AN IMPROVED METHOD FOR SIMULATING THE CHARGE OF DIELECTRICS IN A CHARGING ELECTRON ENVIRONMENT

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Abstract

Due to their dielectric nature and under the effect of the different forms of radiation encountered in space, dielectrics accumulate electrical charges up to the point where electrostatic discharges may occur. To prevent and avoid harmful interference due to discharges, their behaviour under irradiation must therefore be investigated in the laboratory before they are used in space applications. A current and widely used practice is to submit the tested materials to the bombardment of monoenergetic electron beams. Such a practice ignores the presence in space of a spectrum of electrons with energies reaching several MeV, and leads solely to surface charging and surface potentials generally higher than those really induced in space. The new approach used by “SIRENE” is to build an electron source as similar as possible to the one existing in orbit. This paper describes the SIRENE facility, which was developed for simulating the spatial geo-stationary environment during great geomagnetic activity. The range of available electrons goes from 10 to 400 keV. From a monoenergetic electron beam of 400 keV and thanks to a complex diffusion foil (made of several foils of different thicknesses and surface areas) the quantity of electrons of each energy level present in this particular environment is reproduced. However, it is always possible to work at lower energy levels in the monoenergetic range, for instance to simulate the inverted gradient mode. This paper provides information on the spectrum used for testing materials in the geo-stationary environment, and on the potential for adapting it to other orbits. It also gives the first results demonstrating the interest of this new approach. It also mentions the new instruments used to measure the surface potential as well as the space charge through the complete thickness of the material.

Introduction

The space environment may be responsible for numerous disturbances on the various parts of a satellite. Concerning the electrical hazards, the flux of electrons from space may result in problems caused by the electrostatic charging phenomena and the possible resulting discharges [1][2]. Laboratory tests are required for assessing this risk in order to prove, beforehand, the compatibility of the materials with their future environment (these tests can be validated by means of on-board experiments). The complexity of the space environment, and the fact that it is impossible to reproduce all of its components make it difficult to perform any simulation. Several points must be considered:

- The utilization of electron flux only when, in space, the protons and photoelectrons emitted by the surfaces exposed to the sun also contribute to generating the charge (balance of all the interactions) and, consequently, the discharge.

- The locking in the laboratory of the structure potentials by the grounding of the metallizations when these structures, which are the "local grounds" for the electronic equipment, are also charged by the environment.

- The experiments are carried out over relatively short periods of time (some hours or days) whereas, in space, the key properties governing the charging of the materials (conductivity, secondary emission, etc.) undergo changes over much longer periods of time (several months).

- The electron guns or the accelerators generally used for the tests deliver monoenergetic electrons, whereas the electrons from space are distributed over a spectrum with a maximum energy level of several MeV.

This last point, which is particularly important, had to be considered to achieve an experimental simulation representative of the charging environment. Indeed, by taking into account the energy distribution of the electrons from space it is possible to integrate an essential factor relative to a materiel's level of charging which is its conductivity induced under the effect of radiation. Because the effect of an electron's charge is not neutral with respect to its energy, the multienergetic spectral approach is necessary and contributes to giving the tests performed their "qualifying" nature.

ONERA's DESP (SPace Environment Department) based the design and construction of the SIRENE facility on these considerations. The goal is to obtain a simulation system whose electron source reproduces the spectrum of the electrons in the geostationary environment (GEO) as well as possible, on a particular magnetic storm day, chosen because it is considered to be typical of a critical "charging" condition whose hazards must be assessed.

The development of the SIRENE facility was undertaken in technical cooperation with and with the financial backing of the CNES (French Space Agency) through multi-year investment and study actions [3]. The purpose of these actions was to design, construct and qualify a test facility that makes it possible to predict the level of charging of a dielectric material used in space.

The implementation of SIRENE therefore fits into the development of laboratory tests with better performances than those currently performed, avoiding the systematic recourse to more costly evaluations in space.

Geostationary Orbit Electron Flux – Reference Spectrum

The utilization of SIRENE poses the problem of choosing the energy spectrum of the geostationary-type natural environment for an experimental simulation of the electrostatic charging and discharging phenomena. The DESP has adopted the spectrum designated Kp>5 as reference, since AE8MAX is not sufficiently representative for this type of study. In fact, AE8MAX was defined using time-integrated environmental data, only concerning solar cycle No. 20 (low activity). Consequently, AE8MAX is better suited to studies on the effects of aging, where the dose is the decisive factor, than for studies on electrostatic charge phenomena. A comparison between the Kp>5 and AE8MAX integrated spectrums is given in Fig. 1.

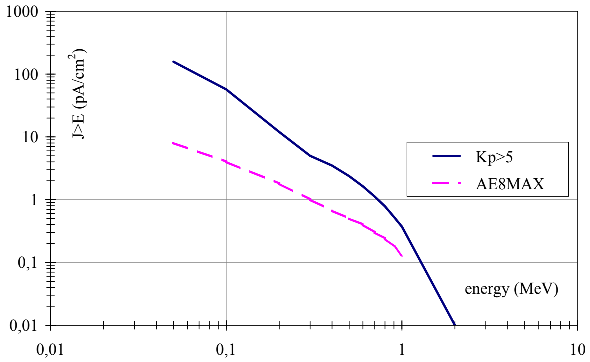

Figure 1. AE8MAX and Kp>5 integrated spectrums

The characteristics of the Kp>5 reference spectrum are described in detail in the study carried out for ESA (European Space Agency) [4]. This spectrum is defined by means of statistics on the flight data recorded on geostationary satellites during agitated periods of geomagnetic activity with a Kp index > 5. This Kp indicator varies between 0 and 9 according to the geomagnetic activity; the measurements were performed on the ground.

The Kp>5 energy-integrated spectrum is interpolated well by the following equation (with E in keV).

$$J(>E) = A\exp(-\frac{E}{Ea}) + C\exp(-\frac{E}{Ec}) \quad [4]$$

$A=9.52*10^7$ Ea= 268.64 keV
$C=2.8*10^9$ Ec =44.16 keV

The Kp>5 spectrum simulates a high-amplitude magnetic storm while remaining realistic, and it was established using dynamic data. Furthermore, it is well-correlated with the GEO models (ONERA/DESP's Salambô) and with the worst-case measurements recorded by the LANL's geostationary satellites [5]. This explains why Kp>5 seems well-suited to serve as reference spectrum for studies examining the problems of electrostatic charging.

Once the reference spectrum has been chosen, the goal is to reproduce it, as well as possible, over the widest possible spectral range. The solution adopted consists of transforming the monoenergetic beam delivered by an electron accelerator into an energy-distributed beam, using complex diffusion foils.

Given the very great dynamics of the space flow according to the energy, it is practically impossible to reproduce this spectrum in its entirety using a single radiation source. In practice, each experimental device can only reproduce part of the Kp>5 reference spectrum. The energy range is chosen so that it corresponds more specifically to an application area. We therefore use two of the devices installed at the DESP as our example (DESP's various simulation systems are described in detail in [6]):

· firstly GEODUR which is a device suited to studies on the phenomena linked to the internal charge. Thus, the structures or materials tested are irradiated behind a shielding representative of the satellite's outer casing. The energy spectrum is representative of the GEO spectrum in the energy range comprised between 0.2 and 1 MeV, and it is obtained by transforming the 1.1 MeV monoenergetic beam from a Van de Graaff accelerator.

· secondly SIRENE, which is a facility designed for external charge studies on materials with a thickness of less than approximately 450 µm (equivalent thickness of aluminium), or for internal charge studies when the thickness of the shielding is slight (< 200 µm of aluminium). The energy spectrum is representative of the GEO spectrum in the energy range comprised between 40 and 400 keV, it is obtained by transforming a 400 keV mono-energetic beam delivered by a Van de Graaff accelerator. For many of the applications in SIRENE (without shielding), the electron spectrum's low-energy component, which is the most intense, has to be reinforced with a second radiation source. An electron gun is used to do this. It is possible, using the same procedure, to simulate spectrums other than the Kp>5 reference spectrum. However, it must be underlined that the development of complex windows suited to these spectrums, and the experimental validation of the beams obtained, represent a significant amount of costly work.

Another solution for carrying out this type of simulation is to use radioactive sources. However, although they have the advantage of providing energy-distributed radiation, they do have major safety and procurement drawbacks.

SIRENE Experimental Facility

The originality of the SIRENE experimental simulation facility is that it includes equipment making it possible to reproduce the effects of the charges induced by the electrons from the space environment in an energy range lower than or equal to 400 keV.

Description of the SIRENE Facility

The SIRENE facility has the following main components:

- A large-dimension cylindrical vacuum chamber (L≈1.5 m, Ø≈0.5 m) designed in 3 sections to ensure modularity. The horizontal opening of the chamber makes it easy to set up experiments *in situ*. At the level of the vessel, the influence of the terrestrial magnetic field on the electron flow trajectory is compensated for by the magnetic field induced by the two pairs of windings (vertical and horizontal) surrounding the chamber. The body of the chamber is fitted with several standardised diameter extensions enabling the installation of various control and metrology instruments (vacuum gauge, visualisation camera, electrical outputs, analysis probes, connections to the radiation sources, etc.).

- A primary and secondary pumping unit which ensures a pressure of the order of 10^{-6} hPa after some hours in operation.

- A specimen door, with temperature regulation within a range comprised between -180°C and +100°C.

- The facility is equipped with two electron sources:

  - A Van de Graaff type accelerator capable of delivering a monoenergetic electron beam whose energy level can be adjusted between 100 and 400 keV. In the case of experiments carried out using a simulation of electron flux from space whose energy spectrum is distributed, the accelerator's operating energy is of the order of 400 keV (most frequent case).

  - A low-energy electron gun which delivers a beam whose energy level can be adjusted between 1 and 35 keV. This electron beam can be used alone (many tests are requested on the basis of specifications such as: $E=20$ keV, $\Phi=1$ nA/cm^2). It is also used to complete the flow of the Van de Graaff accelerator's electron beam at low energy levels.

- A set of "complex" diffusion windows designed to transform the 400 keV monoenergetic beam delivered by the accelerator into an energy-distributed beam according to a reference spectrum chosen to simulate a type of orbit.

- The analysis instruments specific to the electrostatic studies, that is to say:

  - current probes for detecting discharges and analysing current transients,

  - A potential probe used for analysing charge potentials along a vertical axis.

A further development phase being carried out at present with the CNES concerns the metrology of the charge potentials. The instruments currently in place only enable *in situ* measurements of the potentials according to a vertical axis ($d \leq 15$ cm) and no other analysis probe movements are possible. In the case of studies on a relatively large number of simple specimens, or on more complex structures (solar arrays, antennas, etc.), these instruments are insufficient. Consequently, a new potential probe movement system is in the process of being designed. It should make it possible to analyse charge potentials in a 20 cm x 20 cm plane.

A general view of the SIRENE experimental facility is shown in Fig. 2.

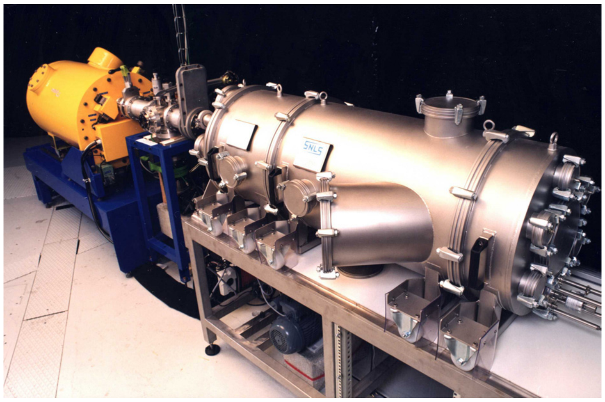

Figure 2. General view of SIRENE

The facility's various components with the positioning and the trajectory of the two electron beams delivered by the electron gun and the Van de Graaff accelerator are symbolised in Fig. 3 (shown in the horizontal plane).

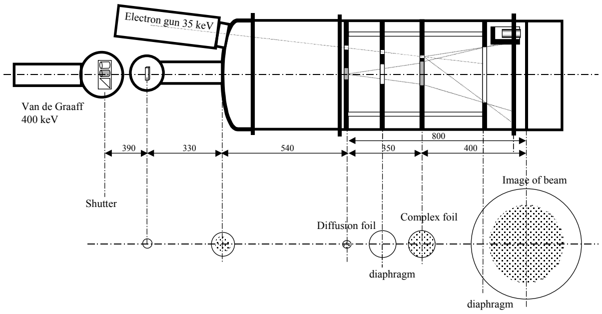

Figure 3. SIRENE schematic diagram

Definition and adjustment of the electron spectrum of SIRENE

The role of the complex diffusion window is to transform the monoenergetic beam delivered by the Van de Graaff accelerator into an energy-distributed beam that is as close as possible to the Kp>5 reference spectrum. The design of these complex windows is based on the association of simple diffusion foils, of different thicknesses and surface areas. The analysis of the flux transmitted by the simple or complex diffusion foils was carried out in cooperation with the CESR laboratory (Radiation Space Studies Centre) using the ERMD detector (EPIC Radiation Monitor Detector) [7].

Fig. 4 shows an example of the flux transmitted by the diffusion foils whose thickness varied between 0 and 550 µm when they were bombarded by a 400 keV electron beam which had been diffused by two 9 µm diffusion foils beforehand. The complex window was designed in such a way that from the 400 keV monoenergetic beam delivered by the Van de Graaff accelerator, the transmitted flow corresponds as well as possible to the Kp>5 spectrum in the 40-400 keV range. Although their density was slight, electrons whose energy was lower than 40 keV were present in this spectrum. It was not possible to quantify them with the ERMD detector since its detection threshold is of the same order. The low energy component was provided by the electron gun by means of a virtually monoenergetic flow of 20 or 30 keV.

The SIRENE integrated spectrum (GEO orbit) is compared with the Kp>5 integrated reference spectrum in Figure , and a good match can be seen between the two spectrums.

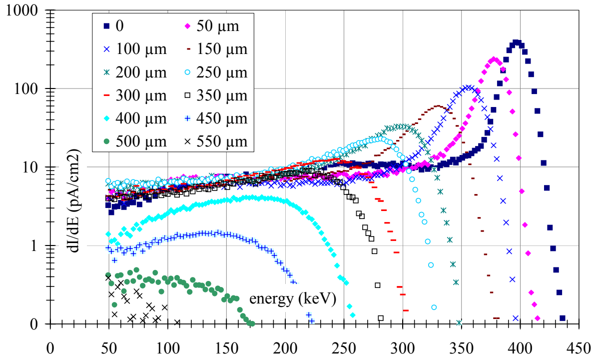

Figure 4. Differential spectrums of the flux transmitted by aluminium shieldings bombarded by a 400 keV electron beam

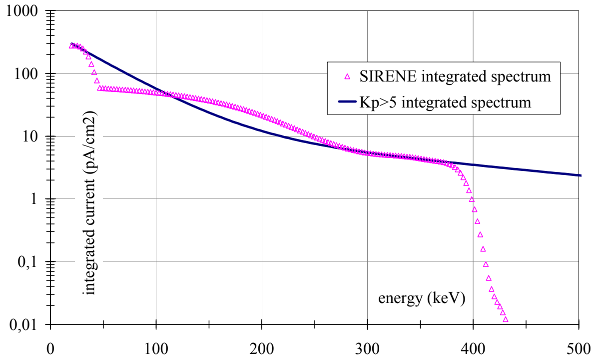

Figure 5. Integrated spectrum delivered by the complex window and Kp>5 integrated reference spectrum

A charge detection system embedded in the volume of polymer films (Teflon®, Kapton®, epoxy resin, etc.) has been developed in SIRENE [8]. The measurements are carried out *in situ* during the irradiation. This test bench, called the PEA (Pulse Electro Acoustic), is based on the pulsed electro-acoustic method. It was developed in cooperation with the Communications Research Laboratory (CRL) in Japan, the LGET (Toulouse Electrical Engineering Laboratory) and the CNES.

Experimental Results - Influence OF The Irradiation Mode

The influence of the irradiation mode on the materials' charge has been assessed in the SIRENE facility with two types of electron irradiations. The flow levels were chosen so that they correspond approximately to the integrated flow of the Kp>5 reference spectrum (E>20 keV). The following parameters were analysed to make this comparison: charge limit potential and the resistivity according to the square root of the electrical field.

- The first series of tests was carried out using the conventional irradiation conditions usually adopted for performing charge tests in the laboratory; in this case the energies were virtually monoenergetic. The conditions for the first irradiation mode were as follows:
  E=20 keV, Φ=250 pA/cm^2

- The second series of tests was carried out with SIRENE's 0 to 400 keV energy-distributed beam delivered simultaneously by the two radiation sources (see Figure). The conditions for this second irradiation mode were as follows:
  E=20 keV, Φ=250 pA/cm^2 + E distributed from 0 to 400 keV, Φ=50 pA/cm^2, giving a total flow of 300 pA/cm^2.

Several representative dielectric materials were tested, they were all metallised on their rear face. When performing the tests, 2 specimens made of different materials were associated so that the charge kinetics were relatively close.

Influence of the irradiation mode on the charge potential (T≈20°C)

For both irradiation modes, the results presented correspond to tests performed at the laboratory's ambient temperature (T≈20°C).

The following materials were tested simultaneously in this way:

- 50.8 µm Kapton®, and 25.4 µm Kapton® (supplied by ASPI Toulouse, with germanium used for the rear metallisation)

- 127 µm FEP Teflon®, and 127 µm Kapton® (supplied by ASPI Toulouse)

- 127 µm RT/duroid®6002 (supplied by Rogers Corp.), and Second Surface Aluminium Coated FEP Tape with 966 Acrylic Adhesive (supplied Sheldahl, ref.: 146379, 127 µm FEP Teflon®)

Different specimens were used for each irradiation series so that that the changes made to the characteristics of the materials by the experiment did not disturb the results of the following tests. However, to ensure that the comparison of the irradiation modes was coherent, all the specimens were taken from the same test bars.

The comparison of the two irradiation modes on the charge potential is illustrated in Figure for the 50.8 µm and 25.4 µm Kapton®, in Fig for the 127 µm FEP Teflon® and Kapton®, and in Figure 8 for the 127 µm RT/duroid®6002 and SSM aluminuium (127 µm Teflon®). The recorded data show the variations of the charge potential versus the irradiation time.

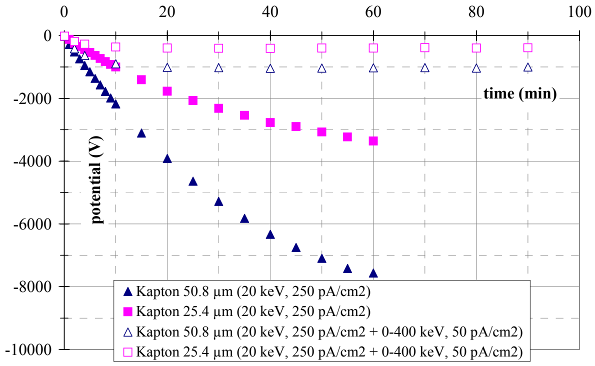

Figure 6. Variation in the charge potential versus the irradiation time for the 50.8 µm and 25.4 µm Kapton® according to the two irradiation modes

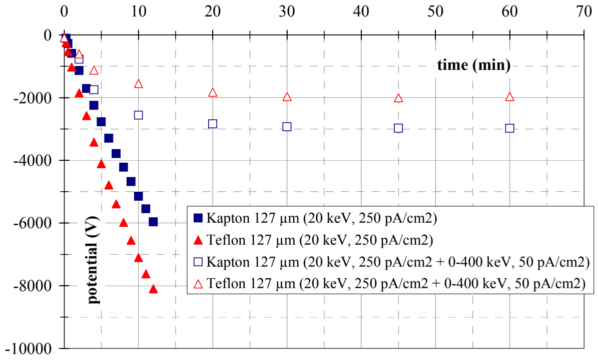

Figure 7. Variation in the charge potential versus the irradiation time for the 127 µm FEP Teflon® and Kapton® according to the two irradiation modes

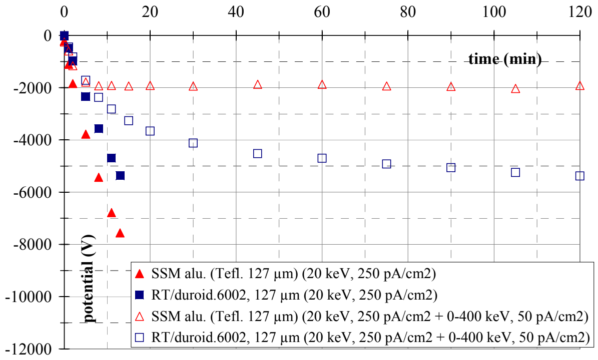

Figure 8. Variation in the charge potential versus the irradiation time for the 127 µm RT/duroid®6002 and SSM alu.(127 µm Teflon®) according to the two irradiation modes

The results shown in Fig. 6, Fig. 7 and Fig. 8 clearly show the large differences observed according to the irradiation mode, both on the charge kinetics and on the maximum potential.

The three tables below summarise the differences observed for the six materials on the maximum charge potential (expressed as an absolute value) according to the two electron flow simulation modes for the GEO orbit.

	maximum charge potential (V)	
	Kapton® thick=25.4 µm	Kapton® thick=50.8 µm
20 keV, 250 pA/cm^2	$\lvert V \rvert > 3360$	$\lvert V \rvert > 7500$
20 keV, 250 pA/cm^2 + 0-400 keV, 50 pA/cm^2	$\lvert V \rvert \approx 390$	$\lvert V \rvert \approx 1030$

	maximum charge potential (V)	
	Teflon® thick=127 µm	Kapton® thick=127 µm
20 keV, 250 pA/cm^2	$\lvert V \rvert >> 8100$	$\lvert V \rvert >> 6000$
20 keV, 250 pA/cm^2 + 0-400 keV, 50 pA/cm^2	$\lvert V \rvert \approx 2000$	$\lvert V \rvert \approx 3000$

	maximum charge potential (V)	
	RT/duroid® 6002 thick=127 µm	SSM Alu. thick=127 µm
20 keV, 250 pA/cm^2	$\lvert V \rvert >> 5500$	$\lvert V \rvert >> 8000$
20 keV, 250 pA/cm^2 + 0-400 keV, 50 pA/cm^2	$\lvert V \rvert > 5000$	$\lvert V \rvert \approx 2000$

It should be noted that for all the irradiations with a 20 keV monoenergetic flow, the irradiation times were intentionally limited to prevent the specimen from discharging. The purpose of this limitation was to prevent the profile of the maximum potential from being disturbed. Indeed, the material's resisitivity is calculated from the relaxation of this potential with respect to time.

Influence of the irradiation mode on the materials' resistivity (T≈20°C)

The resistivity of the materials is defined on the basis of the relaxation of the charge potential versus time after the irradiation is stopped.

It is worth pointing out right from this point that the resistivity value of the experimental results are deducted from registration of the potential relaxation versus to time. The different points of relaxation are acquired when the irradiation is stopped. So the different calculated values do not exactly correspond to real value of radiated induced conductivity (RIC) under irradiation but more to a residual or a delayed conductivity. Naturally, this effect decreases with time.

An example of this relaxation according to time is shown in Figure for the 127 µm Teflon® and Kapton® and in Figure for the 127 µm RT/duroid®6002 and SSM aluminium (127 µm Teflon®). These data, recorded after firing had been stopped, are reported for both irradiation modes. In this case, the charge potential obtained from the monoenergetic flow irradiation (20 keV, 250 pA/cm^2) was intentionally limited. The purpose of this limitation was to ensure that the electrical fields corresponding to the two irradiation modes were of the same order of magnitude.

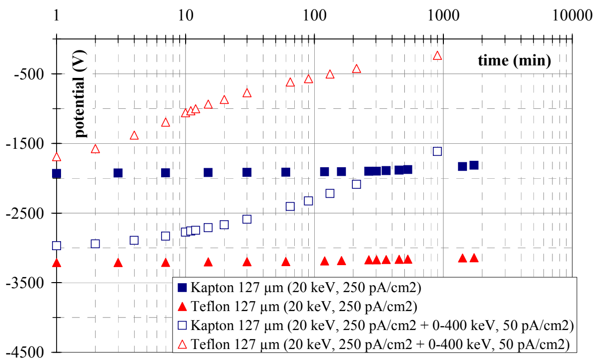

Figure 900. Relaxation of the charge potential versus time for the 127 µm Teflon® and the 127 µm Kapton®

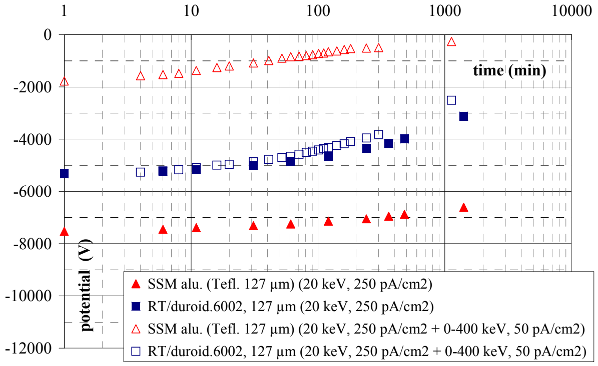

Figure 10. Relaxation of the charge potential versus time for the 127 µm RT/duroid®6002 and SSM alu.(127 µm Teflon®)

The resistivity of each material was calculated from the relaxation kinetics of the charge potentials, using the relation: $\rho = -\frac{1}{\varepsilon_0 \varepsilon_r}\frac{V}{\frac{dV}{dt}}$.

The parameters used for these materials are given in the table below.

	density	e^- (E=20 keV) penetration	permittivity
Kapton®	1.42	≈ 6.6 µm	3.46
Teflon®	2.15	≈ 4.9 µm	2.2
RT/duroid® 6002	2.1	≈ 4.9 µm	2,94 (10 GHz)

The resistivity values calculated according to the square root of the electrical field ρ= $f\left(\frac{V}{e}\right)^{\frac{1}{2}}$ are given in Figure for the 127 µm Teflon® and Kapton® and in Figure for the 127 µm RT/duroid®6002 and SSM alu.(127 µm Teflon®).

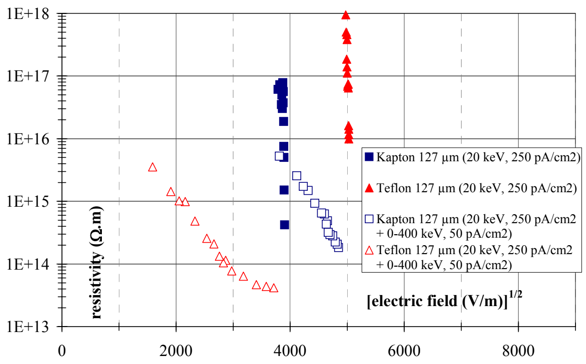

Figure 11. Resistivity variation according to the square root of the electrical field for the 127 µm Teflon® and the 127 µm Kapton®

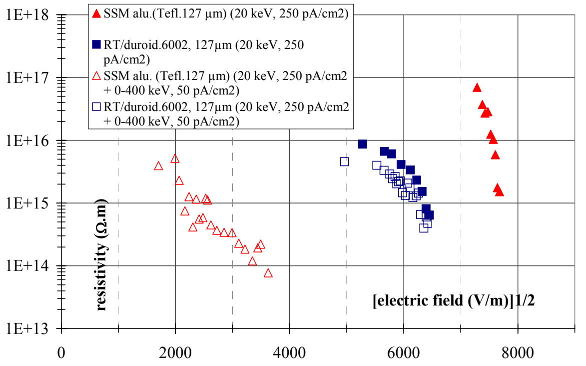

Figure 12. Resistivity variation according to the square root of the electrical field for the 127 µm RT/duroid®6002 and SSM alu.(127 µm Teflon®)

The singular behaviour of the resistivity should be noted in the case of monoenergetic flow irradiation (20 keV, 250 pA/cm^2) in particular on the Kapton®. This singularity concerns the first values calculated immediately after the charging, and which consequently corresponded to the first minutes of relaxation (t ≤ ≈ 10 min). The resistivity values were low and were not consistent with those calculated for longer relaxation times. Without developing explanations that do not come within the scope of this article, the possible influence of several points must be underlined.

– Concerning the experimental conditions:

  · the first resistivity values were calculated from the $\frac{dV}{dt}$ ratios presenting the greatest uncertainty given the slight decrease in the potential. However, since the drift of the signal from the electrostatic probe was systematically taken into account in the measurements, this point would not seem to explain the phenomenon.

  · the passing of the probe in front of the specimens could be a source of disturbances.

– Concerning the materials:

  · the conductivity of the irradiated thickness of the material (≈ 4 to 6 μm) may enable, at the beginning of relaxation, the flow of the charges through the edges of the specimens.

The results presented underline the importance of taking into account the conductivity induced under radiation. Generally speaking, the differences observed between the irradiation modes depend, of course, on the materials.

SIRENE operation involves sufficient levels of energy to create X-radiation in the chamber that could modify the conductivity characteristics of the treated specimens. The effect of this radiation has been quantified. It has not been possible to detect any influence of X-radiation for the flow levels specific to conventional tests.

Conclusion

In the framework of laboratory tests, the SIRENE facility makes a new and significant contribution in terms of representativeness concerning the spectral energy distribution of the flux of electrons in space. Its operational possibilities can be summarised as follows:

- treatment of specimens in a temperature range comprised between -150°C and +100°C

- irradiation with a virtually monoenergetic beam:

  - in an energy range comprised between 1 and 35 keV (electron gun)
  - in an energy range comprised between 100 and 400 keV (Van de Graaff accelerator)

- irradiation with a 0 to 400 keV energy-distributed beam:

- irradiation according to a spectrum close to Kp>5 (GEO orbit),
- possible irradiation according to an orbit of another type (GTO, MEO),
- in all cases, the representativeness of this type of test is limited to specimens whose thickness is of the order of 450 to 600 µm depending on the density,
- no influence of any possible X-radiation in the chamber has been detected.

The results presented on some dielectric materials show the importance of taking into account the conductivity induced under radiation on the charge limit potential. They thus demonstrate the importance of the way the charge electrons from space are simulated. These results clearly underline that, for most of the dielectric materials used on satellites, the conventional tests carried out with 20 or 30 keV monoenergetic beams are poorly suited and, very often, lead to an overestimation of the risks.

References

1. Lévy L., Material charging. Space Technology Course-Space Environment: "Prevention of risks related to spacecraft charging" - April 2002 - Toulouse (CEPADUES-EDITIONS)

2. Payan D., Vacuum electrostatic discharges. Space Technology Course-Space Environment: "Prevention of risks related to spacecraft charging" - April 2002 - Toulouse (CEPADUES-EDITIONS)

3. Reulet R., Dirassen B., Inguimbert C., Aït Zaïd L., Simulation en laboratoire des effets de charge par électrons. Instrumentation et analyse du faisceau d'électrons du nouveau dispositif SIRENE. Contrat CNES - RTS 2/05408 DESP - November 2001

4. Soubeyran A., Estienne J. P., Borde J., Rudenhauer F. G., Fehringer H. M., Betz G., Kensqek R. P., INTERNAL ELECTROSTATIC CHARGING - FINAL REPORT - ESTEC Contract N°9203/90/NL/JG. July 1992

5. Inguimbert Ch., Bourdarie S., Etude de l'environnement électronique en orbite MEO et GEO. Contrat CNES – RTS 1/07608 DESP – Mars 2003

6. Viel-Inguimbert V., Bourdarie S., Reulet R., Lévy L., Laboratory Ground Simulation of GEO and LEO Environment. 7th Spacecraft Charging Technology Conference, Noordwijk, The Netherlands, 23-27 April 2001

7. Reulet R., Dirassen B., Liébart S., Simulation en laboratoire des effets de charge par électrons. Rénovation du dispositif SIRENE. Contrat CNES - RF/CS0306501 DESP - Octobre 2000

8. Griseri V., Fukunaga K., Maeno T., Payan D., Laurent C., Levy L.. Internal space charge measurement of materials in a space environment. 9th International Symposium on "Materials in a Space Environment", Noordwijk, The Netherlands 16-20 June 2003