National Research University Higher School of Economics

As a manuscript

Mullakhmetov Ilshat Ramilovich

INVESTIGATION OF THE INFLUENCE OF LOW TEMPERATURES ON THE ELECTRIZATION OF POLYMER DIELECTRICS OF SPACECRAFT

Dissertation summary
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Academic Supervisor:
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Professor
Pozhidaev Evgenii Dimitrievich

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Practical applications of spacecraft include precision mapping, weather forecasting, global positioning, communications and a variety of other applications for both scientific research and dual use. Satellites are expensive to design, build and launch, and are often impossible to repair. Therefore, it is extremely important that spacecraft are designed to withstand the conditions of space factors, and in particular, the space plasma environment in which they are located. It is especially important to mitigate the effects of electrostatic discharges, which account for more than half of spacecraft failures associated with interaction with space factors. One of the key factors in outer space is ionizing radiation. It consists of photons, protons, ions and electrons that interact with the surface of spacecraft. Of these particles, electrons make the largest contribution to charging spacecraft due to their high mobility. Therefore, the interaction of electrons with spacecraft will be the focus of this dissertation research. Thus, the main factor influencing charge dissipation in a dielectric material is radiation induced conductivity.

Polymer materials have found wide application in space technology as structural elements of a spacecraft, layers of screen-vacuum thermal insulation to maintain the temperature conditions of a spacecraft, electrical insulation of cable products, printed circuit boards of on-board electronic equipment, etc. Polymer dielectrics have extremely low intrinsic electrical conductivity and at the same time are exposed to flows of ionizing radiation for a long time. In this regard, there is a problem associated with the charging of dielectrics, which leads to the occurrence of electrostatic discharges in polymers. The main physical parameter of a dielectric that controls the accumulation of electrical charges during irradiation is the radiation induced conductivity of this dielectric. The lower it is, the greater the likelihood of electrostatic discharge occurring. It should also be noted that during the day there is a change in temperature on the surface of the spacecraft from 120 K to 350 K. At low temperatures, both the radiation and dark electrical conductivity of dielectrics decreases significantly, which leads to an increase in the likelihood of electrostatic discharges in dielectrics used in spacecraft devices. Electrostatic discharges, in turn, lead to malfunctions and failures of the on-board radio-electronic equipment of the spacecraft. All this determines the **relevance of studying** the

radiation induced conductivity of polymer dielectrics at low temperatures (120 K and below).

The degree of development of the issue of radiation induced conductivity of polymer dielectrics is quite wide. This area was studied by domestic scientists, among whom are such names as: Tyutnev A.P., Saenko V.S., Pozhidaev E.D., Novikov S.V., Nikitenko V.R., Ikhsanov R.Sh., Khatipov S.A., Vaisberg S.E., Arkhipov V.I., Rudenko A.I., Vannikov A.V., Mingaleev G.S., Sadovnichy D.N. It is also necessary to note a number of foreign scientists who worked on this topic: B. Gross, A. Rose, J.F. Fowler, H. Bessler, H.B. Garrett, G.M. Sessler, J.E. West, J.R. Dennison, R.K. Hughes, G.R. Freeman, A. Humel.

The radiation induced conductivity of polymer dielectrics has been studied experimentally and theoretically under pulsed and continuous irradiation, mainly at normal (298 K) and elevated temperatures. However, in the literature there are practically no results of measurements and modeling of the radiation induced conductivity of polymer dielectrics at low temperatures.

The scientific school of the Laboratory of Functional Safety of Spacecraft and Systems obtained experimental data on the low-temperature radiation induced conductivity of polymers when exposed to millisecond pulses of accelerated electrons. However, to study the possibility of the occurrence of electrostatic discharges in on-board electronic equipment of spacecraft, it is necessary to obtain experimental data on long-term (up to three hours) irradiation of polymer dielectrics.

The laboratory staff also developed a method for assessing the occurrence of electrostatic discharges in polymer dielectrics at normal temperatures. In the resulting technique, radiation induced conductivity is described using an approximating function, starting from the maximum value of radiation induced conductivity and scaling depending on the absorbed dose rate. This approach is not applicable to describe radiative electrical conductivity at low temperatures, since the maximum of radiation induced conductivity at low temperatures occurs 2–3 orders of magnitude later, which does not allow taking into account the initial change in radiative induced conductivity.

The purpose of this dissertation is to increase the service life of spacecraft through the use of polymer dielectrics with reduced electrification at low temperatures.

To achieve this goal, the following **tasks** were solved:

– An experimental technique has been developed for measuring the long-term radiation induced conductivity of polymer dielectrics at low temperatures, characterized by the possibility of maintaining it for a long time due to the placement of a polyethylene terephthalate film under the cathode of the electron beam gun, as well as the protection of the measuring cell with a heat-conducting rod from external heat flows by screen-vacuum thermal insulation. The experimental technique takes into account: absorbed dose rate for various polymer dielectrics; the intensity of the internal electric field due to the injection of external electrons; the ability to eliminate noise when measuring the radiation induced conductivity of polymer dielectrics.

– Using the example of a model polymer dielectric – polystyrene – experimental and theoretical studies of radiation induced conductivity at room and low temperatures were carried out with the possibility of comparing them. It has been shown that the radiation induced conductivity in polystyrene at 79 K is 40 times lower than at room temperature. This means that polystyrene, which is resistant to electrostatic discharge at room temperature, becomes a material in which electrostatic discharge is possible at low temperatures. The values of the parameters of the Rose-Fowler-Vaisberg model for polyimide and polyethylene terephthalate at 103 K were also determined. For this purpose, a procedure was developed for determining the shift of thermalized charge carriers based on experimental data.

– A model of radiation charging of polymer dielectrics at low temperatures has been developed, a feature of which is the use of the semi-empirical Rose-Fowler-Vaisberg model of radiation induced conductivity, the parameters of which are determined experimentally from the curves of the dependence of radiation induced conductivity on irradiation time at the appropriate temperature.

– An engineering technique has been developed for modeling the radiation charging of polymer dielectrics at low temperatures, which allows one to assess the

possibility of the occurrence of electrostatic discharges and, from this point of view, determine the feasibility of using a specific polymer dielectric.

The dissertation work achieved an important goal – increasing the service life of spacecraft through the use of polymer dielectrics with reduced electrification at low temperatures. This problem is relevant at the stage of preliminary design of a spacecraft when considering various options for polymer dielectrics, the use of which is possible on a spacecraft.

The dissertation work shows that the main influence on the deterioration of the electrification of polymer dielectrics at low temperatures is exerted by a significant decrease in the radiation induced conductivity of this polymer. In this regard, it is necessary to conduct low-temperature studies of the radiation induced conductivity of polymer dielectrics.

Prospects for further development of the topic are:

– refinement of the experimental methodology for controlling the given temperature regime;

– study of the radiation induced conductivity of polymer dielectrics at various temperatures from 79 K to 298 K with a given step;

– further research in the field of protection of radio-electronic equipment for space applications from the harmful effects of electrostatic discharges and the creation of discharge-free spacecraft.

The object of research is polymer dielectrics for space and radiation materials science.

The subject of the study is the radiation charging of polymer dielectrics under the influence of cosmic plasma at low temperatures.

The scientific novelty of the work lies in

– development of an experimental technique for measuring long-term radiation induced conductivity of polymer dielectrics at low temperatures, characterized by the ability to maintain a constant low temperature value for a long time (up to three hours), with the accuracy of measuring a copper-constantan thermocouple, due to the placement of a polyethylene terephthalate film under the cathode of the electron beam gun, as well

as protection of the measuring cell with a heat-conducting rod from external heat flows by screen-vacuum thermal insulation;

– the first results obtained from studying the radiation induced conductivity of polymer dielectrics and determining the parameters of the Rose-Fowler-Vaisberg model for subsequent modeling of radiation induced conductivity at low temperatures;

– a developed model of radiation charging of dielectrics, characterized in that the radiation induced conductivity used in it is determined using the Rose-Fowler-Vaisberg model.

The research methods used in the work are physical experiment, physical modeling method, and numerical methods.

The provisions submitted for defense are:

– methodology for experimental studies of the radiation induced conductivity of polymer dielectrics at low temperatures in a wide time interval;

– results of studying the radiation induced conductivity of polymer dielectrics at low temperatures and determining the shift of thermalized charge carriers directly from experimental data, which makes it possible to determine the parameters of the Rose-Fowler-Vaisberg model for subsequent modeling of radiation induced conductivity at a given temperature;

– model of radiation charging of dielectrics, which can be used at low temperatures by modeling the radiation induced conductivity of polymer dielectrics with the Rose-Fowler-Vaisberg model;

– an engineering technique for modeling the radiation charging of polymer dielectrics at low temperatures, which is based on a model that allows one to estimate the field strength and compare it with a criterion value, after reaching which discharges occur.

The author's personal contribution lies in the formulation of the problem; refining the experimental technique for measuring the radiation induced conductivity of polymer dielectrics at low temperatures, as well as conducting experiments; choosing a model of radiation induced conductivity and selecting its parameters. The analysis and presentation of the results were carried out by the author personally. As part of the dissertation research, the author received certificates of state registration of the computer

program № 2021664635 dated September 10, 2021 «Digital filter for eliminating noise when measuring radiation-induced current of composite polymers» and № 2023661020 dated May 25, 2023 «Program for collecting and subsequent verification of experimental data on the electrification of polymer dielectrics of space technology».

The dissertation consists of an introduction, four sections, a conclusion and a list of references.

In the first section, a review and analysis of literature data on the radiation induced conductivity of polymer dielectrics at normal and low temperatures is carried out, the significance of these studies is given from the point of view of the problem of electrification of dielectric materials of spacecraft, and the purpose and objectives of the dissertation research are formulated as a result of the analysis.

The second section describes the method of experimental studies of the radiation induced conductivity of polymer dielectrics at low (nitrogen) temperatures. The difficulties that may arise during low-temperature measurements of the radiation induced conductivity of polymer dielectrics and how to avoid them are described.

In the third section, using polystyrene as an example, an approach to studying radiation induced conductivity at normal and low temperatures is described, the well-known approximation function of the depth variation of the dose is improved, a solution is given for determining the shift of thermalized charge carriers from experimental data, and the parameters of the Rose-Fowler-Weisberg model for polymer dielectrics for space applications at low temperatures.

The fourth section presents a model of radiation charging of polymer dielectrics, as well as an engineering technique for assessing the occurrence of electrostatic discharges in polymer dielectrics for space applications at low temperatures.

In conclusion, the main results obtained in the dissertation work are formulated.

The purpose of the study is to increase the service life of spacecraft through the use of polymer dielectrics with weak electrification at low temperatures. Thus, the work **corresponds to the passport of the specialty** 05.27.01.

As part of the dissertation research, the following articles were published:

– Tyutnev A.P., Saenko V.S., Mullakhmetov I.R., Agapov I.I. «Radiation-induced conductivity in polystyrene, a common insulating polymer with a hopping conduction» in journal «Journal of Applied Physics». 2021. Vol. 129. № 17. Article 175107 (Q2);

– Tumkovskiy S.R., Mullakhmetov I.R., Pozhidaev E.D., Saenko V.S. «Идентификация модели радиационной проводимости полимерных материалов» in journal «Информационные технологии». 2022. Vol. 28. № 5. С. 233-239 (К1);

– Tyutnev A.P., Saenko V.S., Mullakhmetov I.R., Abrameshin A.E. «Radiation-induced conductivity in polystyrene at extremely low (79 K) temperature» in journal «Journal of Applied Physics». 2022. Vol. 132. № 13. Article 135105 (Q2);

– Mullakhmetov I.R., Saenko V.S., Tyutnev A.P., Pozhidaev E.D. «Низкотемпературная радиационная электропроводность полистирола под действием электронов низких энергий» in journal «Журнал технической физики». 2023. Т. 93. № 1. С. 130-134 (К1);

– Mullakhmetov I.R., Saenko V.S., Tyutnev A.P., Pozhidaev E.D. «Low-temperature radiation-induced conductivity of polystyrene under the action of low-energy electrons» (translation from Russian) in journal «Technical Physics». 2023. Vol. 68. №. 1. P. 123-126 (Q3);

– Tyutnev A.P, Saenko V.S., Mullakhmetov I.R., Pozhidaev E.D. «Experimental and theoretical investigations of the radiation-induced conductivity in spacecraft polymers at extremely low temperatures» in journal «Journal of Applied Physics». 2023. Vol. 134. № 9. Article 095903 (Q2);

Tolstikov S.U., Mullakhmetov I.R., Pozhidaev E.D., Tumkovskiy S.R. «Компьютерное моделирование радиационного заряжения полимерных материалов космического применения при низких температурах» in journal «Технологии электромагнитной совместимости». 2024. Vol. 88. № 1. С. 57-62 (К2).