrons with different energy passing through the shield layer is calculated as shown in Figure 2 and Figure 3.

Figure 2 shows the distribution of injection current density \( J(x) \) and charge deposition rate \( \rho_e(x) \).

According to the empirical formula of the range of electrons in aluminum, the range of electrons with energy of 0.7 MeV and 0.8 MeV in aluminum is 0.926 mm and 1.15 mm, respectively [12]. Therefore, only electrons with energy exceeding 0.75 MeV can penetrate aluminum shield with thickness of 1 mm. From the simulation results in Figure 2, it can be seen that when the electron energy exceeds 0.8 MeV, the electron has penetrated the aluminum shield with thickness of 1 mm. As the energy of irradiated electrons increases, the ability of electrons to penetrate aluminum shield becomes stronger, and the injection current density in Teflon dielectrics becomes larger and larger. It can be seen from Figures 2 (a) and (b) that when the electron energy is less than 3 MeV, the electron first penetrates the aluminum shield layer with a thickness of 1 mm and then enters the Teflon dielectric. With the increase of the Teflon dielectric depth, the injection current density decreases rapidly at first and then slowly at a certain depth. For example, for electrons with energy of 1 MeV, the injection current density decreases rapidly from 4.43E-14 A/cm² in the range of \( x = 0-0.12 \text{cm} \) in Teflon dielectric, which decreases by two orders of magnitude. For electrons with energy of 1 MeV, the injection current density decreases from 4.2E-16 A/cm² to 1.3E-16 A/cm² in the range of \( x = 0.12 \text{cm}-0.6 \text{cm} \), only about three times. When the energy of the electron exceeds 3 MeV, the electron first penetrates the aluminum shield layer and then completely penetrates the Teflon dielectric layer. The injection current density of the irradiated electron in the Teflon dielectric is higher as a whole, and the injection current density decreases slightly with the increase of the depth of Teflon.

Figures 2 (c) and (d) show the distribution curves of charge deposition rate in Teflon dielectric irradiated by electrons with different energy penetrating aluminum shield with thickness of 1 mm. It can be seen from the results that when the electron energy is less than 3 MeV, the negative charge is deposited in the Teflon dielectric as a whole. When the energy of radiated electrons is high, positive charges are deposited on both sides of Teflon dielectric (i.e. near the shielding layer and far from the shielding layer), while negative charges are mainly deposited on the middle part of Teflon dielectric. The deposition of positive charges on both sides is due to the emission of electrons from the medium to the outside of both ends, leaving a net positive charge. When the energy of irradiated electrons is less than 3 MeV, the charge deposition rate increases first and then decreases with the increase of dielectric depth, and a peak appears at a certain depth, called Bragg peak, which is the result of the
combined effect of transmission electron and backscattering electron. Comparing the distribution curves of deposition charge rate produced by different energy electrons, it can be seen that with the increase of irradiated electron energy, the position of Bragg peak moves deeper into the medium, while the height of the peak decreases. When the energy of irradiated electrons exceeds 6 MeV, most of the irradiated electrons penetrate aluminum shield layer with 1 mm thickness and Teflon with 6 mm thickness, so no obvious Bragg peak can be seen.

Figure 2. Distribution of injection current density and charge deposition rate of Teflon irradiated by different energy electrons when the thickness of aluminum shield is 1 mm.

Figure 3 shows the radiation dose rate distribution curve in Teflon dielectric and the radiation induced conductivity distribution curve calculated from the radiation dose rate. As can be seen from figure 3(a) and (b), the higher the energy of irradiated electrons, the higher the radiation dose rate produced in Teflon dielectric. When the electron energy exceeds 1.5 MeV, the radiation dose rate increases firstly with the depth, shows a maximum at a certain depth, and then gradually decrease. The maximum radiation dose rate decreases with the increase of irradiated electron energy, but the depth of the maximum radiation dose rate increases with the increase of irradiated electron energy. Figure 3(c) and (d) are radiation induced conductivity distribution curves calculated from radiation dose rate. The variation trends of radiation induced conductivity with depth are basically the same as that of the radiation dose rate. The corresponding radiation induced conductivity is larger at the depth where the radiation dose rate is higher.

3.2. Effect of aluminum shield thickness on deposition parameters
The thickness of aluminum shield in the simulation model is changed from thin to thick, and the energy of irradiated electrons is 2 MeV, and the radiation current density is $J_0=1 \text{ pA/cm}^2$. The parameters of injection current density, charge deposition rate and radiation dose rate in Teflon dielectric with 6 mm thickness were calculated out under various thicknesses of aluminum shield as shown in Figure 4.
From the injection current density distribution curve of Figure 4 (a), it can be seen that the thicker the aluminum shield, the smaller the injection current density at $x=0$ of Teflon dielectric surface. In the cases of absence of aluminum shield, aluminum shield with thickness of 1 mm and aluminum shield with thickness of 2 mm, The injection current densities at $x=0$ of the dielectric surface are 0.98 pA/cm$^2$, 0.84 pA/cm$^2$ and 0.57 pA/cm$^2$, respectively. The thicker the aluminum shield, the smaller the depth of the injection current density to the medium. Figure 4 (b) shows the distribution curve of charge deposition rate with depth, and there is a peak value of charge deposition rate in the medium. The thicker the aluminum shield, the shallower the position of the peak value of charge deposition rate, and the smaller the absolute value of the peak charge deposition rate. Figure 4 (c) is the distribution curve of radiation dose rate with the depth of the medium. With the increase of the depth of the medium, the radiation dose rate increases first and then decreases, and peaks appear at a certain depth. The greater the thickness of aluminum shield, the lower the peak radiation dose rate and the shallower the peak position. Under the same thickness of aluminum shield and irradiation conditions, the position of the maximum charge deposition rate in the medium is deeper than that corresponding to the peak radiation dose rate. Figure 4 (d) shows the variation of radiation induced conductivity with the depth of Teflon dielectric, which is basically consistent with the radiation dose rate distribution curve.

More calculations were carried out, in which the thickness of aluminum is selected as 0.0001 mm, 0.0002 mm, 0.0005 mm, 0.01 mm, 0.02 mm, 0.05 mm, 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm, respectively. The results show that the value of the radiation induced conductivity which is approximately proportional to dose rate with $d_{Al}<0.3$ mm is less than those with the thicknesses $d_{Al}>0.3$ mm at $x≈0.5-0.6$ cm. This is because that, for an electron with energy of 2 MeV, it has strong penetration ability. Its range in Teflon is about 0.46 cm$^2$. After adding a thinner thickness of aluminum shield, the electron energy is weakened when it passes through the aluminum shield, and then the electrons which could have penetrated the Teflon medium are deposited in Teflon.
3.3. Effect of electron irradiation current density on deposition parameters

According to the guidance manual of space radiation effect issued by NASA, when the magnitude of radiation current density is $10^{-13}$-$10^{-12}$A/cm², the possibility of electrostatic discharge in satellite is high [13]. In this paper, the radiation current density is 0.1 pA/cm² to 10 pA/cm², the electron energy is 2 MeV and the thickness of aluminum shield is 1 mm. The radiation dose rate distribution in Teflon dielectric and the corresponding radiation induced conductivity distribution curve are obtained by Monte Carlo simulation. The results are shown in Figure 5.

![Figure 5](image)

**Figure 5.** The radiation dose rate and radiation induced conductivity distribution in Teflon dielectrics when the thickness of aluminum shield is 1 mm and the electron energy is 2 MeV.
Figure 5 shows that the radiation dose rate and the radiation induced conductivity in Teflon dielectric are basically proportional to the radiation current density. The higher the irradiation current density is, the higher the radiation dose rate in Teflon dielectric is, and the higher the radiation induced conductivity is.

4. Conclusions
In the paper, the calculation model of aluminum shield and Teflon irradiated by high energy electrons is established. The parameters of injection current density, charge deposition rate, radiation dose rate and radiation induced conductivity of Teflon dielectric under different electron energy, different thickness of aluminum shield and different radiation current density are obtained by Monte Carlo simulation. The results show that the parameters such as the energy of radiated electrons and the thickness of aluminum shield will affect the deposition charge parameters in the dielectrics. The higher the electron energy, the stronger the ability to penetrate the aluminum shield and the higher the injection current density formed in the dielectrics. The thicker the aluminum shield is, the shallower the peak position of the charge deposition rate and radiation dose rate is, the smaller the absolute value of the peak value of the charge deposition rate is, and the lower the peak value of radiation dose rate is. The radiation dose rate and radiation induced conductivity in the dielectrics are basically proportional to the radiation current density. The higher the irradiation current density is, the higher the radiation dose rate in the medium is, and the higher the radiation-induced conductivity is.

Acknowledgments
The work is supported by State Key Lab of Intense Pulsed Radiation Simulation and Effect Basic Research Foundation (No.SKLIPR1504).

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