Technical Physics, 2022, Vol. 67, No. 6

01

Research and development of discharge free insula-tion of wires for space application

© S.Yu. Tolstikov, V.S. Saenko, A.P. Tyutnev

Laboratory of Space Vehicles and Systems' Functional Safety, MIEM, HSE University, Moscow, Russia
e-mail: stolstikov@hse.ru

Received January 31, 2022
Revised March 9, 2022
Accepted March 10, 2022

The present research aimed to investigate a charging of the cylindrical insulation layer of wires for space applications under the influence of isotropic electron radiation with an electron injection uniform in the volume of the dielectric. An analytical solution of the first-order differential equation resulting from the proposed charging model is obtained. A software has been developed and received state registration that allows for a complete calculation of the physical parameters of space-application wires resistant to electrification effects. The obtained results are proposed to be used for modeling and testing of wires for space applications in order to completely exclude the physical possibility of the occurrence of electrostatic discharges (ESR) of the „insulation–core"type during the operation (of the spacecraft) in orbit during geomagnetic disturbances in the Earth's magnetosphere.

Keywords: electricity, bulk charging, insulation, dark conductivity, electrostatic discharge.

DOI: 10.21883/TP.2022.06.54409.20-22

Introduction

The study [1] concludes that more than a half of failures of spacecraft (SC) board electronics (BE) at the geostationary and highly-elliptical orbits occur as a result of SC electrification, which is accompanied by occurrence of the electrostatic discharges (ESD), which create some difficulties for BE operation. First of all, it is a very short (3–5 ns) advanced front of the discharge pulse; secondly, the amplitude of this pulse reaches 100 A [1]. These ESD parameters allow inducing significant currents in the BE circuits, thereby resulting to reversible and irreversible failures in their operation [2]. While presently the electrification problem of the SC external surface is almost solved by correctly selecting design and material solutions, a relevant question in the today?s agenda is to protect the BE against damaging factors of the internal electrification. The internal electrification is defined by electrons of the energy of 1–2 MeV and above, which are available in a spectrum of the Earth radiation belts and penetrate the SC body with some losses of their energy to charge the BE dielectric materials inside the body. That is why today there is the biggest concern about protection of the SC body against the effects of internal electrification. Thanks to the data received from the CRRES spacecraft [3], the ESDs are observed even at insignificant total electron fluence of about $2 \cdot 10^{10}$ e/cm^2 as accumulated for 10 h. The SC internal electrification results in accumulation of bulk charges in polymer bodies of the equipment [4] and semiconductor devices [5], as well as in the dielectric materials of printed circuit boards [6]. The cited studies provide ways of solving the electrification problems for the dielectric materials of the polymer bodies of the semiconductor devices and the printed circuit boards. The present study considers an issue of protection of aerospace wires against the electrification effects. When the spacecraft is inside the low earth plasma, the charges are accumulated in the dielectric materials of the wires and cables of the SC. The present study is focused on a process of accumulation of the bulk charges in the wire insulation (Fig. 1), as well as on searching possibilities to prevent electrostatic discharges between the insulation and the electric conductor.

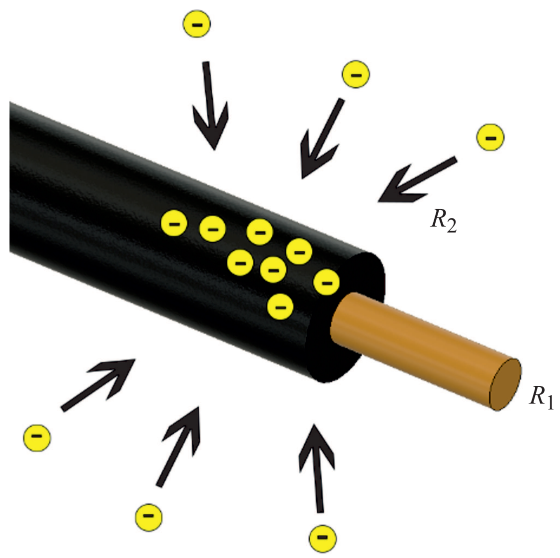

Figure 1. Electron charging of the dielectric layer of the wire insulation layer, where R_1 — the radius of the metal conductor of the wire, R_2 — the external radius of the dielectric layer of the wire.

1. Physical model of charging of wire insulation

All the metal elements of the SC structure are galvanically interconnected not only by common thread connections, but using bridges of controllable junction resistance. The electrical SC capacity relative to its surrounding space plasma is calculated as the capacity of a solitary sphere to be 150–200 pF. When the SC is at the geostationary orbit, it takes fractions of a second to charge and discharge this sphere. The charge injected from the plasma into the dielectric material is preserved much longer and defined by the Maxwell time of relaxation. That is why the spacecraft wires should be designed by avoiding high-quality dielectric materials with preference to the dielectric materials of increased conductivity. It should be noted here that the increased conductivity of the wire insulation can fully exclude ESD occurrence, while not impairing the BE operation. We have convincingly shown it in the study [6].

Presently, the SC still have the dielectric materials with conductivity, which is insufficient to avoid ESD [7].

As noted above, the important result from the studies on the CRRES spacecraft [3] was experimental establishment of a new criterion of ESD occurrence. It is the total electron fluence $2 \cdot 10^{10}\,\mathrm{e/cm^2}$ accumulated by the 10 h irradiation. It should be noted that at the same time the electron current density is negligibly small (about $10^{-10}\,\mathrm{A/m^2}$) and the radiation electrical conductivity of the dielectric material can be neglected. That is why when developing the physical model of charging we take into account only the dark (initial) electrical conductivity of the wire insulation, and this will provide discharging the injected charge to the electric conductor. Previously, based on results of the operation of SCATHA [7], an additional criterion has been formed — the electric field within the dielectric material bulk with possible space ESD is $F_{\max} = 2 \cdot 10^7\,\mathrm{V/m}$. We accept this criterion as the main one for further consideration.

We have proposed the physical model to be described by the following selected provisions:

1. We consider a current-conducting solid cylinder of the radius R_1 (Fig. 2). The metal conductor of the wire is effectively grounded, i.e. it has a zero potential.

2. Let S_o, $\mathrm{A/m^3}$ (Fig. 2) — the rate of uniform injection of electrons into the volume of the cylindrical dielectric layer R_2–R_1 (Fig. 2) when irradiating with the isotropic flux of electrons.

3. It is accepted that the dielectric layer has the constant dark conductivity γ_T, which provides for partial discharge of injected electrons to the electric conductor.

4. The simulation has been performed by using a differential equation, which describes accumulation of the bulk charge within the dielectric material at uniform electron injection:

$$\frac{\partial \rho}{\partial t} = -\mathrm{div}(\gamma_T \cdot F(R)) + S_0. \tag{1}$$

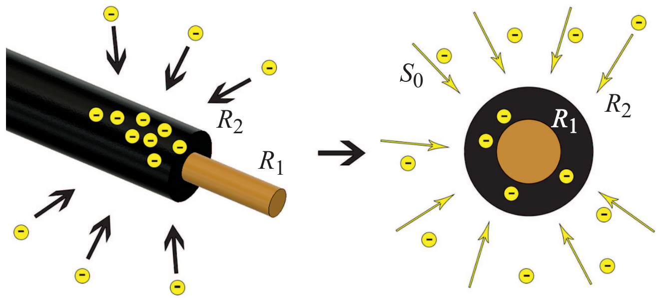

Figure 2. Model (to the right) of accumulation of the bulk charges in the dielectric layer.

Figure 3. Sample of the wire MS 26–15 1×0.08 mm.

5. The differential equation (1) describing the stationary process of accumulation of the bulk charges is analytically solved by $F_{\max}$ — the maximum electric field, at the radius R_1, at the interface of the metal with the zero potential — the charged dielectric material.

$$F_{\max} = -\frac{S_0}{\gamma_T \cdot R_1} \cdot \left(R_2^2 - R_1^2\right). \tag{2}$$

The differential equation has been solved for the most required stationary case, when the electric field in the dielectric material of the insulation is a maximum one.

2. Discussion

We note that the analytical calculations take conditions of the worst-case scenario when operating this spacecraft at a given orbit. It is understood that these conditions are defined either by a point of the geostationary orbit or the orbit itself in other cases and can be greatly different. The formula (2) is used to calculate the maximum electric field intensity within the dielectric layer of the wire.

The electric voltage in the dielectric material has been calculated on a selected sample of the connecting wire MS 26-15. According to TU16.K76-160-2000, the sample is a copper silvered conductor with polyimide insulation (Fig. 3), whose dark conductivity is $10^{-14}\,\Omega^{-1} \cdot \mathrm{m}^{-1}$. The technical characteristics of this sample are the following: the maximum alternating voltage up to 250 V (the frequency up to 10 kHz) or the constant voltage up to 350 V. The calculations for the selected sample with a conductor section from 0.08 to 0.5 mm² and the external radius from 0.25 to 1.25 mm is exemplified on Fig. 4.

It is clear from the figure that the maximum electric field intensity at these irradiation conditions increases with decrease in the radius of the electric conductor of the wire

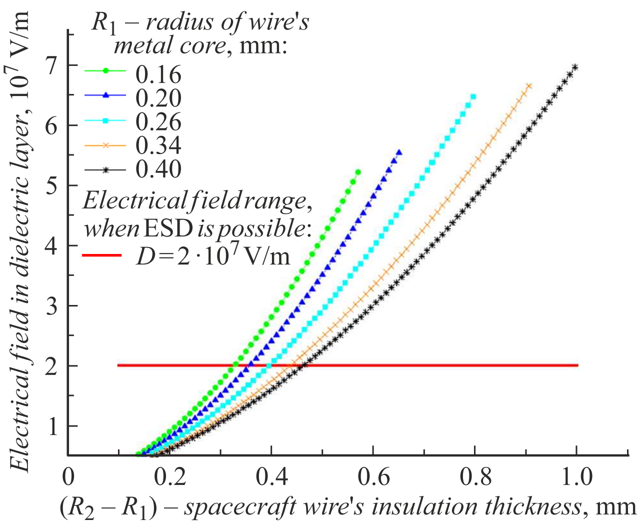

Figure 4. Results of the calculation of the electric field in the dielectric layer as per the proposed model for various radii of the conductors and the insulation thickness corresponding thereto, the material — polyimide.

and increase in the thickness of its insulation layer. Figure 4 shows a line parallel to the abscissa axis, which corresponds to the electric field of $2 \cdot 10^7$ V/m. The area below this line is characterized by no possibility of occurrence of the electrostatic discharges. The area above the separation line is characterized by possible ESD, whereas the wires with parameters typical for this area should not used in space equipment to be operated at the geostationary orbit or at the highly-elliptical orbits, which intersect the Earth radiation belts.

Conclusion

Using the proposed analytical model and our developed calculation program, it is possible to select for each radius of the electric conductor the respective insulation thickness and the specific bulk conductivity of the insulation dielectric material, thereby avoiding the dielectric layer?s electric field sufficient for ESD. Thus, the developed calculation program supposes a required change of the electric conductor radius, the insulation thickness and the electrical conductivity of the insulation material. A criterion of selecting a required set of wire parameters is a design electric field not exceeding $2 \cdot 10^7$ V/m.

If required, it is also possible to analyze the data for the specific samples with given parameters of the electric conductor and insulation. Otherwise, it is necessary to select a proven substitution.

The software [8] has been developed and passed the state registration. It is designed to fully calculate the physical parameters of the aerospace wires, which are resistant to the electrification effects. The obtained results are supposed to be used when simulating and testing the aerospace wires in order to avoid ESD of the „insulation–conductor“ type when operating the spacecraft at the orbit in the geomagnetic disturbances in the Earth magnetic sphere.

Acknowledgments

The authors would like to thank the Fundamental Research Program of the National Research University Higher School of Economics.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M. Soria-Santacruz. Introductory Tutorial // Spacecraft Charging Technology Conference. 23 June 2014. Pasadena, USA. Poster 254.
[2] M. Tafazoli. Acta Astronautica, **64**, 195 (2009).
[3] H.B. Garrett, A.C. Whittlesey. *Guide to Mitigating Spacecraft Charging Effects* (Wiley, NY, USA, 2012)
[4] V.S. Saenko, A.P. Tyutnev, M.A. Afanasyeva, A.E. Abrameshin. IEEE Transactions on Plasma Science, **47** (8), 3653 (2019). DOI: 10.1109/TPS.2019.2893186
[5] A.P. Tyutnev, G.A. Belik, A.E. Abrameshin, V.S. Saenko. Perspektivnye materialy, **5**, 28 (2012) (in Russian).
[6] V. Saenko, A. Tyutnev, A. Abrameshin, G. Belik. IEEE Transactions on Plasma Science, **45** (8), 1843 (2017).
[7] *NASA-Technical Handbook: Mitigating in-Space Charging Effects — A Guideline* (document Rec. NASA-HDBK-4002A, Mar. 2011)
[8] S.Yu. Tolstikov. *Programma rascheta maksimal?nogo electricheskogo polya na dielectricheskom sloe provoda.* (Svvo o gos. registratsii programmy dlya EVM № 2021660525. 30.11.2021) (in Russian).