ELECTROSTATIC BEHAVIOR OF DIELECTRICS UNDER GEO-LIKE CHARGING SPACE ENVIRONMENT SIMULATED IN LABORATORY.

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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 consist in using in laboratory an electron source as similar as possible to the one existing in orbit. This paper describes the result obtained in the SIRENE facility, which was developed for simulating the spatial geostationary or MEO [1] environment during great geomagnetic activity comparatively with monoenergetic irradiation. The range of available electrons in SIRENE goes from 10 to 400 keV. It points out the effect of the radiated induced conductivity. This paper provides results obtained on classical dielectrics as Teflon® Kapton® and Duroïd® of different thickness under mono and multi-energetic irradiation at ambient temperature and at -150°C. This paper showed also that even in the case of very low flux of high energy electrons, the surface voltage measured remains deeply affected

Based on those results the usual habit to use monoenergetic irradiation for qualification of space dielectrics should be reconsidered. For example surface voltage obtained of Teflon® is lower than the one obtained on kapton® under the same irradiation condition.

1 - 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 moralisations 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.

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[1] Middle Earth Orbit

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, Onboard power system & Electrical equipments service" (Chaîne d'Alimentation Bord et Equipements Electriques) 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.

2 - EXPERIMENTAL SIMULATION OF GEO ET MEO ENVIRONMENTS.

2.1 - DESCRITION OF THE PROBLEM

MEO and GEO fluxes versus time were defined in a previous study[2]) realised at DESP (under CNES contract). shows an example of the results obtained.

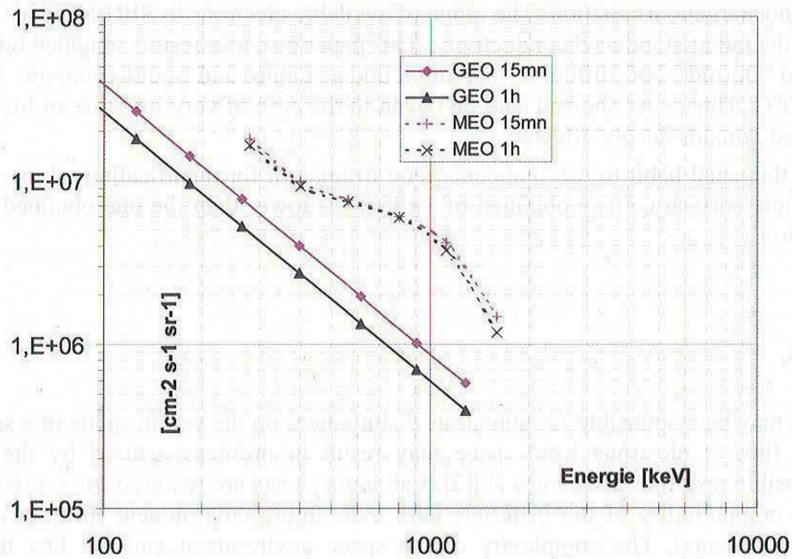

Figure 1 Spectrum comparison between GEO and MEO for different integration scale.

Experimental tests were defined from that previous study. The spectrum ratio for energies below 400 keV the missing part on the curve) stay the same than for higher energies. Uncertainties on the MEO spectrum for energies below 280keV should be lifted.

2.2 - 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 for studies on electrostatic charge phenomena. A comparison between the Kp>5 and AE8MAX integrated spectrums is given in Figure 2 .

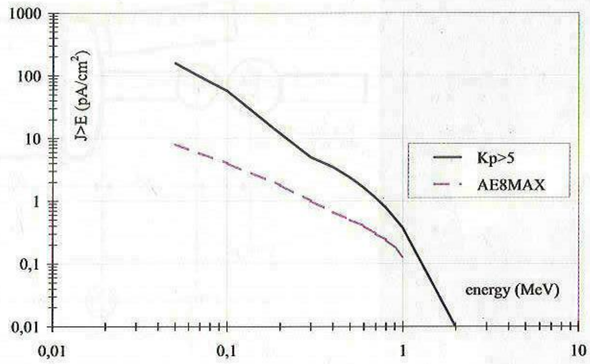

Figure 2 AE8MAX and Kp>5 integrated spectrums

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 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.

2.3 - 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.

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, Φ=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 and a XY potential probe are implemented.

A general view of the SIRENE experimental facility is shown in Figure 3 .

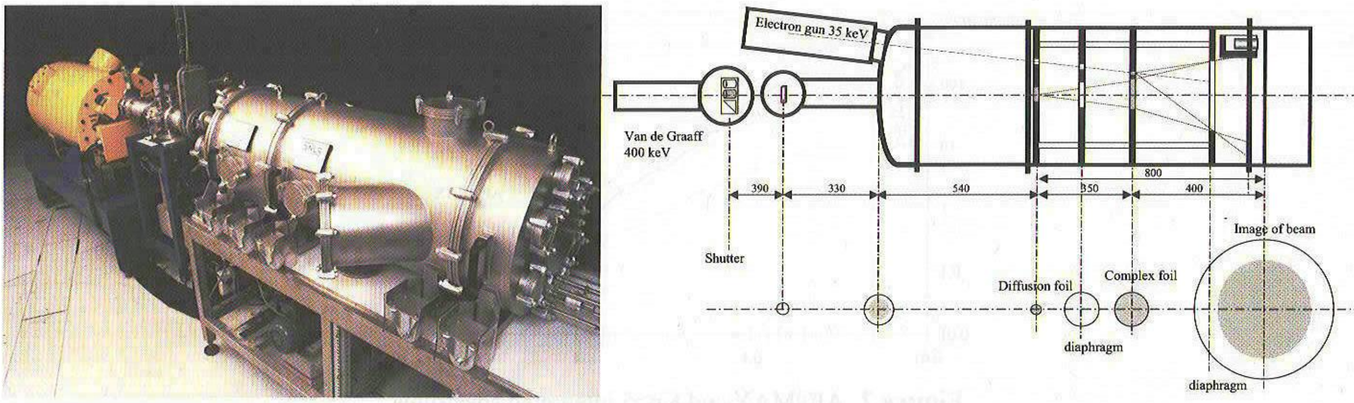

Figure 3 General view & schematic diagram of SIRENE

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 (shown in the horizontal plane).

The SIRENE integrated spectrum (GEO orbit) is compared with the Kp>5 integrated reference spectrum in Figure 4 , and a good match can be seen between the two spectrums.

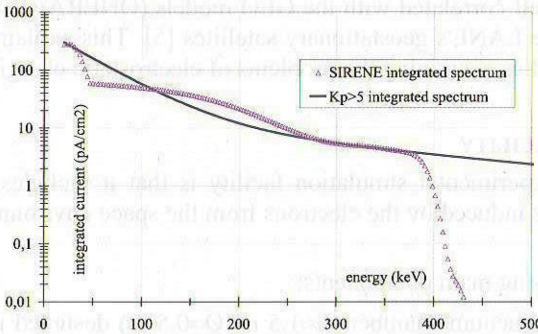

Figure 4 Integrated spectrum delivered by the complex window and Kp>5 integrated reference spectrum

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 NICT in Japan, the LGET (Toulouse Electrical Engineering Laboratory) and the CNES.

2.4 - Flux Influence for a Constant Energy Distribution

The aim is to evaluate the equilibrium surface voltage versus to irradiation flux with a constant spectrum repartition. The distribution chose is the Kp>5 Sirene Spectrum.

Tests are made on 2 mil (50µm) and 5 mil (127µm) samples which are rear face metallised.

Three samples with identical thickness are tested under irradiation each time. New and never irradiated samples are tested each time. A minimum of 20 outgasing hours is observed before each test.

Current measurements on Faraday cage allows to monitored irradiation flux.

2.4.1 - *Samples tested (t=127 µm)*

Material characteristics of Kapton®, Teflon® FEP and RT/Duroïd® 6002are given in the following table.

	Density	Depth penetration (E=20 keV)	Permittivity (bibliography)	Permittivity (measured)
Kapton®	1,42	≈ 6,6 µm	3,46	3,46
Teflon® FEP	2,15	≈ 4,9 µm	2,2	2,2
RT/duroïd 6002	2,1	≈ 4,9 µm	2,94 (at 10 GHz)	4 (DC)

Figure 5 Kapton®, Teflon® FEP, RT/Duroïd® 6002 characteristic

The different irradiation period parameters allows to evaluate the influence of flux level on the voltage as the spectrum distribution remains constant (for 127 µm thickness samples).

Fluxes increase until a factor of ten. Results are showed in Figure 6 for Kapton®, Figure 7 for FEP Teflon®, Figure 8 for RT/duroïd 6002.

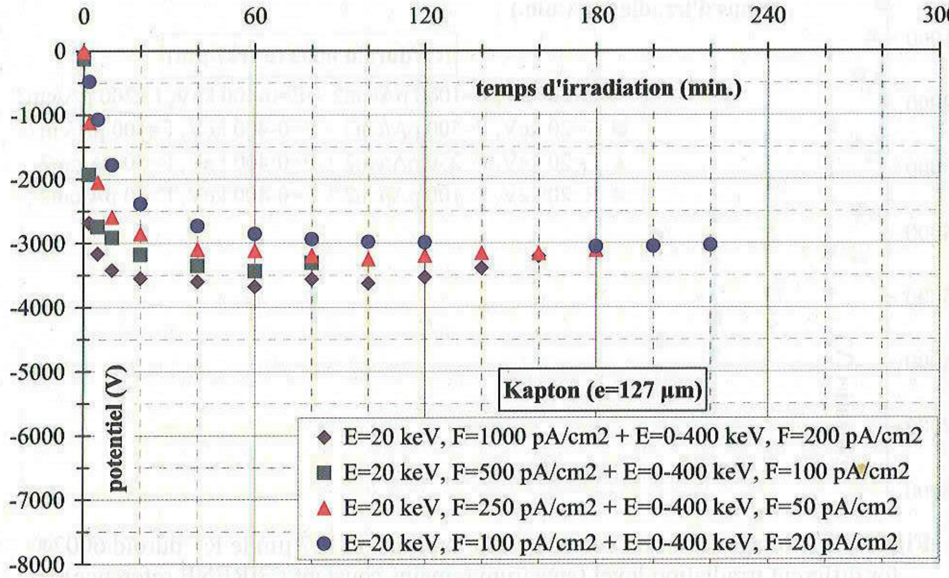

Figure 6 Voltage variation versus irradiation time on 127 µm Kapton® for different irradiation level (spectrum remains constant ; SIRENE reference)

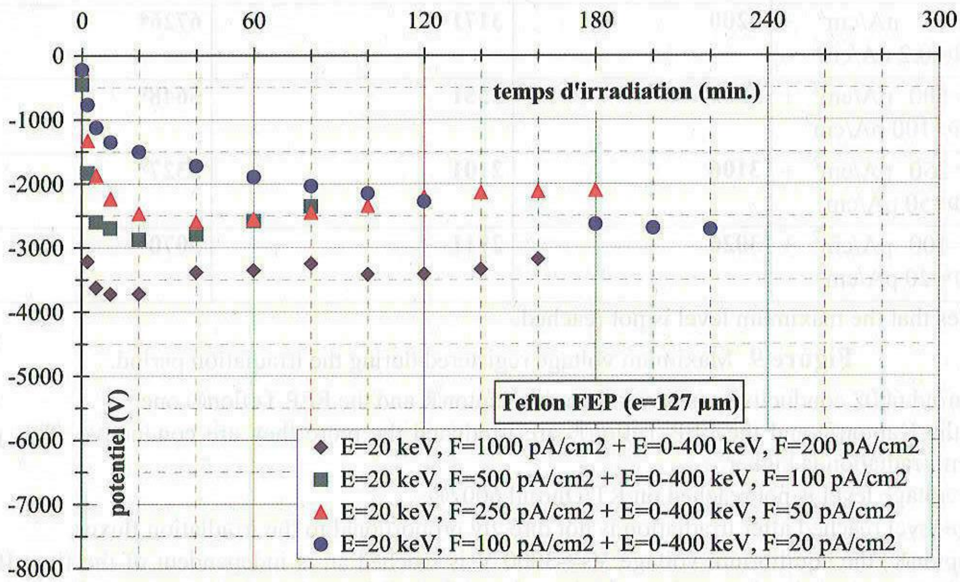

Figure 7 Voltage variation versus irradiation time on 127 µm FEP Teflon® ® for different irradiation level (spectrum remains constant ; SIRENE reference)

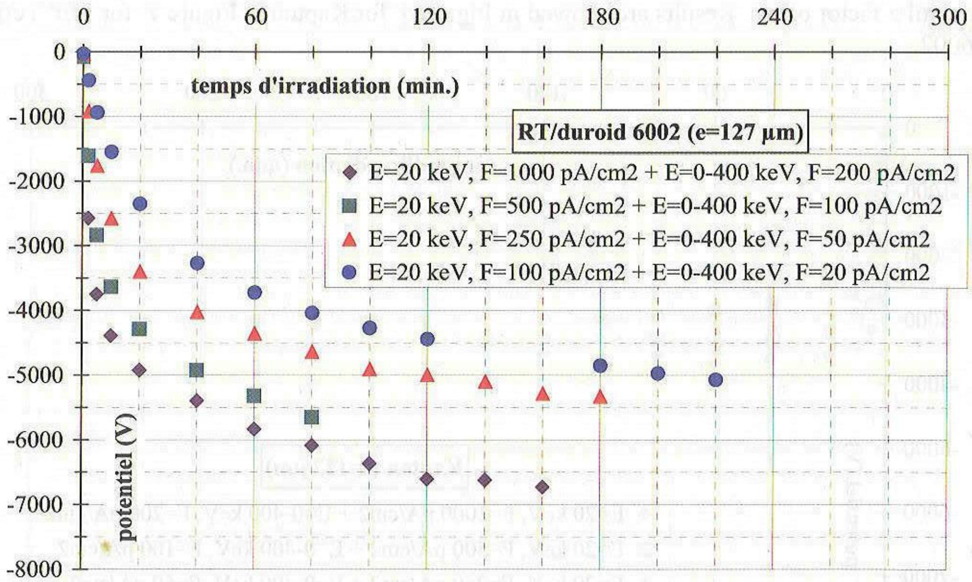

Figure 8 Voltage variation versus irradiation time on 127 µm le RT duroïd 6002® for different irradiation level (spectrum remains constant ; SIRENE reference)

	Maximum equilibrium voltage (|Vs|)		
Irradiation parameters	Kapton® (e=127 µm)	Teflon® FEP (e=127 µm)	RT/duroïd 6002 (e=127 µm)
E=20 keV, Φ=1 nA/cm^2 + E=0-400 keV, Φ=0,2 nA/cm^2	**3200**	**3171**	**6726***
E=20 keV, Φ=500 pA/cm^2 + E=0-400 keV, Φ=100 pA/cm^2	**3302**	**2351**	**5648***
E=20 keV, Φ=250 pA/cm^2 + E=0-400 keV, Φ=50 pA/cm^2	**3106**	**2101**	**5327***
E=20 keV, Φ=100 pA/cm^2 + E=0-400 keV, Φ=20 pA/cm^2	**3026**	**2711**	**5070***

The star indicates that the maximum level is not reached.

Figure 9 Maximum voltage registered during the irradiation period.

- The RT/Duroïd 6002 conductivity is lower than the Kapton® and the FEP Teflon® one.
- The more the Kapton® and the FEP Teflon® are irradiated the more they are conductive. This phenomenon is higher when irradiation is higher.
- Maximum voltage level is not reached on RT/Duroid 6002®.
  - Voltage level reached after irradiation is not directly proportional to the irradiation fluxes.
- For the Kapton®, the equilibrium voltage Vs≈-3000 V is reached an is independent of the flux. If the secondary emission rate is neglected, when making the hypothesis that all incoming electrons are embedded in the material which is quite the case) the radiated induced conductivity can be estimated with by R=$\frac{Vs}{\Phi}$, then the resistivity (under irradiation) $\rho=\frac{R.S}{t}$ with S surface et t Kapton thickness. Results are presented in the following table.

Irradiation parameters	Voltage	Resistivity
E=20 keV, Φ=1 nA/cm^2 + E=0-400 keV, Φ=0,2 nA/cm^2	≈-3000 (V)	2 10^{12} Ωm
E=20 keV, Φ=500 pA/cm^2 + E=0-400 keV, Φ=100 pA/cm^2	≈-3000 (V)	4,1 10^{12} Ωm
E=20 keV, Φ=250 pA/cm^2 + E=0-400 keV, Φ=50 pA/cm^2 (SIRENE spectrum)	≈-3000 (V)	8,2 10^{12} Ωm
E=20 keV, Φ=100 pA/cm^2 + E=0-400 keV, Φ=20 pA/cm^2	≈-3000 (V)	2 10^{13} Ωm

Figure 10 Voltage and estimated resistivity versus to variable irradiation fluxes on Kapton®

- The same constatation could be done for FEP Teflon® although the equilibrium voltage dispertion is higher (Vs between -2000 and -3200 V). With longer irradiation, this difference would have been reduced (we could imagine Vs ≈ -3000 V). The radiated induced conductivity of the RT/Duroid®6002 remains very low.

2.4.2 - *Comparison of results on FEP Teflon®*

The voltage charging curve on FEP Teflon ® versus to irradiation time has a singularity which is independent of the irradiation flux. Results obtains on the two 50 and 127 µm samples are grouped in Figure 11 with the SIRENE irradiation flux and pour l'irradiation avec le spectre SIRENE (E=20 keV, Φ=250 pA/cm² + E=0-400 keV, Φ=50 pA/cm²) and in Figure 12 for the highest flux (E=20 keV, Φ=1 nA/cm² + E=0-400 keV, Φ=0,2 nA/cm²).

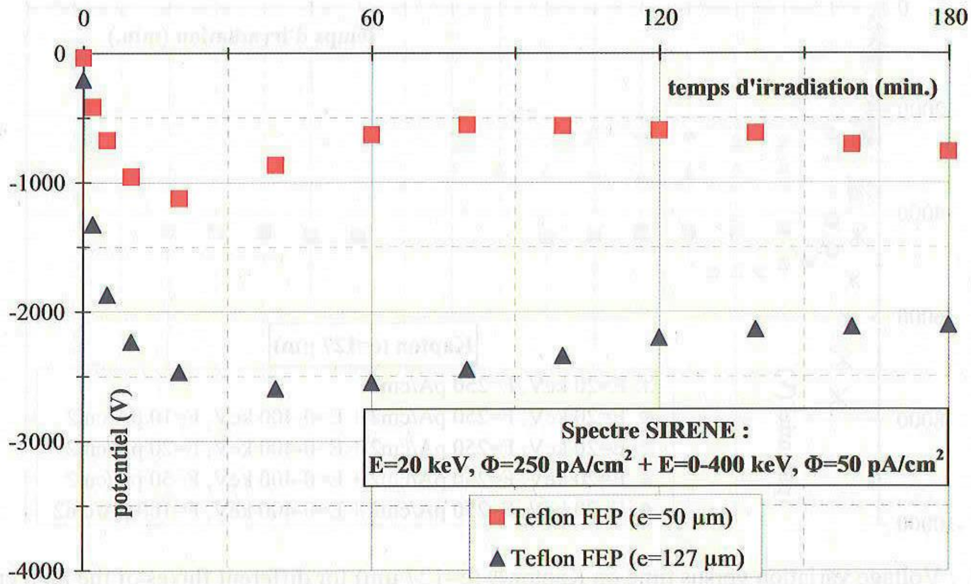

Figure 11 Voltage variation versus time on 50 and 127 µm FEP Teflon® with E=20 keV, Φ=250 pA/cm² + E=0-400 keV, Φ=50 pA/cm² (SIRENE spectrum)

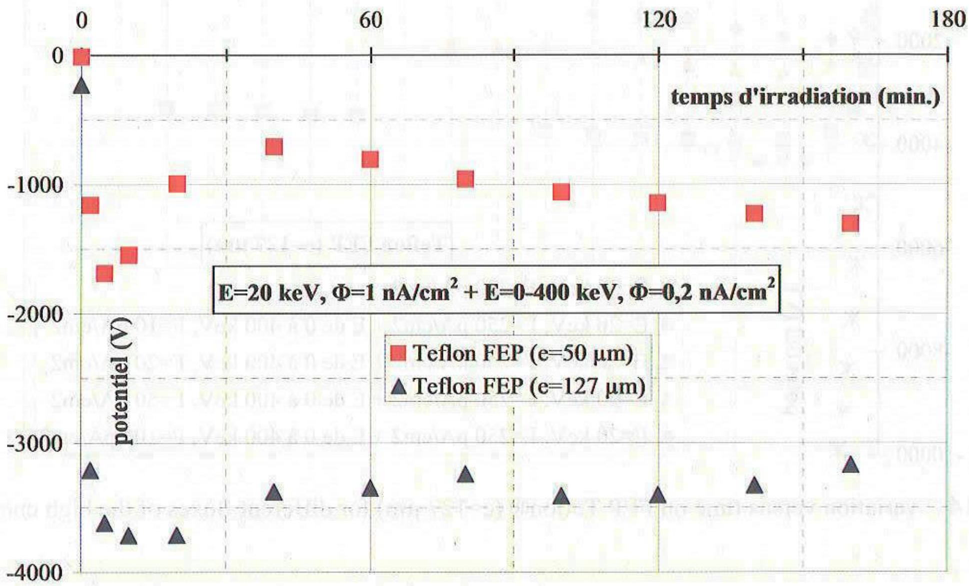

Figure 12 Voltage variation versus on time on 50 and 127 µm FEP Teflon® with E=20 keV, Φ=1 nA/cm² + E=0-400 keV, Φ=0,2 nA/cm² (Sirene spectrum x 4)

Two maxima (|Vs|) are observed independently from irradiation flux and thickness. The first one happens very early (t ≤ 30 minutes). The more the irradiation flux is high, the more this time is low. This would indicate that a minimum irradiation (dose) is needed to « activate » the radiated induced conductivity.

2.5 - INFLUENCE OF THE ENERGY DISTRIBUTION

The objective is to evaluate the equilibrium surface voltage difference when the high energetic flux varies as the low energy electron flux remains constant. Tests are made on the samples of both thicknesses. The three samples of the same thickness are tested simultaneously. Each time, new samples are used. A long duration outgassing (20 hours) is observed before any test.

Material characteristics are given in the Figure 5 Figure 5 . Results are showed Figure 13 for Kapton®, Figure 14 for FEP Teflon®, and Figure 15 for RT/Duroïd® 6002.

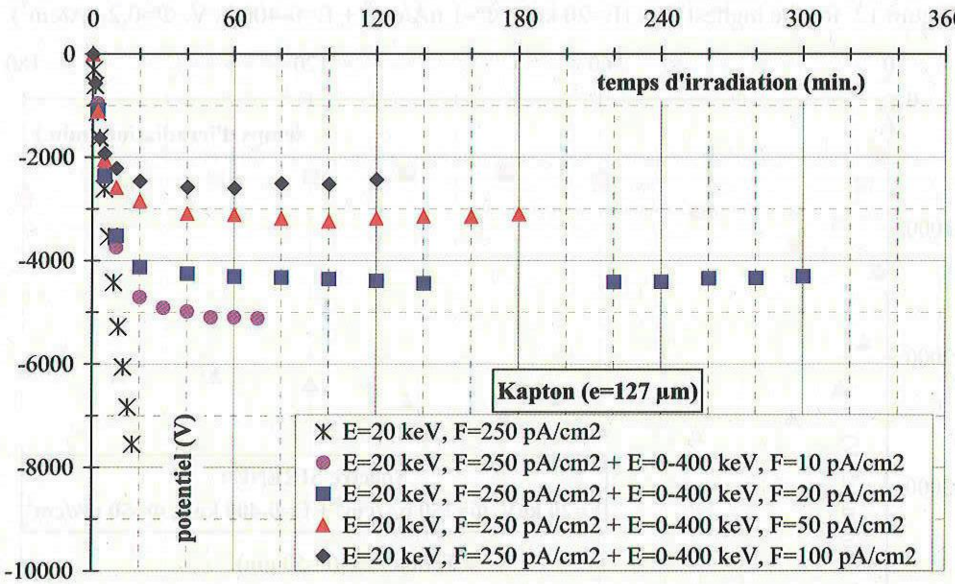

Figure 13 : Voltage variation versus time on Kapton® (e=127 µm) for different fluxes of the high energy beam

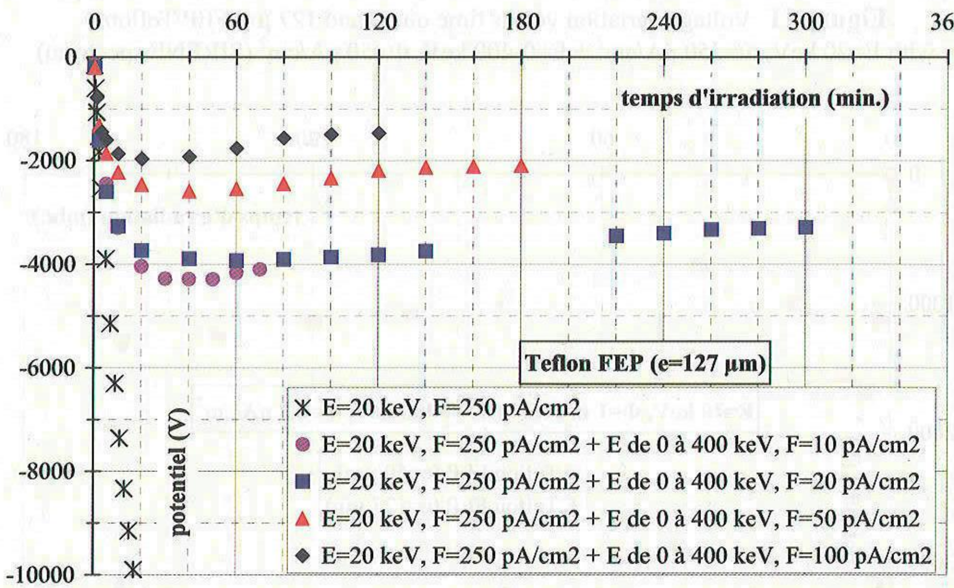

Figure 14 : variation versus time on FEP Teflon® (e=127 µm) for different fluxes of the high energy beam

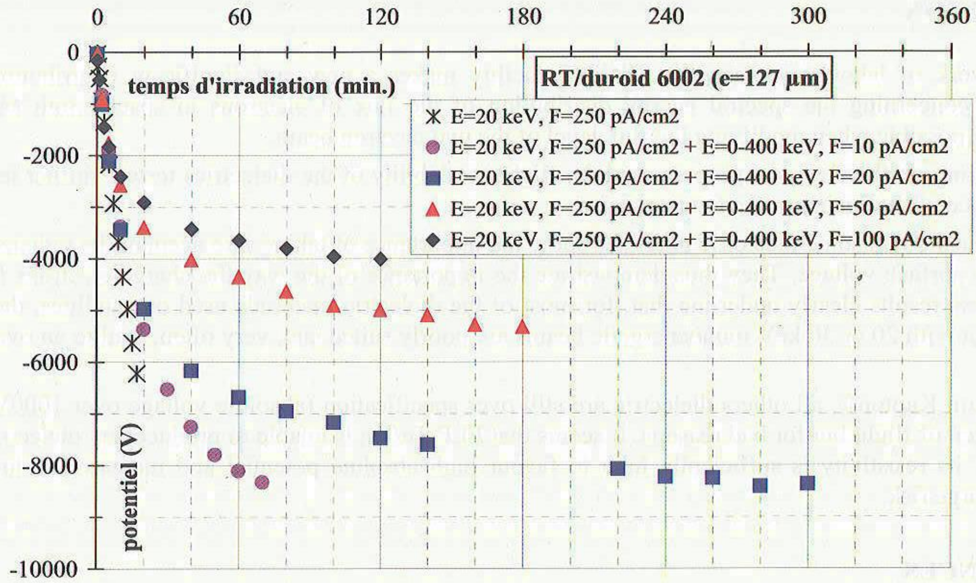

Figure 15 Voltage variation versus time on RT/Duroïd 6002 (e=127 µm) for different distributed energy.

Paramètres d'irradiation	Potentiels de charge maximum ou à l'équilibre (|Vs| en volts)		
	Kapton® (e=127 µm)	Teflon® FEP (e=127 µm)	RT/duroïd 6002 (e=127 µm)
E=20 keV, Φ=250 pA/cm² + E=0-400 keV, Φ=0	**7552****	**9900****	**6223****
E=20 keV, Φ=250 pA/cm² + E=0-400 keV, Φ=10 pA/cm²	**5122**	**4102**	**8332****
E=20 keV, Φ=250 pA/cm² + E=0-400 keV, Φ=20 pA/cm²	**4313**	**3293**	**8367***
E=20 keV, Φ=250 pA/cm² + E=0-400 keV, Φ=50 pA/cm²	**3106**	**2101**	**5327**
E=20 keV, Φ=250 pA/cm² + E=0-400 keV, Φ=100 pA/cm²	**2439**	**1473**	**4008**

The star indicates that the equilibrium voltage is not reached.

Le ** sign indicates that that the maximum voltage is not reached and that the irradiation have been stoppes to prevent discharges.

Figure 16 Maximum voltage reached on samples

For the irradiation: E=20 keV, Φ=250 pA/cm², the irradiation time limited on purpose to prevent specimen's breakdown.

The RT/Duroid® 6002 present a radiated induced conductivity lower than in Kapton® and FEP Teflon ®.

The dose influence versus the irradiation time is observed to be very sensitive on FEP Teflon® whereas it is not so sentisitive on Kapton®, materials become more and more conductive with the irradiation time, this phenomena is obviously more important for higher fluxes.

For irradiation series that include a high energy component, the charge potential maximum (|Vs|) versus the irradiation time is reached on Kapton® and FEP Teflon® that is not the case on RT/Duroid® 6002.

Avery large difference on the voltage level is observed depending on the fact that the irradiation contain or not a very high component. These results show the major role of the radiated induced conductivity for some materials (TEFLON®, Kapton®), even under a very low crossing electron flux. They underline the major importance to take into account the electron beam energetic spectral distribution that is used to simulate charging phenomenon in space environment.

Results show that the SIRENE set-up is well adapted to reproduce a chosen reference spectra (for instance the Kp>5 spectra that represent the GEO orbit) however it allows to reproduce also, in a large range, various environment with different electron energy spectral distribution (as a function of the orbit type, the magnetospheric intensity…).

3 - CONCLUSION

In the framework of laboratory tests, the SIRENE facility makes a new and significant contribution in terms of representation concerning the spectral energy distribution of the flux of electrons in space. Both MEO and LEO irradiations are possible when modifying the flux level of the two electron beam.

Before concluding on the electrical property and the flight availability of the dielectrics tested, further tests are needed like the influence of the ageing or the temperature.

The results presented on some dielectric materials show the importance of taking into account the radiated conductivity induced on the surface voltage. 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.

Except for 25µm Kapton®, all others dielectric are still over specification (absolute voltage over 1000V). Teflon was rightly forbidden of flight but for bad reasons. It seems that FEP Teflon is unable to produce any dielectric electrostatic discharges but its resistivity is sufficiently high to favour high absolute potential and increase the inverted voltage gradient discharge risk.

4 - REFERENCES

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