ABSTRACT
This paper presents experimental results carried out in the SIRENE irradiation test facility, installed at ONERA (Toulouse, France), on stacked polyimide / adhesive structures used on solar panels. This study aims at following the evolution of the charging potential built up at the surface of these structures during an eclipse event in geostationary orbit. We have been able to demonstrate that temperature and light radiation strongly affect charging levels and kinetics and that the presence of adhesive strongly steers these parameters.

1 INTRODUCTION
Former studies [1, 2] carried out on space used raw polyimide material have revealed that this kind of material presents a fairly low charging level under geostationary environment thanks to the increased conductivity induced by electron and photon radiation. These features are still observed at low temperature. Charging behaviour can however be drastically different for real polyimide / adhesive structures used on solar panels, especially during eclipse events. In the current study, polyimide / adhesive solar panel structures have been tested in the SIRENE irradiation chamber, installed at ONERA (Toulouse, France), which allowed the radiation (electron and photon flux) and thermal simulation of an eclipse event under geostationary environment for a solar magnetic activity Kp higher than 5 (see section 2.1). The objective of this work is to study the influence of light, electron radiation and temperature on the charging behaviour of these solar panel components and to analyse the influence of adhesive and carbon mesh size on the electric properties during an eclipse event. This paper aims then at demonstrating that satellite structures, supposedly highly conductive in space environment, may actually be submitted to hazardous charging potentials during an eclipse phase.

2 EXPERIMENTAL SET-UP AND PROTOCOL
2.1 The irradiation SIRENE facility
The SIRENE experimental simulation facility reproduces the distributed electron spectrum in the range 5-400 keV and allows the assessment of charging potential and electric properties of space materials in GEO orbit conditions. The electron spectrum simulation is achieved by use of two monoenergetic electron beams (20 and 400 keV), these two beams being diffused in energy and angle to produce a space-like electron flow with a good flux homogeneity in a diameter equal to 20 cm on the sample holder. Fig. 1 shows the electron beam spectral characteristics of the SIRENE facility with an energy spectrum approaching that of the geostationary charging environment. The major interest of SIRENE is that it combines low energy electrons (that impinge and are implanted within the material bulk and induce electric charging) with higher energy electrons which go through the material without causing any charging but which contribute to modify its conductivity through the radiation induced conductivity mechanism. The nominal integrated fluxes used for the 20 keV monoenergetic beam and the distributed 0-400 keV one are respectively equal 250 pA.cm\(^{-2}\) and 50 pA.cm\(^{-2}\). The temperature of the sample holder can be controlled in the range [-180 °C, +150 °C] allowing to reproduce the temperature variations of materials on flight. A pumping system allows experiments at vacuum of around 10\(^{-6}\) hPa.

![SIRENE spectrum and GEO Kp=5 spectrum](image)

Figure 1: The SIRENE electron beam spectral characteristics (Integrated spectrum delivered by the complex diffusion window) and GEO Kp=5 integrated reference spectrum

A contact-less electrostatic probe, combined with a X-Y motion system, scans the samples at around 5 to 8 mm from their surface and allows the evaluation of the surface potential of the materials. Surface potential is then continuously recorded during the experiments allowing the assessment of the electric conductivity as a function of time and electric field using the relation:
\[ \sigma(E) = \varepsilon, \varepsilon \frac{dV_i}{dt} / V_i \]  

(1)

This relation is derived from the electric potential relaxation after irradiation and by modelling the sample as a combination in parallel of a capacitance and resistance.

A Xenon lamp (Cunow, France) has been installed on the facility to simulate light radiation before and after the eclipse event. A quartz window has been installed on the facility to avoid any UV absorbance induced by the glass transmission. Fig. 2 presents the energy spectrum delivered by the Xenon lamp, in comparison with the reference Thekaekara spectrum [3]. We can notice that the intensity level delivered by the Xenon lamp is 10 times lower than the standard spectrum. Despite this intensity difference, we have been able to notice a drastic effect of photon radiation on the electric charging of the samples.

![Energy spectrum of the Xenon lamp](image)

**Figure 2:** Energy spectrum of the Xenon lamp installed in the SIRENE facility, compared with the Thekaekara standard solar spectrum

### 2.2 Experimental protocol

The experimental procedure was divided into four consecutive steps, simulating respectively the three consecutive flight situations:
- "before eclipse event at Kp>5": electron irradiation of the samples at room temperature under light radiation (in a first preliminary stage, the sample have been submitted to 2 hours or 18 hours photon radiation without electron radiation, in order to study the effect of residual photo-conduction)
- "eclipse entry at Kp>5": electron irradiation of the samples in darkness with decreasing temperature
- "eclipse exit at Kp >5": electron irradiation of the samples under photon radiation with increasing temperature up to room temperature.

The electron radiation conditions similar to those encountered during a solar magnetic activity Kp > 5 are reproduced using the standard SIRENE spectrum produced with the following combined electron beam : (20 keV, 250 pA.cm\(^{-2}\)) (0-400 keV, 50 pA.cm\(^{-2}\)).

A former reference test has been performed following the same stages as described above but in darkness all along the different stages. It enables, in comparison with the following tests, to characterise the effect of photon radiation on the charging properties of solar panel structure and polyimide samples.

Tables 1 to 3 summarise the experimental protocol applied for the reference test and the "eclipse like" ones. We can notice in these tables that the temperature profiles are different from one test to the other. The specifications of the electrostatic probe implies to end phase 2 (eclipse phase) if the electric potential reaches around -8000 V at the surface of the samples. This limit potential is reached at different irradiation times (and therefore different operating temperatures) for the three different tests since light radiation history (and consequently the residual photoconduction level) differs from one test to the other. Phase 4 in each test is just a relaxation stage at room temperature and under light radiation to discharge the sample prior to the following test.

**Table 1 : Reference test (in darkness)**

<table>
<thead>
<tr>
<th>Test</th>
<th>Irradiation</th>
<th>Temperature</th>
<th>Light</th>
<th>Irradiation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>SIRENE spectrum</td>
<td>20°C</td>
<td>NO</td>
<td>1 h</td>
</tr>
<tr>
<td>1.2</td>
<td>SIRENE spectrum</td>
<td>+20°C to -85°C</td>
<td>NO</td>
<td>19’</td>
</tr>
<tr>
<td>1.3</td>
<td>SIRENE spectrum</td>
<td>-85°C to +20°C</td>
<td>NO</td>
<td>41’</td>
</tr>
<tr>
<td>1.4</td>
<td>No irradiation</td>
<td>+20°C</td>
<td>YES</td>
<td>120’</td>
</tr>
</tbody>
</table>

**Table 2 : Eclipse test after 2 h light radiation - Test 2**

<table>
<thead>
<tr>
<th>Test</th>
<th>Irradiation</th>
<th>Temperature</th>
<th>Light</th>
<th>Irradiation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>SIRENE spectrum</td>
<td>20°C</td>
<td>YES</td>
<td>1 h</td>
</tr>
<tr>
<td>2.2</td>
<td>SIRENE spectrum</td>
<td>+20°C to -101°C</td>
<td>NO</td>
<td>23’</td>
</tr>
<tr>
<td>2.3</td>
<td>SIRENE spectrum</td>
<td>-101°C to +20°C</td>
<td>YES</td>
<td>36’</td>
</tr>
<tr>
<td>2.4</td>
<td>No irradiation</td>
<td>+20°C</td>
<td>YES</td>
<td>120’</td>
</tr>
</tbody>
</table>

**Table 3 : Eclipse test after 18 h light radiation - Test 3**

<table>
<thead>
<tr>
<th>Test</th>
<th>Irradiation</th>
<th>Temperature</th>
<th>Light</th>
<th>Irradiation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>SIRENE spectrum</td>
<td>20°C</td>
<td>YES</td>
<td>1 h</td>
</tr>
<tr>
<td>3.2</td>
<td>SIRENE spectrum</td>
<td>+20°C to -137°C</td>
<td>NO</td>
<td>26’</td>
</tr>
<tr>
<td>3.3</td>
<td>SIRENE spectrum</td>
<td>-137°C to +20°C</td>
<td>YES</td>
<td>27’</td>
</tr>
<tr>
<td>3.4</td>
<td>No irradiation</td>
<td>+20°C</td>
<td>YES</td>
<td>120’</td>
</tr>
</tbody>
</table>

This experimental procedure allows the characterisation of photoconduction and temperature effect on the electric potential of the polyimide surface.

### 3 DESCRIPTION OF THE TESTED SAMPLES

Three different samples have been tested in this study and basically differ from each other by the grounding path: one reference polyimide raw sample metallized on the rear face (to allow charge leakage) and two...
polyimide / adhesive samples. The two last samples are stacking of 50 µm thick polyimide film, 50 µm thick epoxy resin (see Fig. 3) and a conductive carbon mesh and vary only by the carbon mesh size, as seen in Fig. 4. For the polyimide / adhesive samples, the connexion to the ground is performed through the carbon fibres electric contact. The path length of the implanted electron between the irradiated surface and the ground differs from one sample to the other. This choice enables to study the effect of adhesive and mesh size on the overall charging potential of the system during the different experimental stages.

![Figure 3: Sketch of the polyimide / adhesive samples](image)

![Figure 4: View of the two polyimide / adhesive samples – (a) low density carbon fibres mesh (1 mm fibre distance), (b) high density carbon fibres mesh (5 mm fibre distance)](image)

4 EXPERIMENTAL RESULTS

4.1 Reference test

This first test is a reference test performed in darkness. It aims to discriminate, in comparison with the following tests, the effect of light radiation from the effect of temperature on the charging potential built up at the surface of the samples.

4.1.1 Phase 1.1: prior to the eclipse phase

Fig. 5 presents the evolution of the charging potential built up on the three samples during the reference test. We can notice drastic differences between the reference polyimide sample and the two polyimide / adhesive ones. During phase 1, the reference sample reaches an electric potential equal to around -800 V, in comparison with a potential close to -6400 V and -6500 V for the other high density and low density samples. The low density sample presents as well a charging kinetics at the start of the test much higher than the high density one. The path length of the electron between the surface and the ground being higher for the low density sample, the equivalent dielectric capacity of this latter is then reduced in comparison with the high density sample and the reference one, leading then to a significant increase of the charging kinetics. The huge increase of equilibrium potential for the polyimide / adhesive samples, in comparison with the reference one, is directly assigned to a large rise of the equivalent electric resistance due to the sample design: the adhesives enlarge the resistive path of the electrons to the ground and the lack of metallization on the rear face of the polyimide film adds a surface resistive element on this face. Fig. 6 summarises the electron path from the surface to the ground. At this stage, we cannot notice any strong influence of the fibre mesh since the equilibrium potential is quite similar for both polyimide / adhesive samples. Adhesive is therefore sure to steer at a great level the charging potential of these samples, which have already reached hazardous charging level after 60 minutes irradiation in darkness at room temperature.

![Figure 5: Evolution of the electric charging level built up on the three tested samples during the different phases of the reference test (in darkness)](image)

![Figure 6: Sketch presenting the electron path in the polyimide / adhesive samples from its surface to the ground](image)

4.1.2 Phase 1.2: eclipse entry

During the second phase, the samples are irradiated in darkness with a decreasing applied temperature. The reference sample does not present any potential drop when temperature decreases, in opposition with the polyimide / adhesive samples, the absolute charging level of which rising swiftly with the decreasing temperature. We have already demonstrated [4] that adhesives are highly sensitive to temperature, their electric conductivity falling down quickly with the applied temperature. The same feature is observed in the current situation with a charging potential mainly ruled by the epoxy adhesive system. This phase had to be stopped after 19 minutes due to the very high hazardous potential (~9000 V) measured on both polyimide / adhesive samples.
4.1.3 Phase 1.3: eclipse exit

During phase 3, the samples are still irradiated with an increasing temperature (up to room temperature). We can notice, at the start of this phase, a steep decrease of the absolute charging potential which is a feature of an electrostatic discharge, likely to occur between the surface of the samples and the ground. This electrostatic discharge is initiated by the high electric potential built up at the surface of the samples. It must take place between the surface of the sample and the grounded support. After a transitory phase following this discharge, we can notice that the absolute charging potential of both polyimide / adhesive samples drops down continuously to reach, at room temperature, the same equilibrium potential met prior to the eclipse entry. Temperature is therefore the main parameter steering the charging potential of the polyimide / adhesive samples. In so far as we do not observe any variation of the charging potential on the reference sample, we can easily conclude that temperature mainly affect the adhesive conductivity: as temperature decreases, this electric conductivity drops down dramatically.

The last phase (phase 4) of this reference test aims only to discharge the sample under light radiation prior to the following eclipse test.

4.2 Test 2: eclipse simulation following 2 hours light radiation

This second test aims to simulate an eclipse event prior to 2 hours light radiation without any incident electron flux. Comparing with test 3 (for which we applied 18 hours light radiation prior to the eclipse simulation), we will be able to study the effect of photo-conductivity on the charging potentials.

4.2.1 Phase 2.1: prior to the eclipse phase

During this phase, the samples are irradiated using the standard SIRENE electron spectrum, under light radiation at room temperature. We simulate the situation prior to the eclipse phase during a high solar magnetic period. Fig. 7 presents the evolution of the charging potential built up on the three samples during this second test. We can notice that the reference polyimide sample reaches an equilibrium potential equal to -300 V, which is noticeably lower that the one measured during the reference test, thanks to the photon induced conductivity. The charging potential reached by the polyimide / adhesive samples drops down continuously with time. The sample is not radiated with light: the effect of this light radiation sustains a residual

As pictured in Fig. 6, the low energy (0-20 keV) electrons are first implanted at the surface of the sample. They can then drift within the polyimide volume under the effect of the applied electric field and the electric conductivity enhanced by photon and high energy electron radiation. Once they reach the rear face of the polyimide film, the only way to be dragged to the ground is to flow along the rear surface thanks to the surface conductivity likely as well to be enhanced by photon and high energy electrons. Arriving at the epoxy adhesive points, they can then easily flow to the ground through the thin adhesive film. For the same increase of the volume conductivity of polyimide under photon and electron radiation, the total volume resistance decrease in a square element (as described in Fig. 8 ) within the polyimide film should be higher for the high fibre density samples (this resistance is in inverse proportion to the square of the fibre distance). As a consequence, when the samples are submitted to light radiation, the absolute potential decrease (in comparison with the reference test) will be higher for the high fibre density, as observed during test 2.

4.2.2 Phase 2.2: eclipse entry

As for the reference test, the samples are irradiated in darkness with a decreasing applied temperature during the second phase. We can notice an interesting feature on the reference polyimide. During this second phase, the charging potential of this sample decreases continuously with time. The sample is not irradiated with light: the effect of this light radiation sustains a residual
photon induced conduction which falls down gradually leading to a continuous increase of the absolute charging potential (due to the enhancement of the total resistance of the system). This feature was not observed during the reference test since no photo-conduction was initiated within the sample. The charging potential of the reference sample during this second test gets then close to the one measured during the reference test at the end of the eclipse entry: we can then assume that photo-conduction has lowered dramatically and that its effect on charging potential is insignificant. At this stage of the study, we do not know if this photo-conduction decrease is ascribed to low temperature effect or to a temporal relaxation of this mechanism, since both low temperature and light shutdown occur at the same period.

The behaviour of the polyimide / adhesive samples is quite similar to the one observed in the reference test. The potential difference between both samples is still maintained during the eclipse exit and the absolute charging potentials in this test are lower than those observed in the reference test at the same temperature level. However, the potential difference is lower than the difference measured at room temperature prior to the eclipse phase: we measure a potential difference between both tests equal to -1000 V at 85°C for the low density sample, to be compared with -2600 V at room temperature. We can indeed notice that the potential drop kinetics is higher during this test (around -190 V.min\(^{-1}\) versus -120 V.min\(^{-1}\) for the reference test) for the same temperature kinetics. This higher potential decrease can still be ascribed to the relaxation of photo-conduction, either with time or temperature. Light radiation effect is therefore quickly annealed during the eclipse phase leading to hazardous potentials after 20 minutes irradiation and -100 °C. For the potential probe safety, the eclipse phase had to be stopped at this temperature level.

4.2.3 Phase 2.3: eclipse exit

The behaviour of the polyimide / adhesive samples during the eclipse exit is similar to the one observed in the reference test. Once the samples are heated up, their absolute charging potential decreases due to an increase of the adhesive electric conductivity. These samples recover the charging potential measured prior to the eclipse entry, for a temperature equal to around 5°C. The effect of temperature is therefore effective for temperature lower than 5 °C but can be considered as insignificant above this level. For temperatures higher than 5°C, the charging potential is basically steered by photon induced conductivity (instantaneous during light radiation, or residual in darkness). At the start of the eclipse exit and for the three samples, we can observe a dramatic decrease of the absolute charging potential: this emphasizes the effect of the instantaneous photo-conduction (or photo-emission) which rapidly drags away the electrons implanted in the volume during the eclipse phase.

4.3 Test 3: eclipse simulation following 18 hours light radiation

This third test aims to simulate an eclipse event prior to 18 hours light radiation without any incident electron flux.

4.3.1 Phase 3.1: prior to the eclipse phase

During this phase, the samples are irradiated using the standard SIRENE electron spectrum, under light radiation at room temperature. Fig. 9 presents the evolution of the charging potential built up on the three samples during this third test. The reference polyimide sample reaches a charging potential equal to -210 V which is 100 V higher than the one measured in test 2. This feature should be explained by an increase of the total dose transmitted to the material under light radiation (prior to the electron radiation) which led to a higher residual photo-conductivity during phase 1 and consequently a lower absolute charging potential. The two polyimide / adhesive samples come up to charging potentials equal respectively to -2000 V for the high density sample (to be compared to -2700 V measured in test 2) and – 3200 V for the low density sample (to be compared with -3600 V measured in test 2). This overall absolute decrease is ascribed, as explained earlier, to a higher residual photo-conductivity induced by a longer light pre-radiation.

![Figure 9](image-url) Evolution of the electric charging level built up on the three tested samples during the different phase of test 3

4.3.2 Phase 3.2: eclipse entry

As observed in test 2, we can notice that the charging potential of the reference sample drops down with the temperature. This can be assigned to the decrease of photo-conductivity due either to the low temperature effect or to a temporal relaxation. The behaviour of the polyimide / adhesive samples keeps up the same feature as observed in test 2, with a dramatic decrease of the charging potential with the temperature. We can as well notice that the charging potential difference (in comparison with the reference test) gradually fades away: we measure a potential difference between both tests (test 3 and the reference test) equal to -1300 V at 85°C for the low density sample, to be compared with -3300 V at room temperature. However, the potential drop kinetics measured on the polyimide / adhesive
samples is quite similar to those measured in test 2 (-180 V.min\(^{-1}\) for test 3 versus -190 V.min\(^{-1}\) for test 2). This feature suggests then that the residual photo-conduction relaxes rapidly in both tests, despite a total initial radiation dose higher in the second test. During the eclipse event, the charging potential of these samples is then basically ruled by the sole effect of temperature. For safety reason, the eclipse phase had to be stopped at -137 °C (and a potential level of -9000 V).

4.3.3 Phase 2.3: eclipse exit

As observed in test 2, the charging potential of the three samples increases swiftly at the start of the eclipse exit under the effect of the instantaneous photo-conduction. The polyimide / adhesive samples recover the equilibrium potential measured prior to the eclipse phase, at a temperature equal to 3°C, which is approximately the same as the temperature threshold assessed in test 2. These experimental characteristics confirm the first conclusions stated in test 2: temperature effect prevails over photo-conduction for thermal level lower than this threshold. Above 3°C, photo-conduction should be the major parameter steering the charging potential of the polyimide / adhesive samples.

5 CONCLUSION

The current work aimed to study the charging behaviour of polyimide / adhesive systems used on solar panels, during an eclipse event. The experimental protocol devised for this study allowed the analysis of the effect of temperature and photo-conduction (instantaneous or residual) on the charging potential of these samples. From this study, we can come to the conclusion that epoxy adhesives steer at a great level the system charging potential, especially at low temperature. We have indeed demonstrated that the electric conductivity of these adhesives dramatically drops down with the temperature leading to hazardous surface charging potential. Moreover, we have noticed that light radiation induces significant photon induced conductivity within the polyimide films allowing the reduction of the absolute charging level. However, this effect gets rapidly insignificant during the eclipse phase. This feature has been assigned to the dramatic relaxation of the residual photo-conductivity, leading then to hazardous charging levels despite a light pre-radiation. We have been able as well to put in evidence the huge effect of carbon fibre mesh size on the charging level: a denser fibre mesh enables to reduce significantly the electric potential outside the eclipse phase.

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6 REFERENCE