ELECTROSTATIC DISCHARGES ON SOLAR ARRAYS.
PHYSICAL MODEL OF INVERTED POTENTIAL GRADIENT ELECTROSTATIC DISCHARGE.

Denis Payan* , François Sévérin*, Jean-Pierre Catani*
Jean-François Roussel**, René Reulet**, Daniel SARRAIL**

* Centre National d'Etudes Spatiales (CNES)
Power Supply and Electromagnetic Compatibility Department
18, avenue Edouard BELIN
31401 TOULOUSE Cedex 4 FRANCE

** Office National d'Etudes et de Recherches Aérospatiales (ONERA)
Space Environment Department (DESP)
2, avenue Edouard BELIN
31055 TOULOUSE cedex FRANCE

Tél. 00 (33) 561 273 554. Fax. 00 (33) 561 282 162 e-mail: denis.payan@cnes.fr

Summary: This study aims to provide manufacturers with a test system to study the sustained arc risk generated by an ESD and maintained by the photovoltaic power of a solar array. In order to do this, it was necessary to lay down the basis of a physical gradient discharge model to find out the sequence of physical events leading to the failure on which depends the solar cell test system, while temporally respecting the power availability during the discharge.

1. INTRODUCTION

Since the power losses on the Tempo and Panamsat satellites attributed to electrostatic discharges in 1997 (15% of the power in three months), the international scientific community has looked into the problem of sustain arc on solar array.

Given their complexity, there is always an electrostatic risk on Solar Arrays. In the event of an ESD (Electrostatic Discharge), the integrity of the solar array is usually not affected during this discharge. The EMC risks, however, remain large for all the satellite. But with the increase in power of solar arrays, and in particular with the increase in voltage, low voltage arcs maintained by solar array photovoltaic power have appeared (**sustained arcs**). These breakdowns take place between two adjacent cells, generally the one at the start and end of the string, where the differential voltage is at its maximum. Current propagation into the inter-cellular gap is made possible in the plasma generated by the **primary discharge** (the ESD) by consuming the emission site.

If by misfortune, this discharge takes place in the gap between two adjacent solar cells where there is sufficient voltage, then the current available in the solar array rushes into the temporarily conductive path between the two cells generating "the sustained arc". This sustained arc is self-sustained due to the solar array's photovoltaic power when it is sunlit. There is probably a sustained arc for any ESD in the gap at a sensitive place (in a gap with a sufficient differential voltage) and it results in the circulation of a leakage current between the cells, in the primary discharge conductive plasma. But as long as there are fairly low values of voltage-current, (typically 2A-50V), this discharge remains transient, causes no irreversible effect and therefore remains "invisible" to the experimenter.

If no precautions are taken, whole sections can be lost prematurely on the solar array.

To prove that the systems are compatible with the environment, samples are tested in vacuum chamber in the laboratory. The validity of the experiments can be proved only if the difference between ground tests and space reality is known. To interpret the results and for space extrapolation in the case of sustained arcs on solar arrays, it is necessary to know the sequence of physical phenomena leading to the electrostatic discharge in order to define the importance of each parameter.

The understanding of the physical mechanisms involved has made it possible to understand the role of the electrostatic discharge as initiator of the failure mechanism. From a phenomenological viewpoint, the sequence of events leading to discharge has been described well for several years. In actual fact, however, the microscopic configuration allowing the field emission current to degenerate in electrostatic discharge remains delicate to apprehend. Indeed, it is an environment specific configuration which, by inducing a particular electrostatic state, leads to a situation where discharge is allowed into the intercellular gap. This situation alone is susceptible of generating the sustained arc.

It was therefore necessary to draw up a discharge theory, with a sequencing of events, by taking into account the energy available at the moment of discharge on the satellite – as on this energy depends the amplitude of the primary discharge, and therefore the associated thermal effect, which totally conditions the arc.

On the other hand, manufacturers, now encountering problems of electrostatic nature on satellites (section losses on high voltage solar arrays), present the problem in terms of efficient solutions. Manufacturers and laboratories still test solar array samples with their own assembly configurations which, for a single sample, can either be disastrous or have not the slightest effect. Indeed, depending on whether the energy developed in the primary discharge comes from a capacitance of 100pF or one of 1µF, the result as regards the direct effects of the primary discharge and the sustained arc risk will be completely different.

To test solar array samples *a priori* in the confinement of an enclosed vacuum, it is necessary to define a laboratory test setup, which represents what the solar array comes across in the geostationary orbit.

The physical and electric model is Denis Payan´s CNES model.

The solar simulator was designed and created in the CNES by MM. Denis Payan, Denis Schwander and Christian Prédine.

The electrostatic discharge activation vacuum tests were carried out in the l'ONERA/DESP of TOULOUSE in the JONAS vacuum room during the CNES R&T, by MM. René Reulet and Daniel Sarrail.

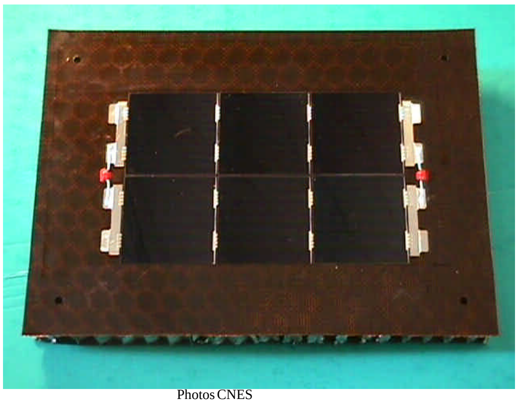
The simulations using the SILECS Software were carried out in the ONERA/DESP by Mr. Jean-François Roussel during the CNES R&T.

The simulations using the AMBRE Software were carried out in the CNES by Mr. François Sévérin.

2. THE SOLAR CELL SAMPLE.

A - Description

1 - The solar cell sample.

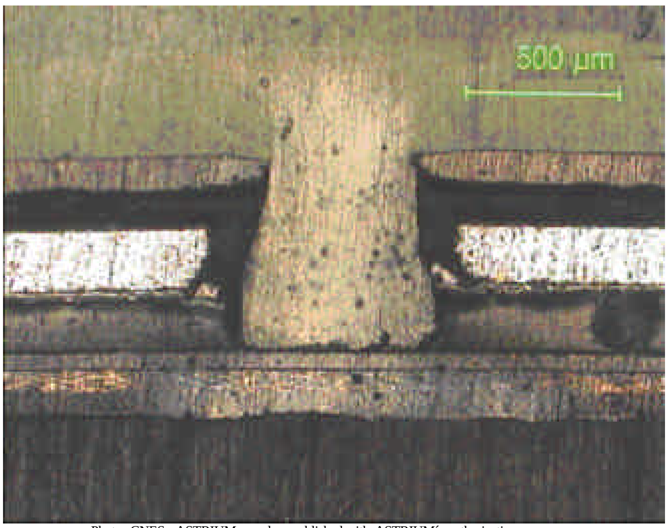


Photos CNES

Figure 1: FRENCH TELECOMMUNICATION solar array sample photograph – Front.

2 - The intercellular gap.

The intercellular gap is not constant, as this is a manual assembly. It is generally of 500 to 900µm.



Photos CNES - ASTRIUM sample - published with ASTRIUM´s authorization

Figure 2: Cell gap cross section detail.

3. INITIAL ELECTROSTATIC STATE.

A - In the satellite.

1 - Capacitances.

To study electrostatic discharge, it is advisable to list all the useful capacitances where the charge contributing to the discharge is stored.

a - Satellite capacitance.

For satellites in geostationary orbit, it is possible to calculate the capacitance of their structure in relation to infinity. Depending on satellite size and on the geometry (sphere, cylinder, ...), values range from about 50pF to almost 200pF. Despite its low value, this capacitance plays an essential role, as the change in its potential pilots all the discharge.

The satellite is embeded in a plasma which forces it to be in a state of electrostatic equilibrium. The structure potential therefore floats at a value which is imposed upon it by the environment. Any modification in the electrostatic state of the other materials at the satellite surface should cause a variation in the satellite electrostatic state by capacitive influence. And all the more so when satellite capacitance is low. But as the environment imposes the satellite its state of equilibrium, charge transfers will take place to bring the satellite potential back to its initial equilibrium value.

In fact, the environment acts as a voltage source which imposes its potential on the satellite capacitance. In response to a modification in the charge state, the voltage source produces a current in order to bring the potential back to its equilibrium value.

b - Coverglass capacitance.

So, as the coverglasses are charged (by secondary emission and/or photoemission), the environment compensates it by charging negatively the satellite (it is the image charge of that of the coverglass) in order to maintain its potential at its equilibrium value.

The coverglass capacitance is therefore charged under the potential difference due to the gradient (potential difference between satellite and coverglass).

Depending on the materials, this capacitance can be estimated at between 20 and 30 pF/cm², that is 200 to 300nF/m². This value is considerable when compared with the capacitance of the satellite itself and despite polarization at lower voltage, the energy contained in this capacitance remains hundreds of times larger than that contained in the satellite capacitance.

The problem will be of knowing which surface will be concerned by the discharge. Is the neutralization of the coverglass, in proportion to the satellite, very local or rather global? The thermal effect associated with the discharge, and therefore the quantity of metal at the tip which will be vaporized in the discharge, will be totally different depending on whether satellite capacitance alone or several square meters of solar array must be taken into account.

2 - Satellite capacitance charging.

It is the environmental conditions which allow satellite charging in a situation of inverted potential gradient. The satellite structure is then negative in relation to the various dielectrics.

Creation of the inverted potential gradient condition:

- Satellite's absolute charge negative.
- Secondary emission and/or photo-emission on the coverglass.
- Coverglass surface potential negative, coverglass charge positive (even in orbit in the presence of potential barrier).

It is very easy to demonstrate experimentally that the coverglass charge is positive. Simply polarize a sample (metallic support covered in dielectric) negatively (-5kV in our example) and put it in a situation of inverted gradient, by irradiating with low energy electrons (a few keV). The irradiation causes, because of the secondary emission, a rise in potential on the dielectrics which become less negative. By bringing the support polarization back to zero, before measuring the potential, the positive charge of the coverglass can be seen thanks through the positive potential.

In fact, the secondary emission has pulled electrons out of the dielectric which then finds itself short of electrons. Its charge is **positive**. In the two graphs below, we can see the potential on kapton and a coverglass with and without support polarization.

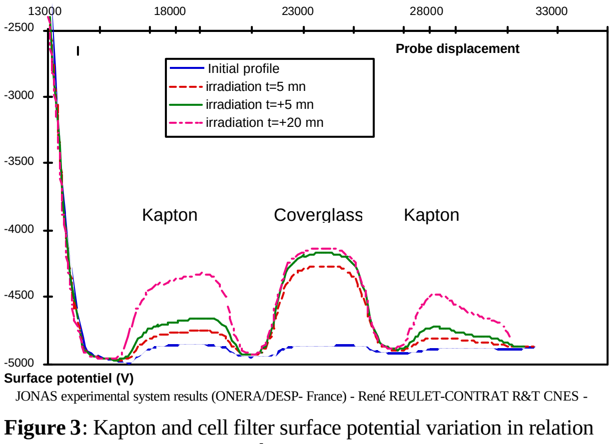


Figure 3: Kapton and cell filter surface potential variation in relation to charging time (inverted potential gradient V_C=-5kV).

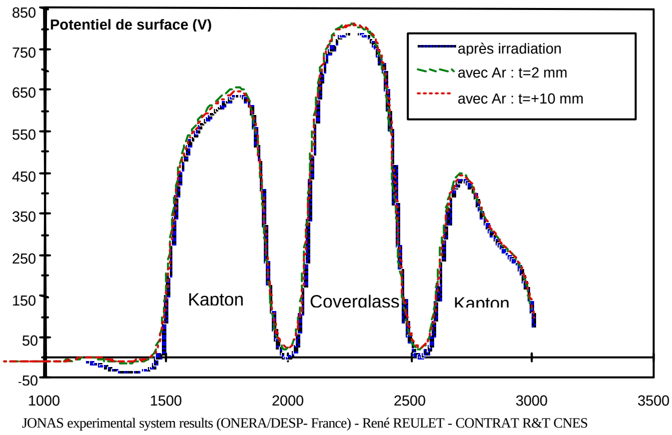


Figure 4: Kapton and cell filter surface potential variation in relation to charging time (inverted potential gradient V_C=-5kV brought back to zero).

The inverted gradient situation imposes the coverglass a positive charge even in the presence of a potential barrier.

This is an important observation, as it means that during the electrostatic discharge, coverglass neutralization will happen inevitably by electron collection.

The potentials in the various satellite capacitances involved in the electrostatic discharge have been deduced from a NASCAP analysis. In the case of A FRENCH TELECOMMUNICATION, satellite potential was calculated at –3750V and that of the coverglass at +1200V relatively to the satellite.

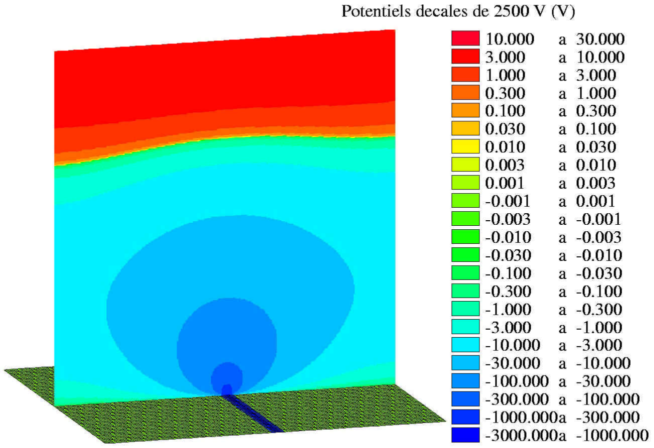
B - *In the solar cells.*

In all the electrostatic discharge tests carried out during the CNES R&T in the DESP (ONERA/TOULOUSE) (around a hundred discharges during the last R&T), no primary discharge outside a cell gap was able to generate a sustained arc. The plasma production condition is so local that the primary electrostatic discharge and the associated sustained arc are at the same place: in the gap. Even in the cases where the discharges take place on the interconnector closest to the gap, the distance remains too large to generate a sustained arc.

In this study, we therefore only concerned ourselves with knowing the electrostatic discharge production conditions in a cell gap.

It is the local field conditions which enable the electrostatic discharge to start. But the presence of satellite potential at the bottom of the gap is not without effect, as it generates a local potential barrier which prevents the photoelectrons and the secondary electrons from leaving (given their low energies). This has a limiting role and the local potential gradient is therefore less pronounced than the large scale one in the coverglass.

The simulation below shows the distribution of potential around the gap in a 4x4x4 cm computation box, the structural potential is -3700V (the bottom of the gap) and the coverglass potential is -2500V. The conditions at the right and left limits (horizontal electric field nil) are symmetry conditions. That makes it necessary to have another gap at 4cm (therefore 4cm cells). This is the case of A FRENCH TELECOMMUNICATION satellite GaAs cells.



SILECS software (ONERA/DESP- France) software result- Jean-François ROUSSEL - CONTRACT R&T CNES -

Figure 5: Potential induced by the gradient situation around the gap. (4x4x4 cm box)

The potential values and the condition at the high limits are deduced from a larger scale calculation using a NASCAP model of A TELECOMMUNICATION satellite electrostatic state as a starting point.

The potentials were shifted by 2500V and the bi-logarithm graph allows a good display of the potentials around zero.

There are potential barriers at -10, -30, -100V which limit the secondary emission. The result will be a local potential in the gap, lower than that in the middle of the coverglass.

This effect can be experimentally verified on the potential profile measurements before discharge where there is a local drop in potential, and this despite the probe resolution (visible locally over 2cm as compared to the 60cm of the potential measurement). See figures 26 to 28.

C - In the intercellular gap.

According to previous simulations, we know that the interior of the gap will be less charged than the coverglass surface. Simulations using an AMBRE (Bidimentional Analysis and Modelization of Electrostatic Risk - Analyse et Modélisation Bidimentionnelle du Risque Electrostatique) CNES software, electron trajectography have shown that the coverglass must acquire an intermediate initial charge to allow the electrostatic avalanche.

Here, we are concerned only with the gap between two cells (the configuration at risk) and we will study which distributions, for the coverglass charge and the emission site, can allow electrostatic discharge.

Two coverglass charge cases and three emission sites were studied.

- The first in the upper part of the cell (which corresponds to an emission from the cell silver comb),
- The second in the lower part (which corresponds to an emission from the lower cell electrode), and
- The third in the middle of the gap (an impossible situation as it would correspond to an emission from the Kapton), but indicated by way of example.

a - Charge on the coverglass surface only.

In this case, only the upper part of the coverglass is charged.

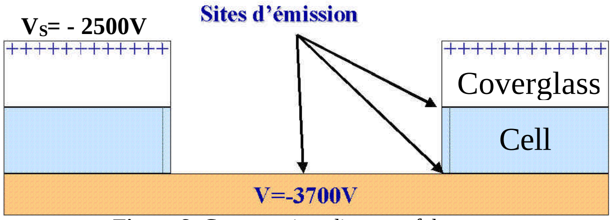
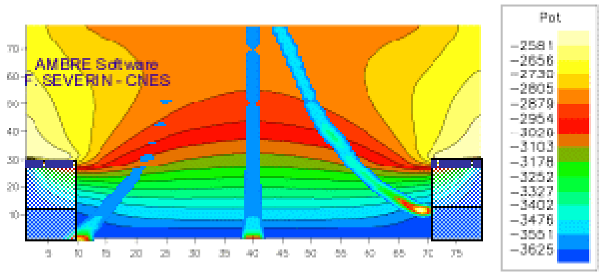


Figure 6: Cross-section diagram of the gap,
Non charged coverglass lateral surface.

In this configuration, none of the emission sites enable the electrons to hit the lateral face of the coverglass, field intensification by secondary emission cannot take place and field emission cannot degenerate in electrostatic discharge.



AMBRE software result (CNES-TOULOUSE France) - François SEVERIN - CNES -

Figure 7: Potential map,
Non-charged coverglass lateral surface.
No avalanche possibility.

The gap acts as an electron gun and the electrons travel too fast to return to hit the coverglass section. For there to be an avalanche, it is therefore necessary for the coverglass section to be charged.

b - Charge on the surface and the coverglass section.

In this case, as well as the coverglass surface charge, the lateral face inside the gap is also charged.

Figure 8: Gap cross-section diagram,
Coverglass lateral surface is positively charged.

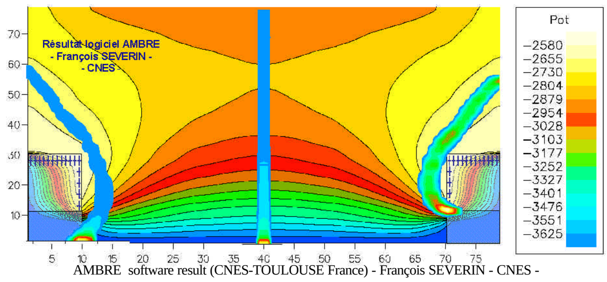


Figure 9: Potential map and field emission electrons trajectory
Coverglass lateral surface is positively charged.
Cell upper side source, **Avalanche** possibility

In this configuration only, where the electrons come from the upper angle of the cell, can electrostatic discharge be generated.

c - Comments.

It seemed natural to think that the coverglass section would become charged, because it is visible from space. We have shown that this is necessary to have a discharge.

Using as a starting point an electrostatic study on the satellite, it has been possible to find the conditions necessary for the development of an electrostatic discharge in the gap between two solar cells. In a gap which can be qualified as normal (with no noticeable geometric fault), the local distribution of the electric field provides the conditions favorable for discharge. These local field conditions are deduced from the potential distribution around the discharge site and it is the environment which imposes this electrostatic state. So, during a geomagnetic storm, the environmental conditions of that day will put the satellite in an electrostatic state favorable for electrostatic discharges in all the gaps between cells. Many discharges will take place, some where there is enough voltage to cause sustained arcs as in the case of Tempo and Panamsat.

Therefore, the discharge seem not to be caused by any particular local geometric configuration (fault), but rather by a particular environmental situation which allows discharge in a normal gap. The only condition is to have a tip of adequate diameter to initiate the discharge. We will see later that, considering the size of the tips necessary (around one µm), one can suppose that all the gaps will be candidates for an electrostatic discharge if the environmental conditions lend themselves to it.

4. ELECTROSTATIC DISCHARGE.

A - Introduction.

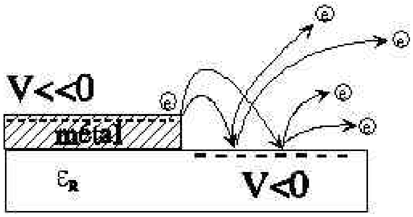


Figure 10: Inverted potential gradient discharge.

The mechanism causing an inverted potential gradient discharge is the result of a synergy between field emission, secondary emission, tip effect and thermal effect.

For greater clarity, the electrostatic discharge account has been divided into two parts.

- The first part will only deal with the electronic motions; this is electrostatic discharge itself.
- The second part will only deal with the ionic motions; these are the expansion and the effects of the plasma bubble which follow the thermal effect on the tip.

In fact, these two processes are linked. During discharge, the two processes compete in neutralizing the various potentials and in extinguishing the discharge. According to the energy available for primary discharge (therefore according to the satellite capacitance size), discharge is mainly of electronic type when the thermal effect on the tip is weak and mainly of ionic type when it is large.

B - Electronic sequence.

1 - The different stages.

- Field emission (Fowler & Nordheim effect) in an inter-cellular gap.
- Field emission intensification by secondary emission.
- Starting the avalanche.
- Global rise of satellite potential (Emptying the capacitance C_{SAT}).
- Beginning of coverglass neutralization by the discharge electrons (Partial emptying of $C_{COVERGLASS}$).
- Discharge extinction by gradient neutralization.

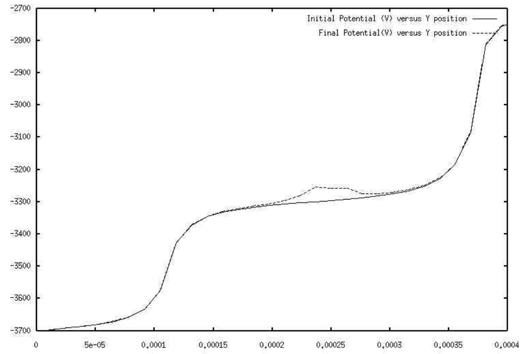
2 - The physical discharge model stage by stage.

a - Field emission and secondary emission.

The process begins when the potential on a metal becomes more negative than that on a neighboring dielectric. As soon as the potential difference between the two is sufficient (about 500V [1]) there is a field emission from the metal towards the dielectric, the electron emitted arrives on the dielectric (it follows the field lines) and pulls away several other electrons by secondary emission, the potential difference then increases thereby causing a field emission increase and the phenomenon starts again until there is an avalanche which discharges the metallization.

This happens when there is a floating metallization near the material or a global rise in satellite potential.

So, when the environment has supplied the configuration with potential enabling the primary electrons (from the tip) to hit the coverglass section, the process of field intensification by secondary emission can start, leading to the avalanche.



AMBRE software results (CNES-TOULOUSE France) - François SEVERIN - CNES -

Figure 11: Coverglass section potential distribution.

Intensifying the field by secondary emission requires the extraction of the secondary electrons. Their potential energy must be sufficient to enable them to cross the local potential barrier (created by the strongly negative potential at the bottom of the gap (cf. figure 9)). Field intensification takes place because of the modification of the coverglass section local charge near the emission site.

We previously saw that the local potential barrier does not cause the same potential difference near the gap as in the middle of the coverglasses. It is the secondary emission due to the field emitted electrons at the ignition of the discharge which enhances the differential potential at coverglass edge, thereby making it possible to obtain locally a field sufficient to start an avalanche.

In a diagram representing the potential map and the barrier around a cell gap (Figure No. 13), we can see that only the secondary electrons having a sufficient potential energy can cross the local potential barrier due to the gap.

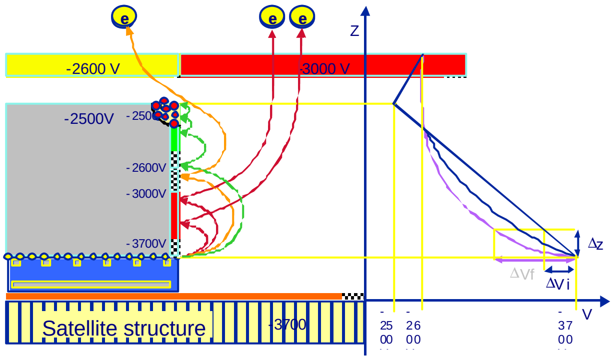


Figure 12: Avalanche start condition diagram.

So :

- The secondary electrons generated in the zone (-3700V,-3000V) (at the bottom on the coverglass section) have sufficient potential energy to cross the central potential barrier; the potential falls.
- The secondary electrons generated in the zone (-3000V,-2600V) (intermediate zone on the section) have a potential energy which enables them to cross not the central potential barrier but the lateral one. They manage to escape and the potential falls.
- The secondary electrons generated in the zone (-2600V,-2000V) (at the top of the section) no longer have enough potential energy to cross the barrier. They are trapped on the coverglass and tend to neutralize it. The potential then increases in this zone. The maximum possible value being that of the barrier potential. Beyond that, the electrons begin to escape again, the field once again becomes an extractor.

Locally, the secondary emission has made it possible to increase the field, there will be an avalanche. To start an avalanche, the environmental conditions must enable the primary electrons to hit the coverglass section as close as possible to the emission site.

b - The avalanche.

The electrostatic discharge takes place in three stages. These stages depend on the electric field at the coverglass surface and therefore of the different potentials. As all the dielectrics are referenced in relation to the structure, their potentials depend on its potential. It is the change in satellite potential, and therefore C_{SAT} charge, which conditions the discharge.

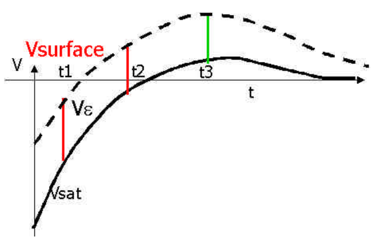


Figure 13: Diagram of satellite potential change during an ESD.

Electrostatic discharge takes place in phases

- Instant t_1: Satellite potential and coverglass surface potential are both strongly negative.

- Instant t_2: Coverglass surface potential becomes positive.
- Instant t_3: Satellite potential and coverglass surface potential both become positive.

Instant t1 : The beginning of electrostatic discharge : $V_{Surface}$ *always negative*

Only C_{Sat} capacitance empties, the condition to empty $C_{Coverglass}$ is not fulfilled as the field remains extractor for the electrons.

The electrons leave in blow-off, they find their « image » at infinity. They have enough energy to cross the potential barrier. C_{Sat} capacitance empties. Coverglass surface potential remains strongly negative, and so the electric field repels the electrons. Given this field, the only possibility for these first electrons is to leave in blow-off. They end their journey by finding their compensation at infinity and therefore come from C_{SAT}.

It is therefore not possible for an electron to leave the emission point in the gap, to acquire an energy equal to the difference in potential between the structure and the coverglass (for example 1000V) and to return onto the coverglass, while the field condition is not present, there is therefore no reason for them to turn round and hit the coverglass.

With a potential of +1000 Volts on the coverglass and 0 V for Vsat, the electrons would arrive at infinity with no energy and so they would not be able to make an about-turn. The satellite potential must first go somewhat positive (certainly some hundreds Volts, depending on dynamics) for the electrons to return, and only then can coverglass neutralization begin.

Instant t2 : Vsat becomes positive.

Despite the positive surface potential and the now attractive field, the electrons keep going (ballistic effect).

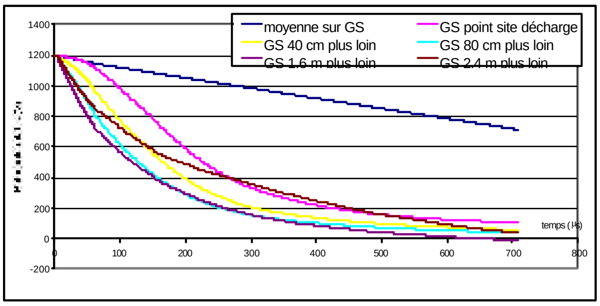
The effects remain the same as for t1, the field at the coverglass surface not being sufficient to cause the electrons to return.

Csat finishes emptying & VCoverglass is neutralized locally.

Instant t3 : Vsurface & Vsat become very positive

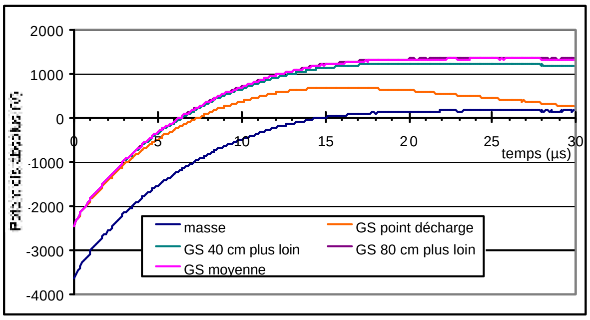
The global increase in satellite potential allows electrons to collect on the coverglass surface.

The field has become sufficient (much larger than the electron energy) to force the electrons to make an about-turn. The electrons then shower back down all over the coverglass.



SILECS software result (ONERA/DESP- France) - Jean-François ROUSSEL - CONTRACT R&T CNES -

Figure 14 : Relative potential simulations at various points on satellite during an ESD (space charge not taken into account, spacecraft discharging computed through a given Csat capacitance).



SILECS software results (ONERA/DESP- France) - Jean-François ROUSSEL - CONTRACT R&T CNES -

Figure 15 : Absolute potential simulations at various points on satellite during an ESD (space charge taken into account, spacecraft discharging computed exactly, i.e. without capacitance equivalence).

The simulations showed that coverglass neutralization took place on the satellite, if space charge was not taken into account. Taking into account space charge forces the electron paths to bend and in that case neutralization takes place on a scale inferior to the mesh (40 cm in this study). Other simulations are necessary to make this result more precise. The plasma generation limits the space charge effect of the previous electrons during the discharge. The experiments carried out with realistic capacitance values also show that neutralization remains partial and incomplete.

C - Ionic sequence.

1 - The different stages.

- Thermal effect and metal tip vaporization while C_{sat} empties.
- Released gas Ionization.
- Return of the leaving ions onto the emission site.
- Large thermal flow and thermo-ionic emission.
- Cathodic spot formation.
- Metal vaporization and ionization in the intercellular gap.
- Discharge extinction: Gap potential neutralization by the plasma.

2 - The physical discharge model stage by stage.

a - Field emission thermal effect.

During the electrostatic discharge, the electrons all pass through the same point causing a large thermal effect. The phenomenon is accentuated by an increase in current density due to the tip effect. This thermal warming can cause the fusion or even vaporization of the material. Only the tips of a sufficient diameter can resist a discharge, the others are consumed before the beginning of a real discharge.

If we look at the thermal effect induced by the passage of a field emission current in a tip, it is possible to derive the size of the tips which are at the origin of the discharges.

The curves below show field emission current and temperature in relation to potential and take into account the field intensification coefficient due to the presence of the tip, and of the thermal effect.

Copper: fusion T° 1083°C, vaporization T° 3000°C.

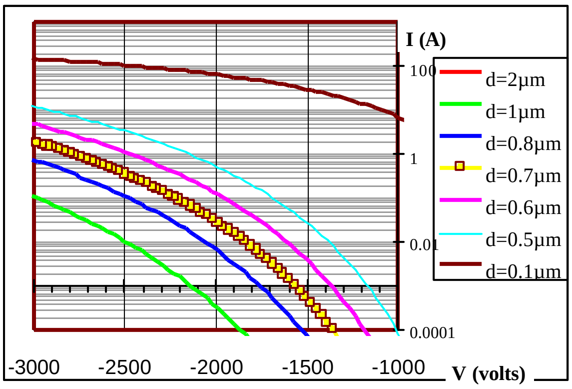


Figure 16 : Field emission current in relation to potential for various tip diameters.

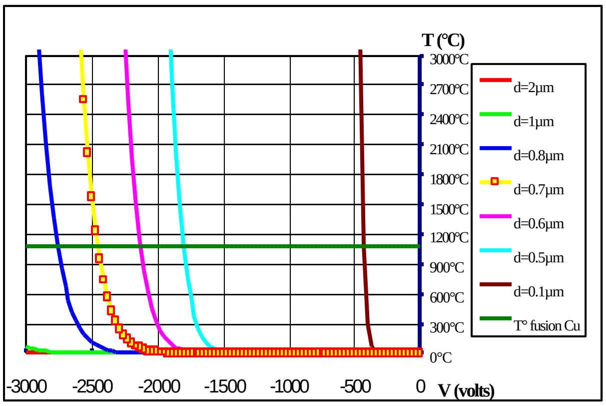


Figure 17 : Temperature induced in relation to potential for various tip diameters.

For a given potential value, if a tip is too large, it cannot cause a discharge, the field emission remaining too low.

For the same potential value, if the tip diameter is too small, it cannot resist the discharge and vaporizes instantly.

It is therefore possible for every discharge potential value to associate the tip diameter necessary for this discharge. For example, for a discharge around -3000V, a 0.9µm tip is needed.

In this study, the current which causes the vaporization is of about 1A. Of course, this is only a rough estimate but this result correlates well with all the experiments.

In conclusion, for discharges at potential levels of -3kV to -5kV, 1µm to 2µm tips are needed to resist the discharge. The energy contained in the satellite capacitance is sufficient to vaporize the tip allowing metallic vapors to be released into the inter-cellular gap favorable for the sustained arc. These discharges are in the region of one ampere. Considering the capacitance values of a satellite in geostationary orbit (300pF max), we can expect discharges of several microseconds (300pFx3000V=1µC, with 1A --> 1µs).

These results are totally consistent with the experiments carried out in the laboratory.

b - Start of thermal effect and tip fusion.

The thermal effect due to the passage of electrons in the tip starts. The electrons passing through the tip and consequently the energy consumed in the heating of the tip come, at that moment, only from C_{SAT}.

The simulations carried out on the thermal effect in the tip (AMBRE software result - François SEVERIN - CNES) show that the thermal effect does indeed take place before the end of the primary discharge and during the C_{SAT} emptying. The energy contained in C_{SAT} is sufficient to cause tip fusion and create plasma.

The tip vaporization process begins and the first metallic vapors are released in the gap.

c - Formation of a cathodic spot.

In very close proximity to the emission point, the field is so intense that the ions leaving or those generated make an about-turn and bombard the tip. Under the thermo-ionic effect of the first ions, a cathodic spot is formed.

d - Neutral vapors release in the interstice between cells.

The tip is slowly consumed and the vapors are released in the inter-cellular gap and beyond.

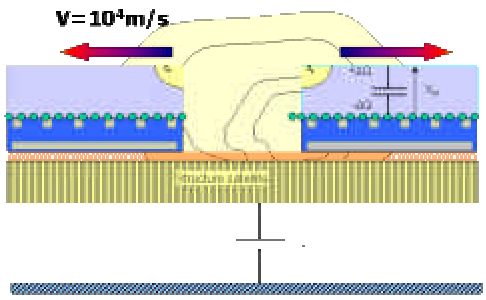


Figure 18: Plasma bubble expansion during an ESD.

As it progresses (at about 10^4m/s), the plasma bubble neutralizes the coverglass charge. The coverglass capacitance is neutralized at the progression speed of the plasma bubble.

Coverglass neutralization begins only when the thermal effect on the tip has allowed the plasma bubble to be created, in other words after absolute capacitance empties. The energy in the coverglass is not immediately available.

e - Discharge extinction condition.

Discharge stops when the coverglass near the discharge site is neutralized. The distance increasing the field becomes too small for field emission.

3 - Comparison between the two processes.

a - Low satellite capacitance (Geostationary case).

Local coverglass neutralization cancels the field emission condition. The thermal effect in the tip remains weak (energy available around one mJ and charge quantity around one µC), only the coverglass capacitance near the discharge is discharged (see experimental result).

b - High satellite capacitance (Low orbit case & certain experimental cases).

Coverglass neutralization can be global. With high capacitance values, the energy involved in discharge (typically 500mJ with charge quantities of 500 to 1000 µC) allows global coverglass neutralization on a large scale (total neutralization was measured over 60 cm with 200µC). It must not be deduced from this experiment that high capacitance values must be used. In that case, it is by using a high absolute capacitance value that large coverglass neutralization can be obtained.

4 - Consequences of the discharge model.

From this discharge model, a certain number of comments can be made.

- The field emission condition is given by the potential gradient.
- The discharge energy is mostly contained in the satellite capacitance.
- The ionized gas comes from tip fusion.
- There is a delay in the coverglass capacitance neutralization. The energy is not available immediately.

For tests in a vacuum:

Satellite capacitance can be artificially increased only when the experiments are carried out using lower polarization values (experiments with plasma polarization, for example). The energy must be constant for discharge. Unfortunately, we lose both the representativeness of the very rapid absolute potential change and of its effects, when the absolute capacitance is low, and the representativeness of the primary discharge where the ambient plasma ions participate directly in the tip heating by thermo-ionic effect even before the avalanche, which favors discharge.

5. Experimental results.

A - Discharge on the GaAs Solar array samples.

The test here presented was carried out using an absolute capacitance of 330pF polarized at -5kV. Various discharges were recorded in the inter-cellular gap (about ten). The profiles show potential before and after discharge. All the discharges recorded are only partial and the discharge current measured corresponds to the neutralization of the absolute capacitance charge.

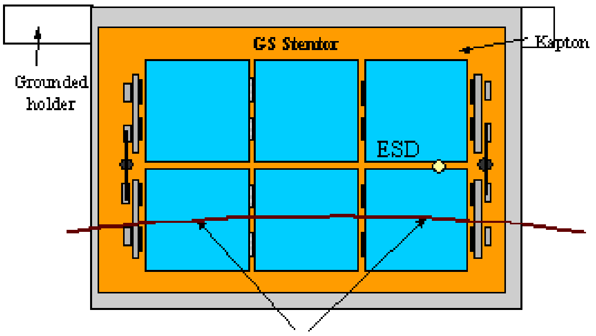


Figure 19 : Principle of Solar Array sample potential measurements.

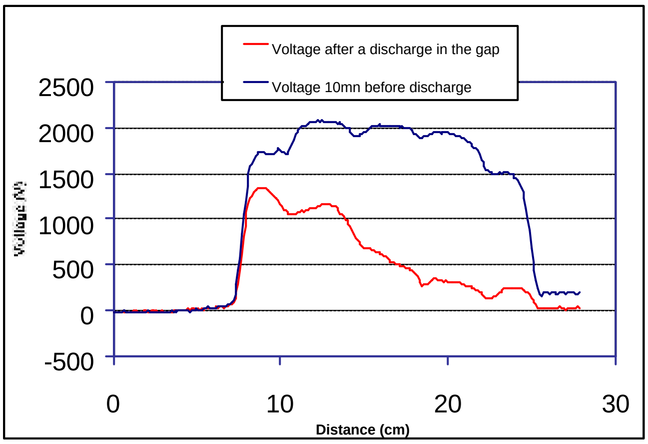


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Figure 20 : Solar Array sample potential measurements.

In none of the discharge experimental tests was the coverglass capacitance completely emptied.

B - Time interval measurement between the blow-off and flashover currents with an assembly whose collector electrode is a dielectric.

a - The experimental device.

A series of experiments was carried out using an epoxy support on which were placed two copper electrodes; on these two electrodes, two Teflon SSM substrates were stuck. This device is illustrated in Figure 22. The aim is to collect the flashover current using a dielectric electrode. The diagram of the wiring for blow-off and flashover transient detection is shown in Figure 23.

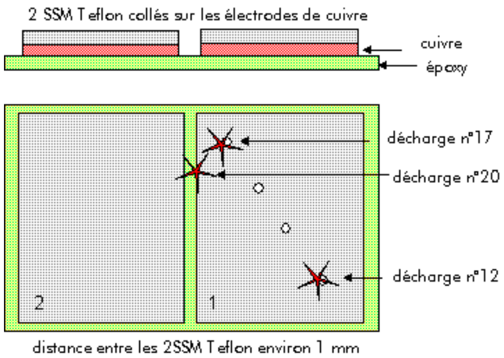

Figure 21 : Study device with 2 Teflon SSM substrates.

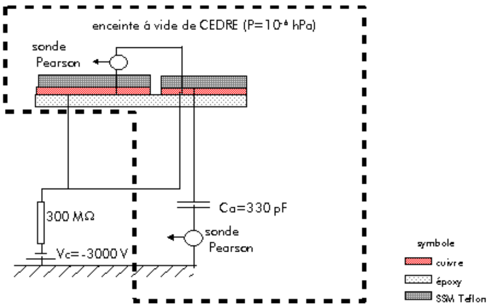

Figure 22 : Wiring diagram of study device with 2 Teflon SSM substrates.

b - Tests.

The video recordings enable the discharge sites to be located. The three discharges shown here took place at different distances away from the collector electrode. For these three discharges, the blow-off and flashover transients are shown in Figure 24.

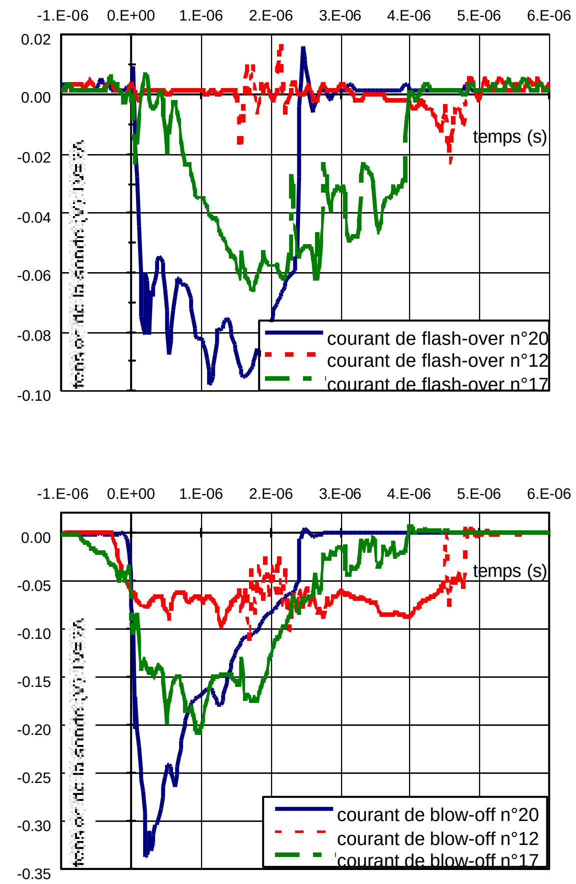

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Figure 23 : Blow-off and flashover transients of the three discharges.

c - Test summary.

The most important points derived from these tests are the following:

- Discharges transients, blow-off currents. Whatever the primary discharge site, the quantity of charges is about the same as that for the capacitance discharge Ca (330 pF) for voltage Vc (-3000 V).
- Discharge transients, flashover currents. The quantity of charges contained in the flash-over current transient collected is directly dependant on the discharge site and consequently on the distance separating this site from the SSM No. 2 collector electrode. The time interval between the signals is also directly dependant on this same distance. The interval corresponds to the expansion time of the plasma bubble emitted during the primary discharge towards the collector electrode. This time interval is:

- zero when the primary discharge is located on the edge (No. 20),
- small (≈1 µs) when the primary discharge is located near the collector (No. 17),
- larger (≈4 µs) when the primary discharge is located far from the collector (No. 12). Note that in this case

the flashover signal is weak and that the transient start is difficult to define.

It therefore seems very probable that it is the expansion of the plasma (V≈10 km/s) emitted by blow-off primary discharge which causes the flashover secondary discharge. This hypothesis is confirmed by the time interval between the two signals, a few µs, time required to travel the distance separating the discharges when the blow-off is located on one or other edge of the Teflon SSM.

C - *Electrostatic discharges on large samples.*

1 - Principle.

This experiment aims to determine which coverglass surface is concerned in an inverted potential gradient discharge in relation to satellite absolute capacitance value.

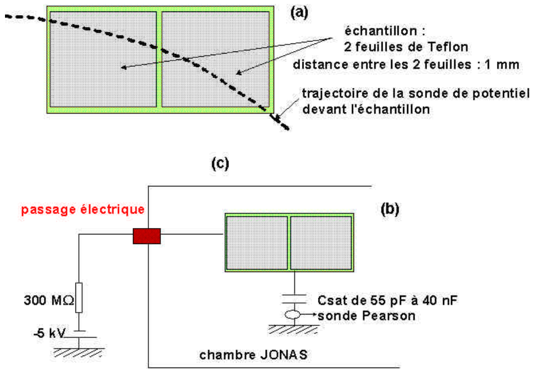

Figure 24: Diagram of large sample experimental principle

2 - Sample description

The dielectric material used is FEP Teflon®, 125 µm thick, aluminized on one face, called: Sheldahl® G400900. In order to correlate more precisely the discharge start with the potential probe trajectory, the sample is constituted of two sheets of Teflon® with dimensions of 21,7x28,5cm. These 2 sheets are fixed, metallization side, on a metallic support whose dimensions are analogous to those of the dielectric: the two short adjacent sides of the sheets are spaced out by about 1 to 2mm.

IVG irradiation conditions

The polarization applied on the sample is Vc=-5 kV. The power supply is decoupled from the rest of the assembly by a resistance of 300 MΩ: everything is placed in the vacuum room.

Results for Csat=55 pF, 330 pF, 10 nF and 40 nF

For the discharge to be treated, the location of this discharge must be situated between the 2 Teflon® sheets, and the optic signature must be evident.

Csat=	55 pF	330 pF	10 nF	40 nF
discharges	8	14	14	9

The results show that the charge potential reduction by the discharge is in direct correlation with the Csat capacitance value. The larger this capacitance, the larger the charge potential reduction. The two examples shown in figures 26 for Csat=330 pF, and in Figure 28 for Csat=40nF, show the extent of the charge potential reduction in relation to the Csat value.

Note that for the potential profile recordings, the polarization of -5 kV is brought back to 0 in order to increase the readability of the curves.

3 - Csat=330pF

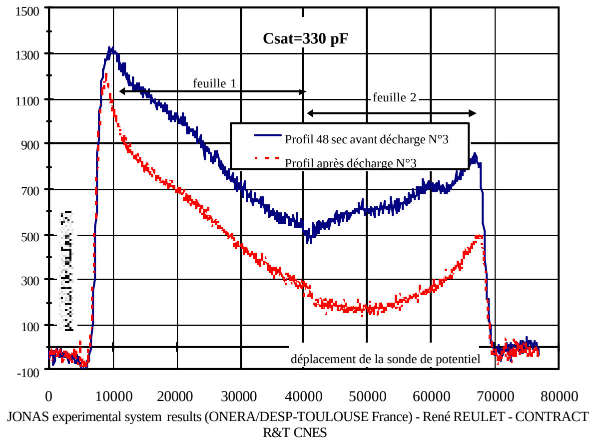

Figure 25 : Potential profiles before and after discharge. Csat = 330 pF

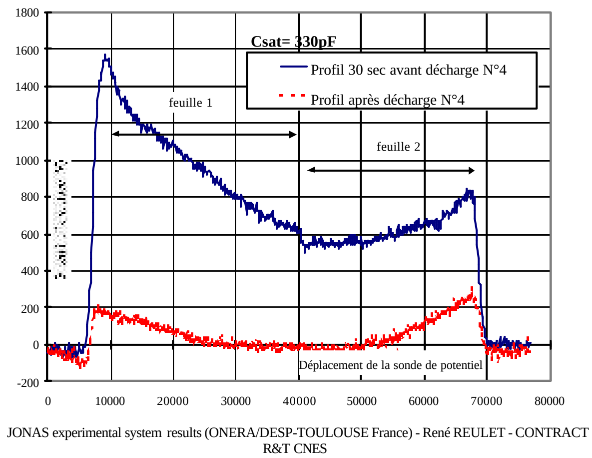

Figure 26 : Potential profiles before and after discharge. Csat = 330 pF

4 - Csat=40nF

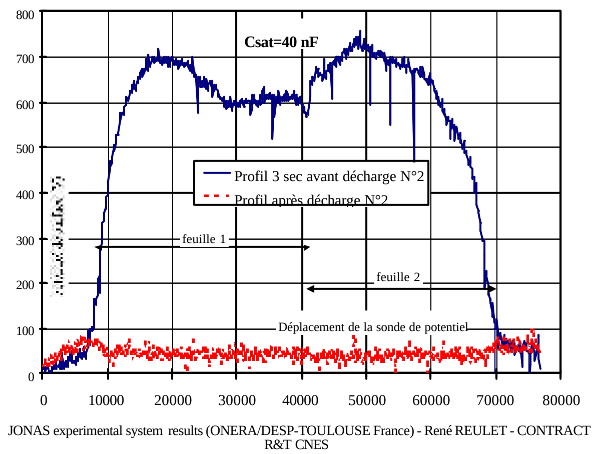

Figure 27 : Potential profiles before and after discharge. Csat = 40 nF

6. CONCLUSION.

This study has made it possible to present an original model of inverted potential gradient discharge applied to electrostatic discharges on solar arrays, representing the geostationary orbit. The objective was to determine the energy available at every moment of the discharge, in order to be able to reproduce the effects in the laboratory on solar array samples.

The solar cell test system deduced from this model and used in the CNES forms the subject of a poster presented during this conference (see article).

The important point arising from this study is that the test representativeness requires a satellite representative capacitance. The coverglass capacitance cannot be considered by simply adding it to the satellite capacitance, as that would remove all representativeness from the test. Indeed, the energy available and the speed at which it is released distorts the experiment.

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