SOLAR ARRAY TEST SET-UP PROPOSED BY CNES IN THE FRAME OF EUROPEAN STANDARDIZATION. PREVENTION OF SECONDARY ARCING INDUCED BY ELECTROSTATIC DISCHARGE

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Abstract: The validation of new solar cell for geostationary satellite application sets the problem of arcing between solar cells triggered by electrostatic discharges (ESD[1]). The main difficulty of a ground test is to properly simulate the transient behavior of one string from the first microsecond of an electrostatic discharge and to take into account all the energy stored on a panel that would be released during hundreds of microseconds. The test set-up to use, with all the physical data we need to take into account, to properly simulate the response of the string to an ESD, is presented in this paper.

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.

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 (Reference [1] presented at the 7th SCTC)– 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 capacitor of 100pF or one of 1µF, the result with regards to 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 set-up, which represents what the solar array comes across in the geostationary orbit. To finalise this test set-up, we had to know the error made when using a 4 cells sample instead of a real large solar array in terms of primary discharge representativity, available energy stored, and electrical response of the simulating circuit.

This paper will present electrical circuit needed to be representative of the flight configuration. It will explain how to make your own test set-up depending on the solar cells you want to use. This test set-up take into account the energy stored in the coverglass and the way it has to be released.

The solar array test set-up is proposed by CNES in the frame of the ECSS (reference [2]) for the European standardization. It does not take in consideration any commercial aspects or feasibility by such-and-such manufacturers. So one could imagine disagreements even oppositions to those propositions whom all are based on pure technical aspects. Although, the draft proposed is based on seven years of experiments (reference [3]), last one of which was shared with Japan to set basis of an universal standardization (reference [4]).

1 - INTRODUCTION

In the laboratory, the ESD tests on solar array samples raise the issue of the representativity in relation to the real flight configuration. Indeed, we have a sample of only several cells whereas we should effectively represent a string or even a complete section of a solar array in the process of supplying power.

In the secondary arc case, the energy is supplied by the cells themselves and the string outputs into the arc when the cells are illuminated. To carry on a representative test, we must therefore apply SA[2] voltage (to simulate the voltage

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[1] ElectroStatic Discharge

[2] Solar Array

difference between two adjacent cells at the end of the string), but also the nominal current circulating in the cell diodes (this represents the case where the solar array is in open circuit configuration and outputs into the cell diodes) capable of leading to short circuit configuration in several microseconds.

As the blow-off which is the initiating point of the primary discharge lasts only few microseconds, the response time of the system must be several hundreds nanoseconds. But, the best power supplies switch from voltage regulation to current regulation in 50 to 60μs. Additionally, the output capacitor of a laboratory power supply is generally several hundred microfarads to be compared with the value of around 500nF for a SA string. The overvoltage during the secondary arc is too high to ensure a good test representativity. We therefore have found a simple device, using the laboratory power supplies, which could deliver any current and any voltage in a few microseconds (reference [5]).

2 - THE RISK

On account of their complexity, there is always an electrostatic risk on Solar Arrays. In the event of an ESD, the integrity of the solar array is generally not affected during this discharge. The EMC[3] risks remain however high for the satellite as a whole. But, with the increase of the Solar Arrays power, we have seen the appearance of low-voltage arcs sustained by the photovoltaic power of the solar array (secondary arcs). These breakdowns have occurred between two adjacent cells generally those at the start and the end of the cell string where the voltage difference is maximum. The propagation of the current in the inter-cell vacuum is made possible in the plasma generated by the primary discharge (ESD). The secondary arc always exists for each ESD when it appears in a gap between two cells and reflects the circulation of a leakage current between the cells, in the primary discharge conductive plasma. However, whilst the current-voltage values are relatively low (typically 2A-50V), this discharge remains transient, does not lead to irreversible effects and remains therefore "invisible" to the experimenter.

The energy contained in a primary discharge comes from the electrostatic energy stored during the charging of the materials by electrons from the environment. It is low when compared with the secondary arc energy which comes from the solar array itself when it is illuminated.

We speak therefore of the primary discharge and not of primary arc (trigger) for the electrostatic discharge and the sustained arc or secondary arc when the arc is generated between adjacent cells and sustained by the SA[2] power.

If the solar array has no blocking diode on each cell string, the complete section can output into the conductive path between cells increasing the short circuit risk. In failure cases, the complete section is lost.

3 - ECSS DRAFT: SECONDARY POWERED PHENOMENA

3.1 - DESCRIPTION AND APPLICABILITY

Sustained ESD being fed from power sources on the spacecraft leads to an important additional damage mechanism since the power source may become permanently short-circuited. Systems affected include high power solar arrays and high power motors such as those which drive solar arrays.

In this article, requirements for solar arrays apply to any photovoltaic generator including substrates, coverglasses and interconnects.

3.2 - DEFINITIONS

3.2.1 - *General*

Electrostatic discharges can become sustained by being fed from power sources on the spacecraft. This leads to an important additional damage mechanism since the power source may become permanently short-circuited. Systems affected include high power solar arrays and high power motors such as those which drive solar arrays.

[3] *ElectroMagnetic Compatibility*

3.2.2 - *Primary discharge*

The discharge which is called "primary discharge" is the initial phenomenon that leads to an arc by creating a temporary conductive path (generally it is an expanding plasma bubble) instead of vacuum between two electrodes (polarised conductive parts).

3.2.3 - *Primary arc*

It is a breach of language, which should be avoided, generally used for primary discharge. Confusion is possible with the arc which is a part and the last phenomenon of an ESD.

3.2.4 - *Secondary arc*

The arc which leads to the term "secondary arcing" is the resulting phenomenon; the most part of the current which passes through the conductive path created by the primary discharge. This secondary arc is powered by an external source (for instance an illuminated solar array). Each time a primary discharge occurs where a secondary arc can occur, this secondary arc forms (a current flow through the temporary conductive path). Depending on its own energy release this arc can be self-sustained or not.

A **non-sustained arc** is a secondary arc that lasts only during the primary discharge (including the flash-over current). It extinguish when the primary discharge stops.

A **self sustained arc** is a secondary arc that lasts longer than the primary discharge including the flashover current.

A **temporary self sustained arc** is self sustained but it stops by itself even though the external power is still available.

A **permanent self sustained arc** is an arc that does not stop while the external power is available. The very intense current heat in the vicinity of the secondary arc creates a very highly conductive path by pyrolizing materials around the discharge site. When this conductive path is created, power is diverted from the arc and the arcing site cools. A stable permanent short circuit remains.

3.3 - TESTING OF SOLAR ARRAYS

3.3.1 - *Overview*

In addition to the surface charging testing also described in ECSS, the following testing requirements associated with controlling sustained arcs apply to solar arrays.

3.3.2 - *When to test*

Tests showed neither permanent short-circuit nor self sustained arc when the maximum voltage-current couple available between two adjacent cells on the panel, separated with 0.9mm as nominal value, was below the threshold in Table 1 (reference [6] & [7] and CNES R&T Experiments). So, the physical integrity of the used cells were not affected. Depending on their sensitivity electrical overstress effects on component have to be evaluated.

Voltage	Current	Comments
70 V	0.6A	No self sustained secondary arcing possible
50 V	1.5A	No self sustained secondary arcing possible
30 V	2A	No self sustained secondary arcing possible
10 V	No Requirements	Voltage is too low to allow any arcing between non pure electrodes

Table 1: Acceptable voltage-current combinations (gap at 0.9mm)

Further testing as specified hereafter shall be performed for arrays characterised by available current between two cells above the characteristics in Table 1 or with cell separation below 0,9 mm.

NOTE: *The voltage is the maximum voltage between two adjacent cells. It should included possible overvoltage when switching. The current is the maximum current that can flow through a conductive part of the array (usually the current of a single string if each is protected by a diode). The cell separation is the nominal cell separation and assumes a 20% variation about this value.*

3.3.3 - *Objective of the test*

Testing shall demonstrate that ESD primary discharge does not lead to a self sustained secondary arc and does not lead to the degradation of the solar array.

3.3.4 - *Creating the primary discharge*

Testing shall be performed on solar array coupons.

> NOTE: *This testing involves a carefully designed test procedure.*

The triggering of the primary arc should be performed using inverted voltage gradient conditions.

> NOTE: *Greatest realism can be achieved by using keV electron beams to produce charging and so to initiate ESD. It corresponds to the real case. Unfortunately electrons tests are not very productive and it is very difficult to obtain a lot of discharges in biased gap. Representative replacement test has to be defined (see hereafter).*

If other means of generating a primary pulse (e.g. with low energy plasma) are used, it shall be ensured that the size of the primary ESD is at least as large (i.e. resistance within the arc is at least as low) as that produced from the electron beam test.

The test shall show that secondary arcing do not occurs for others reasons than the test itself.

> NOTE: *Although the testing is directed at the most likely cause of a discharge, other triggers can exist, such as micrometeoroid or debris impacts.*

Any kind of triggering that can generate a conductive path between two adjacent cells may be used such that all the available current can flow through this path.

> NOTE: *The validity of this test is based on this rule. The reason is that the objective of the test is not to demonstrate that a realistic ESD cannot lead to secondary arcing but to demonstrate that secondary arcing due to any kind of primary phenomenon cannot lead to cells damages.*

If low energy plasma (temperature less than a few eV) is used to initiate the ESD, the inverted voltage gradient is obtained using plasma instead of vacuum in the chamber and the tests should be modified as follows:

- Modify the absolute capacitances representing the satellite capacitance and solar array capacitance in order to keep the same energy for the primary discharge versus time, since the discharge voltage will be lower.
- Verify that the plasma path impedance is of the same order of magnitude as for the electron beam irradiated inverted voltage gradient discharge i.e. $Z = Varc/Iarc = 1\ \Omega$ to $10\ \Omega$ which would allows all the nominal current to flow through the conductive path between cells.

Vaporisation of a filament (around 10 to 20µm diameter) may also be used to create a conductive path between cells.

> NOTE: *This experiment is simpler than the one using plasma because plasma, electrons and biasing voltage are no more necessary during the tests. On the other hand, the vaporised metal quantity is not easily quantifiable and the vacuum chamber has to be opened after each experiment to install another filament.*

Laser pulse is also able to create a plasma conductive path when vaporising a metallic target near the cells gap.

> NOTE: *The vaporised metal quantity is more easily quantifiable than in the previous test. It is probably the way to explore to define an easily realisable standard test.*

3.3.5 - *Description of the test*

The electron beam test should take place under vacuum in a test chamber with the following characteristics:

- vacuum in the chamber : around 10^{-6} hPa = 10^{-4} Pa (=N/m²),
- a power supply (SAS)[4] capable to reproduce the dynamic response of the array to transient short-circuits,
- high voltage cable feed-through (up to 5 kV) to be connected to the power supply and the coupons,
- non-interacting surface voltage recorders 0 to 20 kV for x-(y) scanning,
- simultaneous ESD current transient monitoring and recording,
- visual observation, photography, and video recording of the test sample during the test,

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[4] Solar Array Simulator

- high voltage power supplies (around - 5kV),
- low energy electron gun (e.g. 8 keV).

The test coupon shall be a flight-representative qualification coupon.

NOTE: As it is impractical to test full size solar panels in sunlight and under vacuum, a smaller test coupon is used. A specific attention shall be paid to the representativity of gap thickness where the minimum thickness in flight configuration shall be used.

The main features of the test coupon are as follows:

2 strings of 2 cells in series shall be bonded head to tail as a minimum.

NOTE:

4 cells allows to have a gap cross in the cells angles where the field configuration should be more favourable in the case of the normal gradient situation. A sample with only 2 cells can be considered. Unfortunately in that case, electrical damages on diodes are not always assessed as all the current does not systematically flow through it.

Solar cell string-to-string connections shall be opened and each string rewired so that the ends of each string can be connected separately at the connector.

The gap between the adjacent strings should be close to the minimum design gap agreed with the customer.

NOTE: This gap is normally about 0.5 mm.

The cells do not need to be illuminated, but the correct current and capacitance shall be simulated by power sources and external capacitors C_{SAT} and C_{SA} representing the satellite and solar array capacitances as shown in Figure 1 .

NOTE: When occurring spontaneously in space, a primary discharge arises from the discharge of the various capacitances on the solar array. A typical order of magnitude of the total absolute capacitance is 200 pF to 500pF under 3 kV (around 1 μC or 1 mJ).

Cells shall be already polarised during the test when the discharge occurs with the nominal current available at once.

NOTE: This condition imposes to have the string/section capacitance directly connected on the coupon sample through representative string/section inductances. It also imposes to have either the nominal current flowing through the cells diodes or part of the nominal current flowing through the cells diodes and the additional current (additional current string or whole section current) available in some hundreds of microseconds.

A minimum string current shall be set up before testing to ensure that cells diodes are conductive.

NOTE: This current is usually about 10 mA. The best representativeness is obtained when using the nominal string current if possible.

The capacitance of the missing cover glasses needs to be included in the test.

NOTE: The possible large neutralisation of the coverglass by plasma expansion has an effect on the discharge. Indeed, the current that heat the discharge emission site when emptying the coverglass capacitance lasts as much as the discharge progresses. Its duration is about some hundreds of microseconds (experiments are described in details in reference [3]. This current has an influence in the establishment of the secondary arc (it contributes to heat the emission point and generate plasma). It has been measured during 120µs which correspond to the neutralisation of our 1.4 meter length SA coupon at 10^4 m/s speed. The maximum current registered was around 3 amps and the shape was a triangle. One could imagine very large neutralisation on a real SA, even if in laboratory experiments involving a whole coverglass discharges were very rare. As a validation test standard has to represent a worst case, a 600µs current which corresponds to a 5m diagonal SA (a $3x4m^2$ size panel) is proposed, with a maximum current value of 6.5 amps (for further details see reference [4] presented in this conference). The effect of this large current on solar cells efficiency has to be tested.

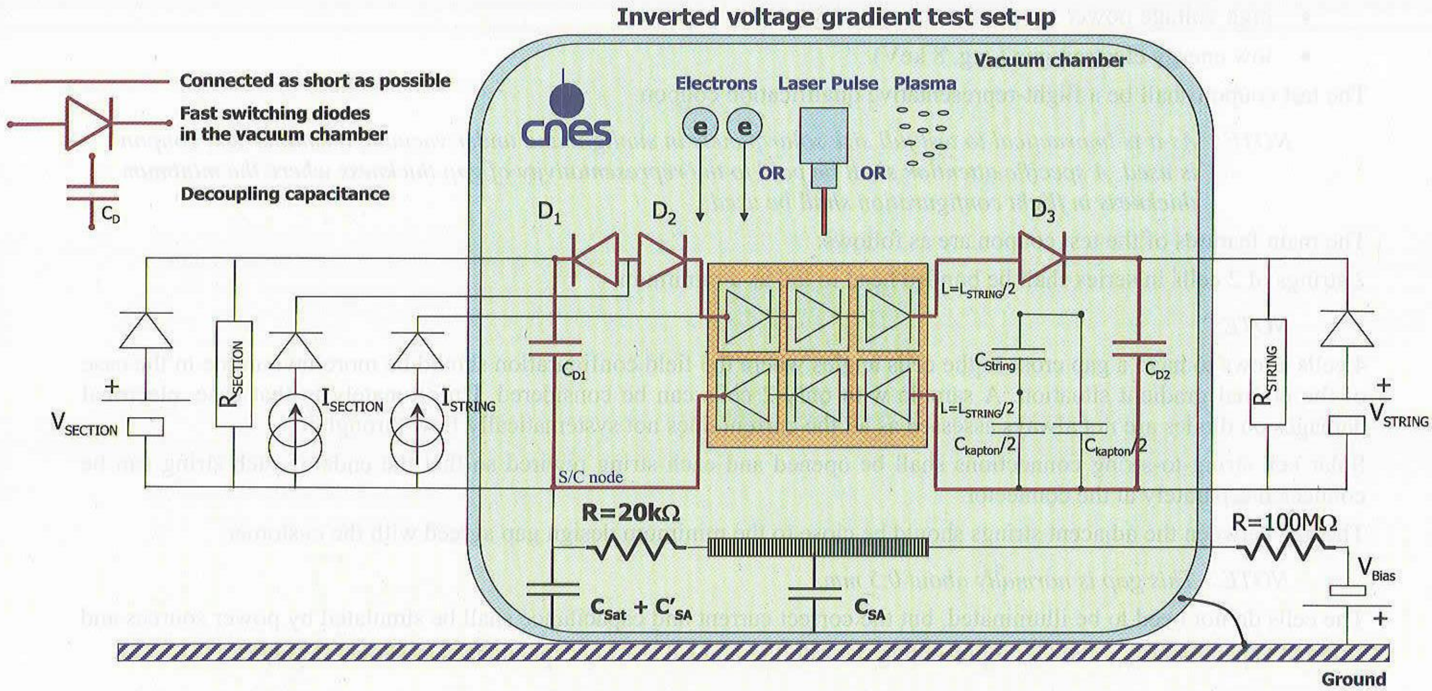

Figure 1 : Solar array test set-up

- All the stored energy in the various capacitors and the power delivered by the SAS shall be available within 500 ns.

NOTE: *At 10^4 m/s the plasma bubble reaches the opposite side of an intercell gap in less than 100ns. A discharge (in the inverted voltage case) lasts some microseconds. The reason of the requirement is that the deadline for the establishment of the nominal current is much lower than the discharge duration, i.e. around 1 μs. The set-up presented in Figure 1 allows reducing rise time below one microsecond as the wires length (the red circuit) can be easily less than 1m. Even in the case of SAS[4] with very short rise time, the wires length (above 1m) will not allow to have the whole current at the gap site in a sufficient short time.*

One could imagine using a very fast power supply connected to adapted coaxial lines which will allows some meters long wires. Any other set-up using simple wires run the risk to be too slow.

Control of inductance in the test

If only a part of the nominal current is flowing through the cells the remaining SAS power (from the current source called $I_{SECTION}$) shall be available during the duration of the primary discharge, the SAS inductance L_{SAS} and the wire length shall be equivalent to the string inductance.

NOTE: *Current below the nominal current can be used to polarise the cells when the Inverted Voltage Gradient Discharge method is used, to avoid heating the cells or when there are no blocking diodes and it is necessary to simulate a whole section.*

NOTE: $\tau = \frac{L}{R_{ARC}}$*, where τ is the discharge duration, L the wire length and R the arc resistivity. If we choose 1Ω for R to include all the possible cases, we obtain τ=L. For a length of two metres, it takes 2μs to obtain the nominal current.*

NOTE: *As it is in practice very difficult to reduce the length between samples in the vacuum chamber and the external power source even when twisted power wires or coaxial cables are used to reduce the inductance. This allows a longer distance between power supply and the solar array sample but it isstrongly recommended to use a set-up as presented in Figure 1 .*

Typical values of inductance are given in Table 2:

Type	Inductance
Simple Wire	2µH/m input and return
Twisted wires	1µH/m and no signal distortion when 100Ω to 300Ω adapted
Coaxial line	500nH to 1µH/m and no signal distortion when 50Ω adapted

Table 2 : Typical inductance values for cables

When all the nominal string current is already flowing through the diodes cells, L_{SAS}, and the wire length need not be controlled.

3.3.6 - *Success criterion*

Testing shall demonstrate that single or cumulative test secondary arcs of any type do not damage the solar array or the cells.

NOTE: Further details of possible test procedures for solar array simulators are described in 4 -

4 - ECSS ANNEXE SOLAR ARRAY TESTING

4.1 - SOLAR CELL SAMPLE DESCRIPTION

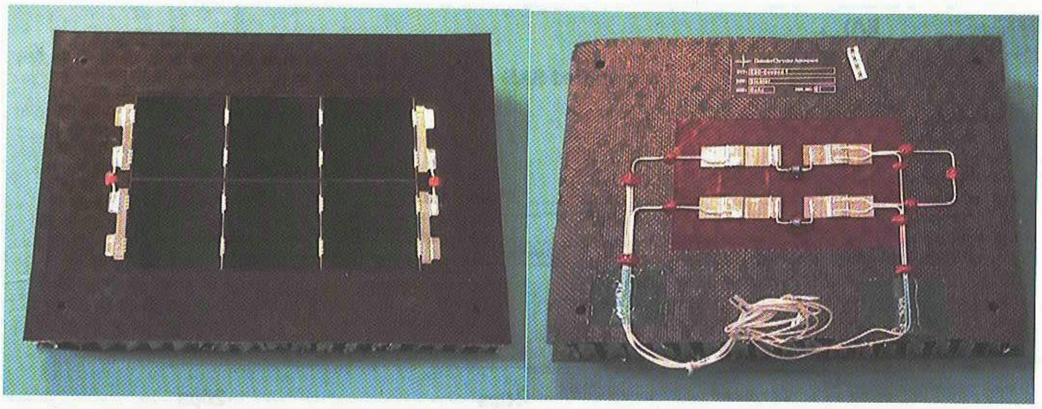

Figure 2 : Photograph of solar cells sample – Front face & Rear face (Stentor Sample. Picture from Denis PAYAN-CNES®).

The spacing between the cells is not constant as the assembly is done manually. It has been measured on the sample at various locations and is generally between 800 and 900µm. The minimum that will be used on board have to be tested.

4.2 - PRE-TESTING OF THE SOLAR ARRAY SIMULATOR (SAS)

A solar array simulator able to reproduce the dynamic response of an illuminated solar array to transient short-circuits between cells is needed for testing.

The dynamic response of the solar array simulator must be the same as the string response during the first microseccond. The quality of the solar array must be evaluated with a specific test set-up.

To test the time response of the various power supplies, the test set-up below can be used:

The test must be performed with the same wire length as used during the solar array test or, even better, directly in the vacuum chamber just before making the test. The real set-up is used and the real slope of the transient is known. We could suggest starting always with that kind of test to evaluate the effect of the set-up on the transient response of the solar array.

To evaluate only the power supply, a test can be done with a set-up with wire length as short as possible.

The success criterion will have been achieved when the transition is made in less than one microsecond.

The test procedure is described below:

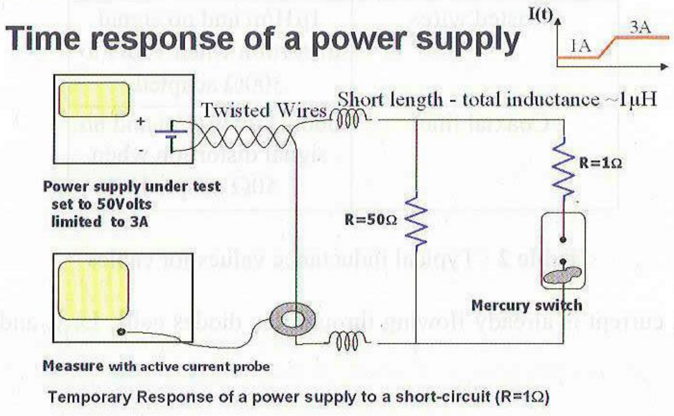

Figure 3 : Schematic diagram of power supply test circuit

The power supply voltage must be adjusted to 50V and the current limited to 3A. The current flowing through the 50Ω impedance is equal to 1A.

The 50Ω impedance is suddenly short-circuited with an 1Ω impedance (using a mercury switch to avoid rebound). The power supplies then switch from voltage limitation state to current state. We therefore see the current varying from 1A to 3A.

Wire length should be chosen so that total inductance does not exceed 1µH. If the wires are too long, the maximum rise slope that can be measured will be fixed by their length and the real rise time of the power supply will not be achieved.

Only power supply with very low output capacitor should be used. If it is not possible, an electronic current regulator should be used to conceal the capacitance.

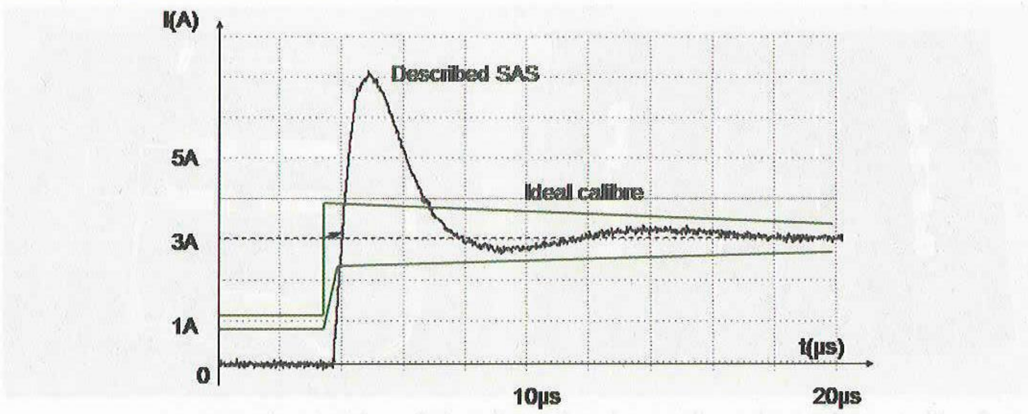

Figure 4 : Example of a measured power source switch response

4.2.1 - *Example of SAS that can be used*

Any kind of SAS meeting the success criteria at the gap site can be used. This one is given as an example.

This SAS set-up allows choosing both the voltage between the two end cells of a string and the current trough the cells.

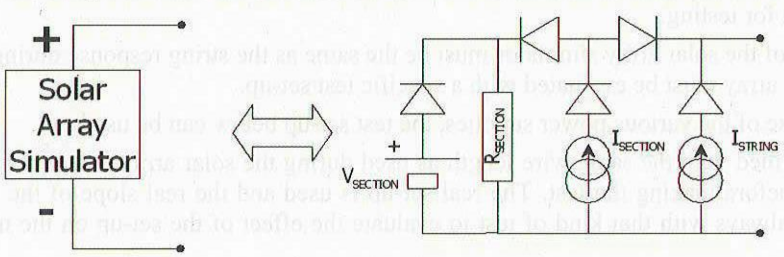

Figure 5 : Example of SAS that can be used

Details of this set-up are explained in Reference [5]

4.3 - Solar array test procedure

4.3.1 - *Preliminary measurements*

The test is performed respecting the following steps:

- Coupon preparation
- The solar cells' (I,V) characteristics are measured with the help of standardised flasher tests. Visual inspection and electrical continuity control are achieved.
- The gap size measurements between the strings are performed prior to ESD testing.

4.3.2 - *Test on biased Solar Array coupon in vacuum*

The test is described for inverted voltage situation by electron. When another method is used, this procedure shall be modified when necessary.

- Outgas the coupon in the best possible vacuum ($<10^{-6}$ mbar) for 10 or 12 hours.
- Apply the bias (-5 kV) to the coupon structure with a power supply through a resistor of 100 MΩ.
- Verify that no discharge appears (with the help of Pearson probes and video recording).
- Irradiate the coupon (solar cell side) with 8 keV electrons at low current density (few tens of picoamperes per cm²) to obtain the inverted voltage gradient until primary discharges appears (Another triggering methods are possible).
- Verify that at least 5 primary discharges occur in the intercell gap.
- After exposure, verify that all strings are isolated from each other and from the structure (nominal resistance is > 1MΩ).
- Power the solar cell string with an ESD representative Solar Array Simulator at nominal interstring voltage and nominal string current, including margin (TBD[5]) and the switching transients (overshoot) due to the power regulator operation.
- Record a few typical discharge signatures (I(t), V(t)).

4.3.3 - *Success criteria*

The test success criteria are be the following:

- Success in the standardised flasher test.
- Success of electrical continuity checks.
- Success of electrical insulation checks.
- Success of visual inspection (no visible degradation)

NOTE: Attention must be paid to the heating of the cells which generally forbid the inverted voltage situation. Thus it is generally not possible to bias the cell strings with the nominal current, so a low current source should be used for voltage biasing.

4.4 - Solar array test set-up

4.4.1 - *Electrical parameters of the coupon (Réf[12]).*

All the electrical parameters of the solar array string in its environment are carefully determined and simulated on the coupon.

[5] To Be defined

String and section voltages

String and section currents

Solar array absolute bias voltage (-5 kV as worst case for geostationary orbit)

Absolute satellite capacitance

- Spacecraft absolute capacitance Csat.

NOTE: This is the capacitance of the satellite structure to infinity. On the geostationary orbit 200pF is a typical value

- Solar array absolute capacitance C_{SA}.

NOTE: This is the capacitance of the panel structure to infinity. On the geostationary orbit 100pF is a typical value

We know today that the satellite capacitance plays a role of prime importance in the ignition of the inverted voltage gradient discharge and that its value is low (typically 300pF) (Ref [1]). We also know that the representativity is achieved by taking into account the true capacitance value of the satellite without adding the coverglasses capacitance in parallel to it. It would lead to false transient response.

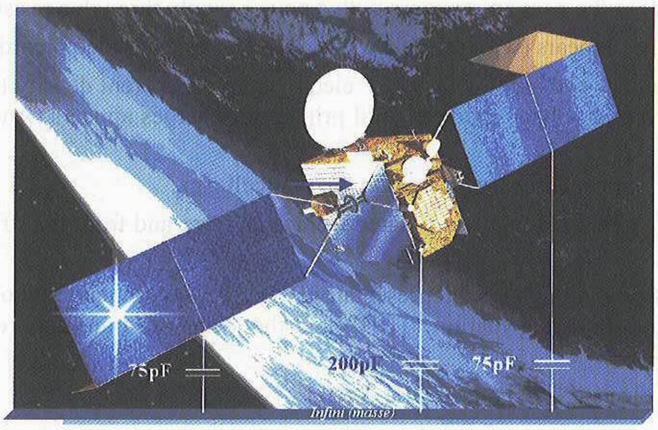

Figure 6 : Absolute capacitance of the satellite

Structure/string capacitance

Common mode capacitance measured between the short circuited solar cell string and the solar panel structure.

The Kapton® capacitance for one cell

For Kapton capacitance for one cell (typical value C_k=15 to 30 pF/cm².) deducted from the following formula

$$C_K = \varepsilon_0 \varepsilon_r \cdot \frac{S(m^2)}{e(m)} (F)$$

To get to the right value, network analyser measurements are recommended.

The Kapton® capacitance for one string (common mode capacitance)

For the capacitance through the Kapton for the missing cells, we need to evaluate the capacitance between the string and the structure through the Kapton. This capacitance C_{Kapton} is chosen at its highest possible value which is

$$C_{Kapton} = N_s \cdot C_k .$$

NOTE: The value is deduced from the capacitance underneath the cell across the dielectric (ie Kapton®).

The string capacitance (differential mode capacitance)

String capacitance: differential mode between the two ends of the string.
The capacitance of the missing cells chain is simulated by only one capacitance between the (+) and the (-) wires. In the case of a floating solar array structure (during fast transients, when there is a bleeder resistor), we can approximate the impedance of the SA by a capacitance:

$$C_{String}(V_s) = \frac{1}{2} \cdot \frac{\sqrt{C_k \cdot Cj(v)}}{th\left(\frac{N_s}{2} \cdot \sqrt{\frac{C_k}{Cj(v)}}\right)}$$

C_k = Capacitance through the kapton fo one cell

C_J = Junction capacitance for one cell

V_s = String voltage

v = Cell voltage $= \frac{V_s}{N_s}$

N_s = number of cells for one string

We need to take the right value of the Cell junction capacitance due to its non-linearity (estimation of the capacitance for voltage values between 0 and Vnominal).

$$C_J(v) = C_{Ttransition} + C_{Diffusion}$$

$$300nF < C_{Transition} < some\ \mu F$$

$$some\ \mu F < C_{Diffusion} < some\ hundreds\ \mu F$$

GaAs Cell *SI Cell*

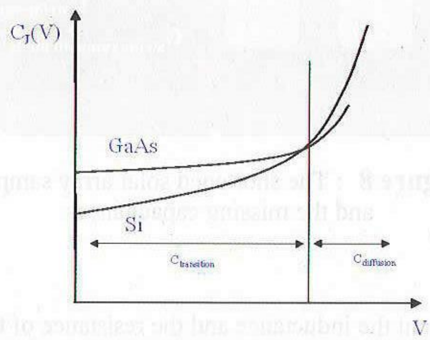

Figure 7 : Junction capacitance of a cell versus to voltage

- **For high value of C_J, (Si cells near Voc: open circuit voltage)** $\frac{N_s}{2} \cdot \sqrt{\frac{C_J}{C_k(v)}} < 1$ **then,** $\boxed{C_{string} \approx \frac{C_J(v)}{N_s}}$

As there are about one hundred cells per string, you have $C_c > 2500\,C_s$ **. This is the case when $C_{String\ Common\ Mode}$ is negligible; the equivalent capacitance of a whole string corresponds to the capacitances of all the cells (C_c) in series.**

- **For low value of Cj** $\frac{N_s}{2} \cdot \sqrt{\frac{C_J}{C_k(v)}} > 1$ **then** $\boxed{C_{string} \approx \frac{1}{2} \cdot \sqrt{C_J(v) \cdot C_k}}$

Most of the time, the Cj value is intermediate and one needs to use the complete equation for the capacitance.

String inductance.

The capacitors are put close to the coupon (on the rear face of the coupon inside the vacuum chamber), connected to the cells with simple wires. The length of those wires simulates the whole string inductance which typical value is below 1μH (which authorizes length around 1m)

Coverglass capacitanc

Coverglass capacitance is capacitance measured between the front face of the cell and the front face of the coverglass. This capacitance is not taken into account in the calculation of the spacecraft capacitance.

$$C_{\varepsilon} = \varepsilon_0 \varepsilon_r \cdot \frac{S(m^2)}{e(m)} \ (F)$$

This capacitance is evaluated for each coverglass. In fact it is hard to insert it in the test set-up. Caution: we cannot add this capacitance to the satellite capacitance. We cannot use a metallic electrode and we need to use a large enough dielectric for the tests. The best solution seems to use a power source between the "+" wire and an electrode beyond the cell. This source will deliver an equivalent current to the flashover current that would have been delivered when neutralising the coverglass.

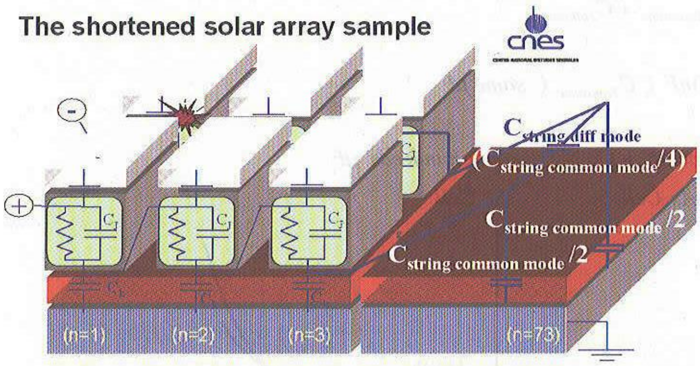

Figure 8 : The shortened solar array sample and the missing capacitances

4.5 - Others elements

To be realistic we need to take into account the inductance and the resistance of the string.

Inductance

All connecting wires used in the test set-up set inductances, which slow down rise time of current available for the secondary arcing. They must be representative of the flight configuration.

Resistances effects

The insertion of a serial resistance, during laboratory tests, in the loop of the secondary arcing allows sustaining the arc. It avoids under damping in the oscillating circuit and consequently avoids stopping the secondary arcing. (Its increase R with respect to L). However, to obtain a representative simulation of the flight configuration, this resistance shall be carefully chosen in order to have realistic behaviour.

In the real case, there are two serial resistances; the arc resistance (value is typically some Ohms) and the string serial resistance which value is lower. In fact, without any more information we consider that it is better not to add any resistance and let the arc developing its own resistance. When the string dumping conditions are well known, they can be simulated when inserting a pertinent serial resistance.

The following lines describe the total resistance effect on the sustaining conditions.

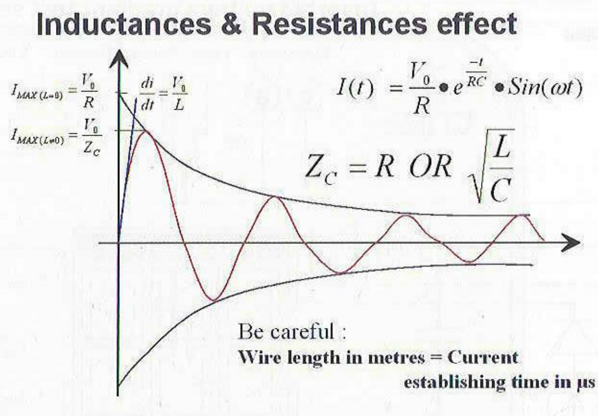

Figure 9 : Discharging circuit oscillations

Over damping condition if

$$R_{TOTAL} = R_{Added} + R_{ARC} > 2\sqrt{\frac{L}{C}}$$

If there is an added resistance to the discharging circuit, it will also affect the operating point on the discharge curve.

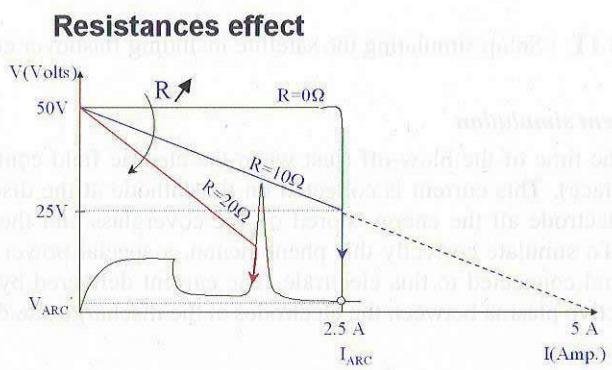

Figure 10 : Effect of an added resistance in the discharging circuit (SAS + resistance)

In conclusion, we must let the arc disconnecting if it is realistic.

4.6 - The solar panel simulator device

4.6.1 - *The test set-up*

The complete test set-up is presented below.

With such a device, it was possible to conduct electrostatic discharge tests in normal situation (the sample structure is connected to the ground and the dielectrics are charged) or in inverted voltage gradient mode.

Under certain environmental conditions, the satellite is charged negatively to several kilovolts and the resulting discharges are discharges of metallic origin when the structure discharges. In a laboratory, the representativity of such discharges is obtained by biasing the structure of the samples between –3500V and –5000V. The complete measurement and current injection device must also be referenced to this voltage. During the measurements, all the devices are thus strongly negatively biased.

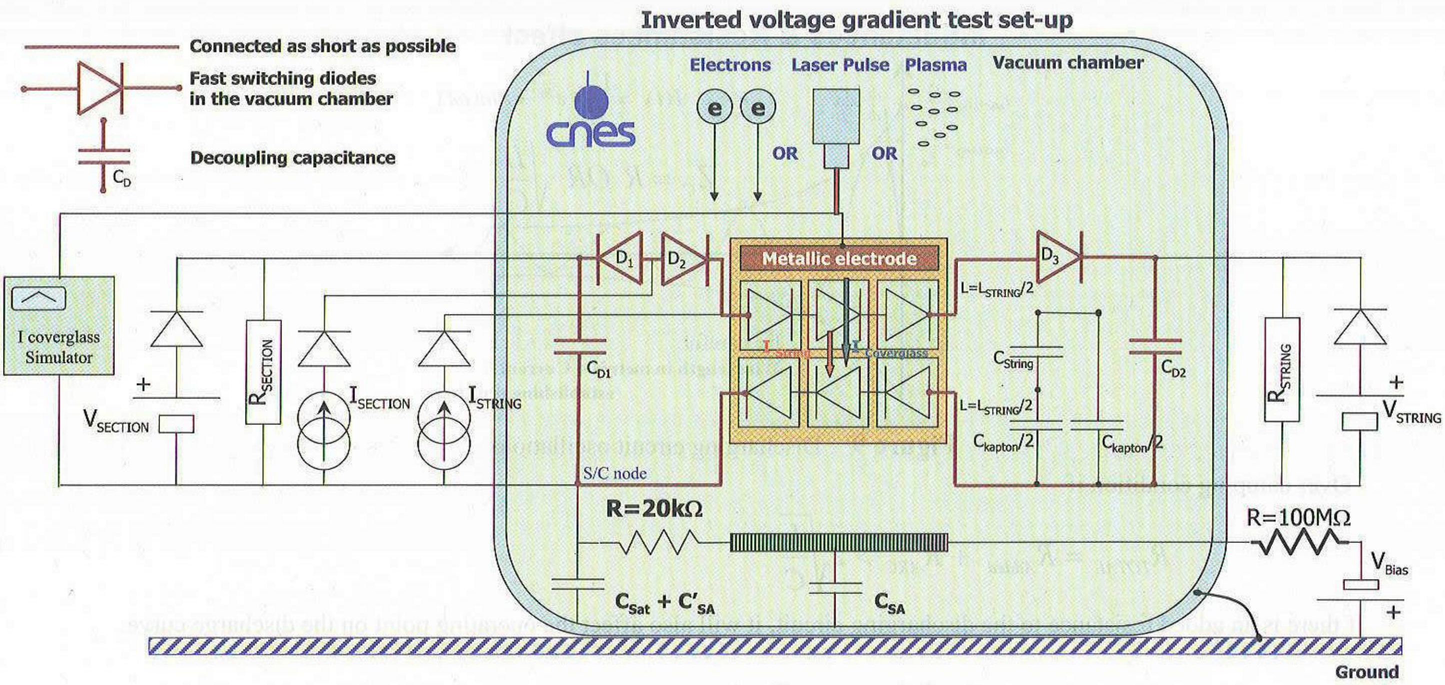

Figure 11 : Setup simulating the satellite including flashover current

4.6.2 - *The flash-over current simulation*

The flashover current starts at the time of the blow-off (just when the electric field configuration allows an electronic collection on the coverglass surface). This current is collected on the cathode at the discharge site. It is impossible to simulate with a single biased electrode all the energy stored on the coverglass and the way it is released during the neutralising plasma expansion. To simulate correctly this phenomenon, a special power supply delivering a triangular current shape has to be added and connected to this electrode. The current delivered by this source is supposed to be sufficient to maintain the conductive plasma between the electrodes at the discharge site during the flashover.

4.6.3 - *What is simulated and what is not, discrepancy with the real case*

This test allows to evaluate if the Solar Array is able to support without damage the self powered secondary arc in real space conditions. It reproduces as exactly as possible the real current shape which occurs during this phenomenon.

The current is perfectly representative of both what happens at the discharge site and the inrush current through the components when the discharge occur. However the direction of the static current through the diodes can be reversed compared with the real case depending where it happens. So component destruction due to an electrical stress shall be exactly analysed (especially when using fragile bypass diode).

In any case it could not be considered as an electrical susceptibility test which shall be done during a dedicated EMC test in air.

5 - CONCLUSION

The simulation of the solar array behaviour in flight configuration with respect to ESD and Secondary arcing risk allows to prove *a priori* its compatibility with geostationary charging environment.

To do so, we need to know all the physical processes leading to the secondary arcing.

It is very important to take into account:

- ❖ The response time of the power supply.
- ❖ The availability of the energy during the electrostatic discharge with respect to time.
  The structure voltage increase which drives the discharge and the energy distribution in time during an ESD of a 30nF capacitor biased at -500V (inverted voltage gradient due to plasma) will never be the same than the one delivered by a 300pF capacitor biased at -5kV (inverted voltage gradient due to electronic irradiation).

Nevertheless, the energy available is the same. Be careful to the representativity of the test set-up when using plasma.

- ❖ No need to hot up the satellite capacitance with the coverglass capacitance. Tests would not have been representative any more.

But you must pay attention

- ❖ To the different values of capacitances String, Satellite, Kapton
- ❖ To take into account the right value of the inductance and the resistance of a string
- ❖ To get the wire length and the capacitances position (the nearest the sample as possible) under control.
- ❖ To simulate correctly the role of the coverglass in the neutralisation phenomenon. One solution, if we need more, is perhaps to use another electrical circuit including a capacitor (the coverglass capacitance interested in the discharge),
- ❖ To the different EMC aspects.
- ❖ Transient currents measurements.
- ❖ Connect power supply structure to the sample structure

The aim of this ECSS is to recomend a solar cell test device to the manufacturers that represents what really occurs in flight on the geostationary orbit. For this, we needed to know the sequence of events which led to the failure, where the charges were stored and how the energy was released. It allowed us to know which elements were indispensable and which are not (Physical model of ref[1]). Also, the device had to be as simple as possible. It is according to this principle that we designed the CNES Solar Array Simulator and the test set-up associated.

With four laboratory power supplies (two of them having low output capacitors, HP™ SAS type) and some fast switching diodes, it is possible to correctly simulate the operation of a string (or even of a complete section) of a solar array faced with the secondary arc triggering risk during an electrostatic discharge or during the ignition of a thruster.

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