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As a manuscript

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Investigation of the effect of charge accumulation processes in composite polymer dielectrics on the onboard electronics of spacecraft

Dissertation summary
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Relevance of the research topic

When designing spacecraft, an important role is played by the correct selection of electronic circuits for on-board electronic equipment used for the stable functioning of spacecraft subsystems, including those providing its orientation and stabilization in space, communication, etc. Strict requirements are imposed on the element base of spacecraft. One of the key points is the stability of the onboard electronic equipment of the spacecraft to electromagnetic interference, since these interferences arising from electrostatic discharges can disable the device, or significantly distort the operation of satellite subsystems. Electrostatic discharges occur more often when geomagnetic disturbances of the Earth's magnetosphere occur.

Currently, the use of microelectromechanical systems that combine both mechanical and electrical components of micron sizes is actively developing. The corresponding technology is used to create various microcircuits, including those used in space instrumentation. However, although this technology allows you to create smaller printed circuit boards without compromising the payload, there is a risk of failure of the electronic circuit due to exposure to electrostatic discharges, as the sensitivity of the element base becomes higher.

Failures of electronic systems are dangerous because the spacecraft may be lost in outer space, which entails material damage for developers. According to NASA statistics, 54% of spacecraft failures in near-Earth orbits occur due to the impact of electrostatic discharges on the electronic base of the spacecraft. Thus, scientists face an urgent problem of protecting on-board electronic equipment

Therefore, it is important to improve not only the onboard electronics, but also to improve the modern spacecraft at the design stage to reduce the impact of destructive electrification factors on the electronics of the spacecraft.

For spacecraft operating in geostationary orbits, highly elliptical orbits, in auroral zones of the Earth's magnetosphere, it was revealed that the main cause of electrostatic discharges is the differential charging of elements on the outer surface

of the spacecraft. If we consider a special case, namely a spacecraft in geostationary orbits, then the potential difference on the surface of the spacecraft can reach 20 kV, which can lead to the occurrence of electrostatic discharges with an energy of 6-200 MJ. As a result, pulsed currents flow through the body of the spacecraft, up to 100 A. This process entails the appearance of electromagnetic interference in the cables of on-board electronic equipment, which can lead to a complete failure of the spacecraft, or to irreversible distortions in the operation of on-board electronic equipment.

Russian scientists Saenko V.S., Pozhidaev E.D., Kechiev L.N., Kirillov V.Yu., Novikov L.S., Khodnenko V.P., Tyutnev A.P., etc. They are successfully working in the field of research of electrification of the spacecraft and protection of the onboard electronic equipment of the spacecraft from the effects of electrostatic discharges, they have developed effective methods for testing it and increasing noise immunity. It should also be noted a number of foreign scientists working in this field, among them G. Garrett, A. Wittlesi, M. Bode, R. Hughes, S. Minow, D. Parker, M. de Santa Cruz and a number of others.

When designing a spacecraft for on-board electronic equipment of a new generation, complex structures are created, which causes difficulties during modeling and conducting experiments to determine the effects of electrostatic discharges on the structures of the spacecraft and on-board electronic equipment. This causes difficulties in developing new design concepts both at the stage of creating theoretical foundations and at the stage of creating a methodology for designing the onboard electronic equipment of the spacecraft, therefore it is necessary to apply in practice the latest developments to prevent the influence of electrostatic discharges on the spacecraft. Scientists are faced with the task of ensuring the resistance of the electronic equipment of satellites to the influence of electrostatic discharges, which will reduce the possible damage from the loss of the spacecraft, on-board electronic equipment that is exposed to them.

Thus, improving the design quality of the onboard electronic equipment of the spacecraft by eliminating electrification caused by the impact of space plasma is an

urgent scientific and technical task, and its solution will be an urgent and important step in the development of various areas of the country's economy, and will also make a certain contribution to the country's defense capability.

The aim of the study is to increase the active life of the spacecraft by increasing the stability of on-board electronic equipment to the occurrence of electrostatic discharges due to the use of composite dielectrics with increased conductivity in it, excluding electrostatic discharges while maintaining unchanged the performance characteristics of this on-board electronic equipment.

In accordance with **the purpose** of the work, the following scientific and applied tasks were set and solved:

1. Based on a carefully conducted analytical review of literature sources on electrification, physical factors determining the occurrence of electrostatic discharges due to the internal electrification of the spacecraft have been identified. It is shown that there are currently no sufficiently effective methods to protect against it. The analysis made it possible to formulate the purpose and objectives of the dissertation research.
2. A physicomathematical model describing the kinetics of radiation charging of composite polymer dielectrics is proposed. The model takes into account the value of the specific volumetric (dark) conductivity of the polymer composite in the form of a parameter, and the radiation conductivity arising under the action of plasma in the form of a dependence on the irradiation time and on the density of the plasma electron flux. The model makes it possible to calculate changes in the magnitude of the electric field strength in composite polymer dielectrics during electron irradiation, as well as to determine the conditions leading to the occurrence of an electrostatic discharge.
3. A modeling technique has been developed to identify and substantiate the values of the conductivity of these dielectrics, which ensures the discharge of the accumulated charge and the absence of electrostatic discharges. The method is based on an experimental study of the dependence of radiation

conductivity on the exposure time of plasma electrons, subsequent data processing to obtain an approximation function and transform the latter into a working function of the dependence of radiation conductivity on the irradiation time and on the density of plasma electron flux.

4. For a number of model polymers, experimental studies of radiation conductivity necessary for calculations have been performed and simulation of radiation charging of composite polymer dielectrics under the action of cosmic plasma under conditions of a calm geomagnetic environment and under conditions of a sub-storm has been performed. On this basis, the values of the specific volumetric conductivity of these materials are found, which ensures the absence of electrostatic discharges. The value of the specific volumetric conductivity is obtained and justified, at which, even in the conditions of a geomagnetic substorm, a sufficient charge drain will be provided for all polymers to prevent electrostatic discharges.
5. Spice models of radioelectronic devices have been developed - a heterodyne and a broadband amplifier, the distinctive feature of which is the consideration of current leaks in printed circuit boards using a composite polymer dielectric with increased conductivity.
6. Using the developed models, computer simulation of the performance characteristics of a heterodyne and a broadband amplifier with a polymer composite material of a printed circuit board, which has increased conductivity, was carried out. The limits in which these characteristics remain unchanged are revealed. Experimental studies of the layouts of the corresponding devices confirmed the simulation results.
7. An engineering technique has been developed for selecting a composite polymer dielectric as part of the on-board radio electronic equipment of the spacecraft, implemented on printed circuit boards with a composite dielectric having increased conductivity and ensuring the absence of electrostatic discharges while maintaining the performance characteristics of the corresponding devices unchanged.

Scientific novelty of the results of the work:

1. A kinetic model of radiation charging of composite polymer dielectrics is proposed for the case when the extrapolated electron path is less than its thickness. The model differs in that it takes into account the value of the specific volumetric (dark) conductivity of the polymer composite in the form of a parameter, and the radiation conductivity arising under the action of plasma in the form of a dependence on the irradiation time and on the density of the plasma electron flux. The model makes it possible to calculate the electric field strength depending on the time of electron irradiation of composite polymer dielectrics, and to establish the conditions for the occurrence of an electrostatic discharge.
2. An appropriate modeling technique has been developed, which is based on an experimental study of the dependence of radiation conductivity on the exposure time of plasma electrons, subsequent data processing to obtain an approximation function of experimental data using parametric identification methods, converting the latter into a working function of the dependence of radiation conductivity on the irradiation time and on the density of plasma electron flux. The technique provides calculations for the electron flux density corresponding to a calm geomagnetic environment and the flux density corresponding to the flow of a sub-storm. In this case, the value of the maximum achievable electric field strength is found, and it is compared with the criterion value of the electric field corresponding to the beginning of the occurrence of electrostatic discharges.
3. For a number of polymer dielectrics, using computer modeling, the values of the specific volumetric RP have been established, which ensures the discharge of the accumulated charge and the absence of electrostatic discharges. The value of the specific volumetric conductivity is obtained and justified, which is the following value of 10^{-9} Ω^{-1} m^{-1}, at which, in the conditions of a geomagnetic substorm, a sufficient charge drain will be provided for all polymers to prevent

electrostatic discharges.

4. Spice models of radio-electronic devices are proposed – a heterodyne and a broadband amplifier, in which a composite polymer dielectric is used in the printed circuit board, whose conductivity is higher compared to commonly used polymers. The proposed models differ from the traditional ones in that additional resistances are introduced into the circuit, characterizing current leaks between device nodes and leaks to the zero conductor caused by a decrease in the specific volume resistance of the printed circuit board.
5. The results of computer modeling and experimental study of the performance characteristics of these devices, which showed that the frequency and amplitude of the output voltage of the heterodyne remain unchanged as long as the specific volume conductivity of the dielectric of the printed circuit board does not exceed the values of $2 \cdot 10^{-7}$ Ω^{-1} m^{-1}, and the bandwidth and gain of the broadband amplifier remain unchanged as long as the specific volume the conductivity of the dielectric of the printed circuit board does not exceed $1.2 \cdot 10^{-5}$ Ω^{-1} m^{-1}.

Practical significance of the work:

1. Using the example of a heterodyne and a broadband amplifier, the efficiency of using composite dielectrics with increased conductivity is shown. Dielectrics of this type can be used in radioelectronic devices used in the space industry to prevent the occurrence of electrostatic discharges and equipment failures.
2. An engineering technique has been developed for the selection of a composite polymer dielectric that excludes the occurrence of electrostatic discharges and ensures the operability of radio-electronic devices for space applications without changing the performance characteristics.

The main provisions submitted for protection:

1. Kinetic model and method of modeling radiation charging of composite polymer dielectrics.
2. The results of modeling the kinetics of radiation charging of composite polymer

dielectrics, which made it possible to determine the values of their total conductivity, ensuring the absence of the occurrence of electrostatic discharges.

3. Models of radio-electronic devices (heterodyne and broadband amplifier), a distinctive feature of which is the consideration of current leaks in printed circuit boards using a composite polymer dielectric with increased conductivity.
4. . The results of computer modeling and experimental study of the performance characteristics of these devices.
5. Engineering methodology for the selection of a composite polymer dielectric as part of the onboard electronic equipment of a spacecraft, ensuring the absence of electrostatic discharges, and ensuring operability without changing the performance characteristics of radio-electronic devices for space applications.

The applicant's personal contribution consists in taking part in the formulation of work tasks, finding solutions, creating an original experimental method for determining the values of the dose accumulation factor for polyethylene terephthalate at various electron radiation energies, creating models of a heterodyne and a broadband amplifier in which the dielectric of the printed circuit board is replaced by a composite dielectric with increased conductivity. The author personally developed a physical model and a method of radiation charging of composite polymer dielectrics. The technique makes it possible to calculate the change in the magnitude of the electric field strength in composite polymer dielectrics during electron irradiation. The author personally made experimental models of a heterodyne and a broadband amplifier and conducted studies of their performance characteristics. The author personally and with the participation of the author prepared the main publications on the work performed. As part of the dissertation research, D.A. Abrameshin as the author received a Certificate of state registration of the program for an electronic computer No. 2016618166 dated July 22, 2016. "Calculation of the absorbed dose of electron radiation taking into account the accumulation factor" (Appendix 1).

Approbation of the work

The following All-Russian and international conferences give an idea of the sufficient approbation of the results presented in the dissertation:

1. «Moscow Workshop on Electronic and Networking Technologies (MWENT)». Moscow, Russia, 2018, «Research of output characteristics of the heterodyne executed on the printed circuit board with the increased resistance to electrostatic discharges»
2. The 15th Spacecraft Charging Technology Conference, Kobe, Japan, 2018, «Computer Simulations and Experimental Investigation for Heterodyne Characteristics on PCB with the Increased Resistance to Electrostatic Discharges»
3. International Seminar on Electron Devices Design and Production (SED) Prague, Czech Republic, 2021, «Calculation of The Absorbed Dose of Electron Radiation in Polymer Cases of Microelectronic Devices, Considering the Factor of Its Accumulation»
4. International Conference of Young Scientists "Information Technologies, Telecommunications and Control systems" Innopolis, Russia, 2021, "Virtual space virtual satellite"
5. International Conference of Young Scientists "Information Technologies, Telecommunications and Control systems" Innopolis, Russia, 2021, «Data transfer from satellite to ground station emulator»
6. International Moscow IEEE-Seminar Moscow Workshop on Electronic and Networking Technologies (MWENT-2022), Moscow, Russia, 2022. "Engineering Methodology for the Selection of a Composite Polymer Dielectric that Ensures the Absence of Electrostatic Discharges in the Design of the Onboard Electronic Equipment of the Spacecraft"
7. Interuniversity Scientific and Technical Conference of Students, postgraduates and Young specialists named after E.V. Armensky, Moscow, Russia,

2016, "Development of a subprogram for calculating the absorbed dose of electronic radiation taking into account its accumulation factor"

8. Interuniversity Scientific and Technical Conference of Students, Postgraduates and Young Specialists named after E.V. Armensky, Moscow, Russia, 2020, "Program for processing experimental results on the radiation conductivity of polymer films for modeling their charging process"

9. Interuniversity Scientific and Technical Conference of students, postgraduates and young specialists named after E.V. Armensky, Moscow, Russia, 2021, "Radiation electrical conductivity of polystyrene"

The dissertation work consists of an introduction, 4 chapters, a conclusion and a list of references.

The first chapter presents a review and critical analysis of the literature data on the electrification of near-Earth high-orbit spacecraft, analyzes the main causes of electrostatic discharges caused by the internal electrification of the spacecraft, considers the main methods of protection against external and internal electrification.

The second chapter describes a model and methodology for modeling the radiation charging of a number of composite polymer dielectrics with increased conductivity, presents the results of modeling for conditions of a calm geomagnetic environment and the flow of a sub-storm, and determines the values of the specific volumetric conductivity of polymer composites, at which electrostatic discharges will not occur. This made it possible to establish a criterion value of the specific volumetric conductivity, at which a sufficient charge drain will be provided for all polymer composites to prevent electrostatic discharges.

The third chapter presents the results of computer modeling and experimental study of the performance characteristics of standard analog radioelectronic devices – a heterodyne and a broadband amplifier in order to identify the boundaries of the possible use of a composite dielectric with increased conductivity. It is shown that an increase in the specific volume conductivity of the

dielectric of a printed circuit board to certain values, depending on the type of electronic means, practically does not change the basic performance characteristics of these devices.

The fourth chapter describes the developed engineering methodology for the selection of a composite polymer dielectric with increased conductivity, which ensures the absence of electrostatic discharges for radio-electronic means as part of the onboard radio-electronic equipment of the spacecraft. The technique is intended for the developed radio-electronic means of space applications operating on board a spacecraft operated under conditions of intense exposure to space plasma.

The conclusion of the dissertation outlines the results of the research, recommendations, prospects for further development of the topic.

List of publications

The author's publications in peer-reviewed scientific journals included in the international citation system Scopus and WoS:

1. «Abrameshin D., Pozhidaev E. D., Saenko V. S., Tumkovskiy S. Calculation of The Absorbed Dose of Electron Radiation in Polymer Cases of Microelectronic Devices, Considering the Factor of Its Accumulation, in: 2021 International Seminar on Electron Devices Design and Production (SED). IEEE, 2021»
2. «Tyutnev A. P., Saenko V. S., Aleksey D. Zhadov, Dmitriy A. Abrameshin. Theoretical Analysis of the Radiation-Induced Conductivity in Polymers Exposed to Pulsed and Continuous Electron Beams // Polymers. 2020. Vol. 12. No. 628. P. 1-10»
3. «Abrameshin D.A., Pozhidaev E.D., Saenko V.S., Tumkovskiy S.R. Computer Simulations and Experimental Investigation of the Heterodyne Employing Printed Circuit Board With an Increased Resistance to Electrostatic Discharges // IEEE Transactions on Plasma Science. 2019»
4. «Abrameshin D., Tumkovskiy S., Pozhidaev E. Research of output characteristics of the heterodyne executed on the printed circuit board with the increased resistance to electrostatic discharges, in: 2018 Moscow

Workshop on Electronic and Networking Technologies (MWENT).: IEEE, 2018»

5. «Abrameshin D., Ivliev N., Evdokimova V., Podlipnov V., Petrov M., Ganchevskaya S., Tkachenko I., Yuzifovich Y., Nikonorov A., Skidanov R., Kazanskiy N., Soifer V. First Earth-Imaging CubeSat with Harmonic Diffractive Lens. Electronics (MDPI), 2022»

Author's publications in other journals :

1. Abrameshin D. A., Pozhidaev E. D., Tumkovsky S. R. «Modeling of radiation charging of the bodies of microelectronic equipment for space applications». Information technology. 2021. Vol. 27. No. 2. pp. 59-64."
2. Abrameshin D. A., Zvezdov D. S. «Utilities in Mathcad software for the refined calculation of electric fields during irradiation of polymer films with low-energy electrons» // System Administrator. 2016"

РОССИЙСКАЯ ФЕДЕРАЦИЯ

СВИДЕТЕЛЬСТВО

о государственной регистрации программы для ЭВМ

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Правообладатель: ***федеральное государственное автономное образовательное учреждение высшего образования «Национальный исследовательский университет «Высшая школа экономики» (RU)***

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Руководитель Федеральной службы по интеллектуальной собственности