SPACE CHARGE DETECTION AND BEHAVIOUR ANALYSIS IN ELECTRON IRRADIATED POLYMERS

V. Griseri[1], C. Perrin[2], K. Fukunaga[3], T. Maeno[3], D. Payan[2], L. Lévy[4], C. Laurent[1]
[1]Laboratoire de Génie Electrique de Toulouse, Université Paul Sabatier, 118 route de Narbonne, 31400 Toulouse, France
[2]Centre National d'Etudes Spatiales, 18 Avenue Edouard Belin, 31401 Toulouse cedex 4, France
[3]National Institute of Information and Communications Technology, 4-2-1 Nukui-Kita, 184-8795 Koganei, Tokyo, Japan
[4]Office National d'Etudes et de Recherches Aérosptatiales, 2 Avenue Edouard Belin, 31055, Toulouse cedex 4 France

Abstract : Charges accumulate on spacecraft surface trough various processes such as including conduction, irradiation, ionization and polarization. These charges can affect the space system operations via an electric current flowing in the structure or a locally generated electric field. This work is focussed on the analysis of electron behaviour in polymeric films such as PolyMethylMetaAcrylate (PMMA) and Teflon®, subjected to an electronic irradiation. The charge distribution is detected in-situ by Pulsed Electro-Acoustic (PEA) method. Surface potential and surface current measurements are also performed to get further information on the charge displacement with time.

INTRODUCTION

Surface charging occurs because electric charges in the plasma around the spacecraft are free to move and eventually get trapped on material surfaces with which they come in contact. The accumulation of charges leads to the creation of an electric field that ultimately prevents further charge accumulation. In any case, the spacecraft can only tolerate a limited range of electrical potentials and currents. When this range is exceeded, an unwanted phenomenon, such as an electrostatic discharge, may occur. This process is one of the major causes of spacecraft anomalies and damage to spacecraft electronics [1]. In dielectrics with very low conductivity, the charges can build up to the breakdown level. This charging phenomenon is often called the deep-dielectric charging. The aim of this work is to explore further the mechanism of charge storage and release during the irradiation and relaxation of specific polymer films.

EXPERIMENTAL SET-UP

Irradiation chamber

To understand these mechanisms occuing in dielectric materials used for space applications, it is necessary to study their properties in spatial environment. Considering the cost and the difficulties associated with a satellite embarked experiment, an alternative solution consists in reproducing this particular environment in the laboratory by using an irradiation chamber. In this work, one of the irradiation chambers developed by CNES and ONERA will be used [2]. The vacuum chamber 'SIRENE' enables to reproduce the electronic charge condition on the geostationary orbit. This chamber is equipped with a Van de Graaff accelerator which can produce quasi-monoenergetic electrons in the range 0-400 keV and an electron gun which can produce up to 35 keV electrons. Complex windows are used to transform mono-energetic into multi-energetic electron beam covering all electron energy aspects of the geostationary environment as described by a reference spectrum named Kp >5 [3]. Initially, these studies are focussed on mono-energetic irradiations in order to consider a simple configuration. To do so, only one diffusion foil is used to get a homogeneous irradiation area of about 5 cm radius.

Pulsed electro-acoustic set-up

In order to determine the charge distribution in the bulk of irradiated materials, the PEA detection method has been chosen. However, the classical system [3] can only be used outside the chamber and allows measurements at the end of irradiation in air. This system has been modified to run in-situ. To do so, both electrode units were positioned on the same side of the sample [4] (figure 1). The pulsed electric signal used to probe the material is applied through a thin aluminium or gold coated electrode that does not affect the penetration of the electrons during irradiation. The sample is glued to the detection unit electrode to provide a good contact and ensure a proper transmission of the acoustic wave. This acoustic signal is transformed by a piezoelectric sensor into an electric signal which can be observed directly on the oscilloscope and numerically treated by a software named 'PEANUTS'.

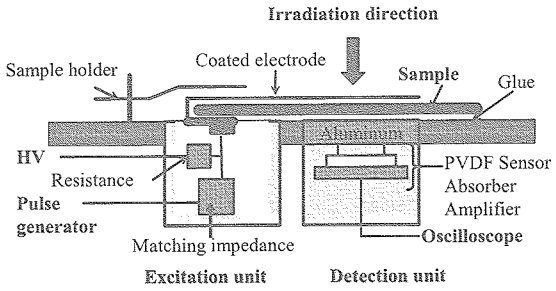

Figure 1 : PEA set-up for in situ measurements.

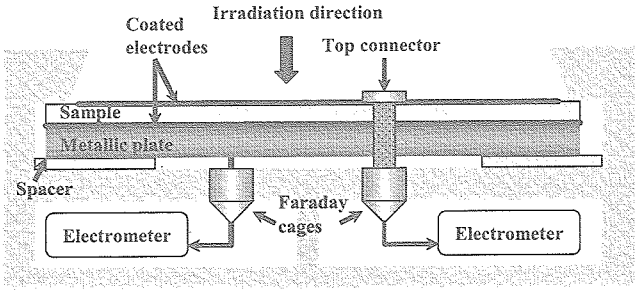

Figure 2 : Surface current detection cell based on the Split Faraday Cup (SFC) set-up.

Surface potential detection system

Surface potential is detected thanks to an electrostatic probe that scans the sample surface. The probe is shifted in front of the sample at a few millimetres. These measurements are performed in vacuum between two irradiation periods or during the relaxation. The voltage recorded gives an information on the sample charging state that is used to stop the irradiation before the breakdown limit is reached. From these data, it is also possible to estimate roughly the charge penetration depth without getting any details on the distribution. The calculation consists in determining the thickness of the non-irradiated zone where no charges were accumulated [6]. To do so, the capacitance of the non-irradiated zone is estimated while the irradiated zone is supposed to be conductive. Results are most of the time in good agreement with the ones obtained by PEA.

Surface current measurement cell

Lately, a surface current detection cell has been introduced in the chamber as a complementary tool to investigate the charge behaviour during and after the irradiation. The principle of the Split Faraday Cup (SFC) [7] technique has been put into practice. The polymer film introduced in the detection cell is coated on both sides (figure 2). Measurements are performed by using the 'short-circuit' arrangement [8]. During irradiation, the front electrode is connected to ground through a low-impedance electrometer while both currents from the front (i_1) and rear (i_2) surfaces are recorded. From such measurement, it is possible to estimate the initial charge penetration depth and to follow the charging state of the material during the irradiation.

EXPERIMENTAL PROTOCOL

The studies reported in this paper have been performed on two types of dielectric materials.
At first, a 250 µm-thick ***PMMA*** film has been studied. It was irradiated under three different energies successively for 40 mn each. For a start, the sample was exposed to a 100 keV electron beam, then after a 5 h relaxation, the second irradiation under a 130 keV electron beam was applied. Finally after 17 h relaxation, the last irradiation under 160 keV was performed. The flux was fixed at 50 pA/cm^2 in the three cases. PEA measurements were recorded during irradiation and relaxation periods.

Afterwards, a 500 µm-thick ***Teflon®*** sample was tested. It was irradiated by a 250 keV electron beam for 36 mn with a flux of 50 pA/cm^2. PEA and surface current data were recorded simultaneously during the irradiation and the relaxation. Surface potential data obtained on similar samples irradiated under the same conditions will also be used to estimate the charge penetration depth. In the next section, all the results obtained with these three complementary techniques will be analyzed and compared.

RESULTS AND DISCUSSION

PMMA

PEA measurements were performed during the whole irradiation period. The charge build up was followed on the oscilloscope screen and data recorded at least every two minutes. During the irradiation under 100 keV, a broad negative peak due to electron injection appears in the volume (figure 3). Simultaneously, two positive peaks of induced charges are detected at the sample/electrode interfaces. The position of the peak is roughly estimated at 80 µm from the surface. There is a large amount of charges in the whole irradiated region, it is more convenient to remark that beyond 135 µm, no more negative charges are detected. During the relaxation period

the sample was kept under vacuum. The curve decreases slightly in amplitude but the shape remains nearly the same signifying that only a small amount of charge is extracted in a few hours.
Then, a second irradiation was applied, the energy was increased up to 130 keV. Progressively the region, where charges are stored, gets enlarged and like in previous cases, a peak is estimated at about 149 µm (figure 3). It is observed that no charges are injected beyond 193 µm. Besides, it is noticeable that the charge built-up exists in the whole irradiated region.

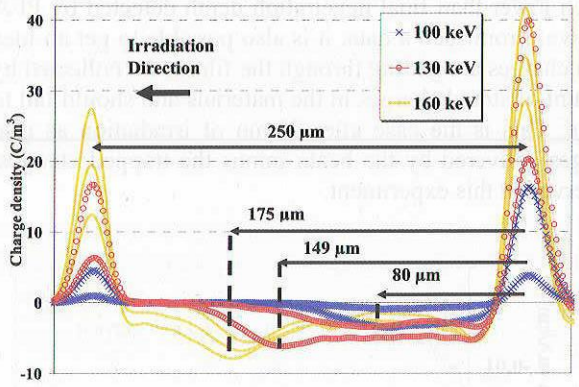

Figure 3 (above) : PEA measurements recorded on a PMMA film during the irradiation for 40 mn under 100 (crosses), 130 (circles), 160 (single line) keV with a flux of 50 pA/cm^2.

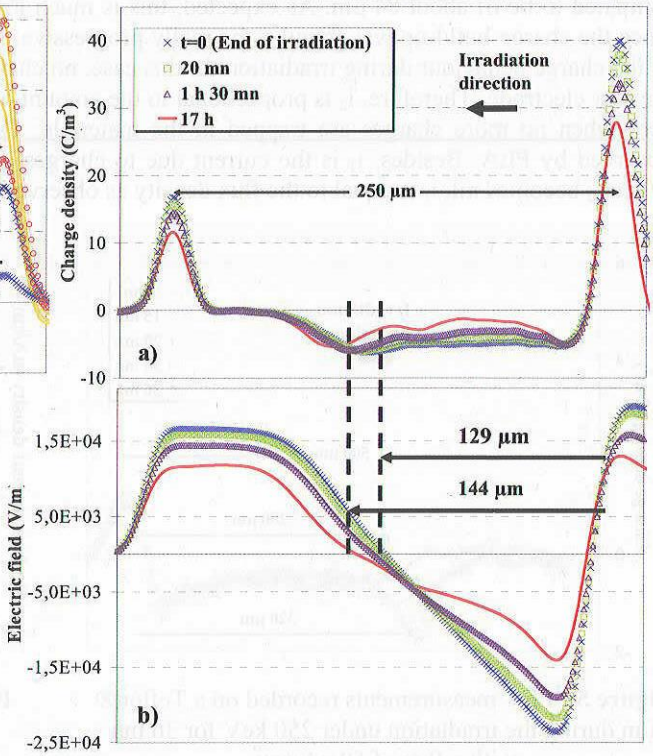

Figure 4 (right) : PEA data recorded during relaxation after 40 mn of irradiation under 130 keV. **a)** Charge density, **b)** Electric field recorded for 17 h after the end of the irradiation.

A part of the PEA data, recorded during the relaxation which followed for 17 h, is reported in figure 4. If we have a look at the curves that represent the electric field in the bulk we can see that during the first 1 h 30 mn the field is negative, up to 129 µm in the irradiated zone. Therefore, charges located in this region where the conductivity is increased during the irradiation tend to be extracted through the metallized electrode. Charges located in the positive field region tend to move toward the rear electrode through the non-irradiated region where the initial conductivity has not been modified. After 17 h, the negative field has been shifted up to 144 µm. A slight displacement of the negative peak toward the rear electrode is detected whereas a large part of the negative charges located in the negative field have been extracted. However, a large amount of charges crowded together remain close to the irradiated surface. Perhaps longer time is required to see any changes in this region.
Finally, the third irradiation sequence under 160 keV was applied. Charges seem to accumulate deeper in the bulk at about 175 µm (figure 3). Some charges seem to go close up to the rear electrode without being extracted as the amplitude of the peak keeps growing with irradiation time. Besides, in the previously irradiated zone charges continue to accumulate but more slowly. The conductivity of this zone has probably been highly modified by the successive irradiations and then, it is difficult to analyse the electron behaviour in this region. The relaxation under vacuum was continued for 4 h during which a slow extraction of the charges located in the first 180 µm from the irradiated surface is observed.

Teflon®

During irradiation PEA measurements were recorded (figure 5). It was observed that the charge build-up was quite long compared to PMMA material. Actually, after 5 mn of irradiations some charges were detected close to the surface with a peak at about 290 µm. Then the slow build-up of the negative peak at 320 µm was observed for 20 mn. After this period, the distribution did not seem to change that much. Therefore, the irradiation was stopped after 36 mn of irradiation and the relaxation studied.

During the irradiation both currents from the front and rear electrodes were recorded by using the SFC cell (figure 6). As soon as the irradiation was initiated, the front and rear currents were i_1 = - 0.03 nA/cm^2 and i_2 = -

0.014 nA/cm^2 respectively. From these data by using the method described in paper [6] it is possible to estimate the initial depth of charge penetration d(0).

$$d(0) = D\frac{i_2(0)}{i_1(0)+i_2(0)} \quad (1)$$

To do so the equation (1), where D is the thickness of the sample, is applied. At the start of irradiation, d(0) is estimated to be of about 84 µm. As expected, this is much lower than final penetration depth detected by PEA since the charge build-up was found to be really progressive. From such a data, it is also possible to get an idea of the charge behaviour during irradiation. In this case, no charges are getting through the film to be collected by the rear electrode. Therefore, i_2 is proportional to the amount of stored charges in the materials and should fall to zero when no more charges are trapped in the materials. This is the case after 20 mn of irradiation as also observed by PEA. Besides, i_1 is the current due to charges delivered by the beam minus the trapped charges. When i_2 becomes nil, i_1 is equal to the flux density as observed in this experiment.

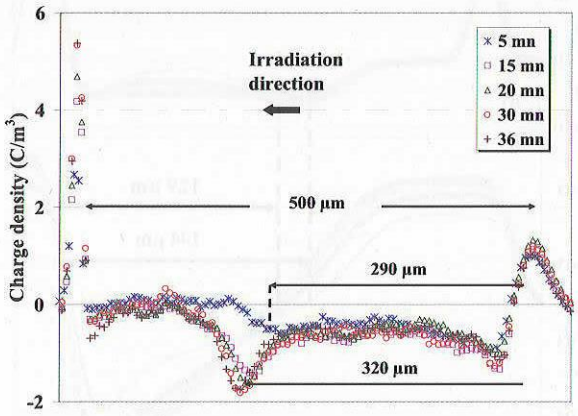

Figure 5 : PEA measurements recorded on a Teflon® film during the irradiation under 250 keV for 36 mn with a flux of 50 pA/cm^2.

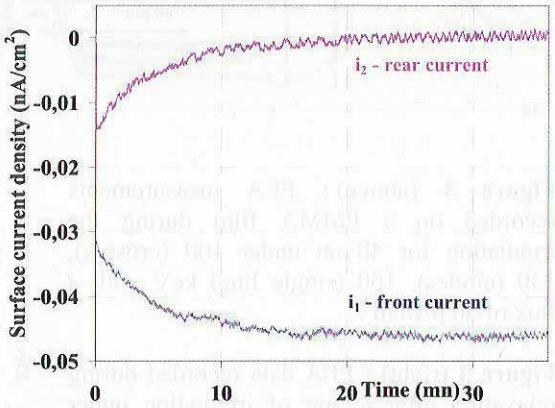

Figure 6 : Surface current data recorded during the irradiation under 250 keV by the SFC cell.

The relaxation was studied for 13 days in vacuum. The charge extraction was really slow and was followed by PEA measurements (figure 7). As in the case of PMMA, charges located in the middle of the irradiated zone tended to be extracted at first. The negative peak close to the surface was not modified with time whereas the peak detected in the bulk tended to shift slightly towards the rear electrode. The same phenomena based on conductivity and electric field influence described in previous sections can be evoked. However, low conductivity after the end of the irradiation is probably at the origin of the slow charge decay.

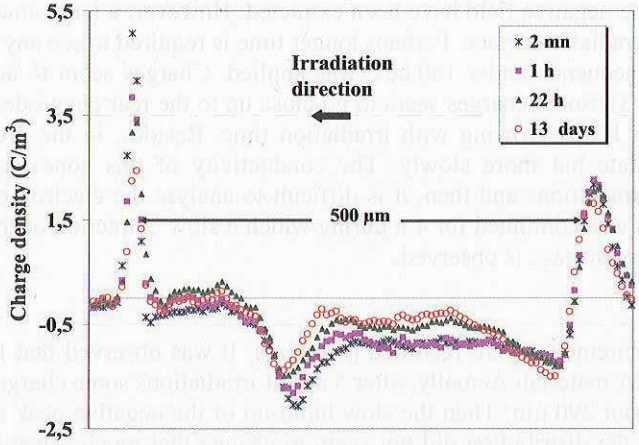

Figure 7 : PEA measurements recorded during the relaxation after irradiation under 250 keV for 36 mn.

Surface potential measurements could be performed only simultaneously with PEA. Therefore, results presented in table 1 obtained by the three techniques mentioned above were obtained during various measurement campaigns but under similar irradiation conditions. Unfortunately, all the configurations have not been reproduced yet and some values are missing in table 1. To estimate the charge penetration depth by surface potential technique, the method described in [7] is used. It consists of estimating the thickness d' of the non irradiated zone by using the equations :

$$I = - C(dV/dt) \quad (3)$$

$$C = \varepsilon_0 \varepsilon_r A/d' \quad (4)$$

Where I is the flux particle intensity (50 pA/cm^2), C the capacitance, V_s the surface potential measured, ε_0 the permittivity of free space ($8.854.10^{-12}$ F/m, ε_r the material relative permittivity, 2.2 for Teflon®), A the area (calculated for 1 cm^2), d' the distance between the charged layer and the back electrode. d'= D-d (D sample thickness, d penetration depth).d is therefore easily obtained. If we compare the results obtained for 200 and 300 keV with the distance extrapolated at the maximum of the charge peak obtained by PEA, we can see that they are in good agreement (table1). These values are a bit lower than the ones obtained by Estar [9] software that gives the maximum penetration depth of the electrons. This last calculated data is in quite good agreement with the value at the end of the peak detected by PEA.

It is also remarked that the values obtained by the SFC technique are always the lowest because they correspond to the initial position of the charges when the irradiation starts. It is clearly observed that the final penetration depth was much greater and was reached after more than 5 mn of irradiation.

d (µm) / E (keV)	PEA		Surface Potential	SFC	Estar
	$Peak_{max}$	$Peak_{end}$			
170	168	213	-	-	200
200	222	246	225	84	250
250	320	354	-	113	355
300	406	457	410	153	468

Table 1: Electron penetration depth 'd' in Teflon® estimated by various experimental techniques (PEA at the maximum of the peak and at the end, surface potential and SFC) and by ESTAR [9] software for various electron beam energies.

CONCLUSIONS

This paper reports the last results obtained in-situ during the electronic irradiation on PMMA and Teflon® films by different techniques. The charge penetration depth dependence on the electron beam energy and on the material has been shown. In the case of PMMA, charges are stored in the whole irradiated region if no relaxation between two periods of injection is allowed. This could be due to a weak radiation induced conductivity (RIC) in this material. This will be studied in a near future. During the relaxation it is observed that charges tend to be extracted through the irradiated surface which shows that this region has become more conductive after the irradiation. The movement towards the non irradiated region of the deeper injected charges is explained by the electric field effects. For Teflon® material, a good correlation between PEA, surface potential and SFC results is noticed. Charges tend to accumulate near the irradiated surface and deeper in the bulk creating a peak of negative charges detected by PEA. Contrary to PMMA, the charging and relaxation are rather slow and charged regions are more localized which must be due to various conduction processes that could not be identified yet. A study of the RIC and delayed RIC should be made by using the SFC cell in addition to other complementary techniques that have been presented.

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