SECONDARY ARCS ON SOLAR ARRAYS : OCCURENCE, THRESHOLDS, CHARACTERISTICS AND INDUCED DAMAGE

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Abstract *: Secondary arcs have been triggered on dummy solar arrays as well as on real solar arrays. Their occurrence and temporal characteristics have been studied versus a series of parameters : Vs, Ilim, inter cell distance (gap), location of primary discharge, electrode material (copper, zinc, AsGa and Si cells). The arcs were characterized by means of electric records (arc and current voltage versus time), and by means of a spectrometer analyzing the species produced in the metal vapor of the arc. Very clear (and severe) macroscopic damage resulted on the samples that underwent well identified arcs: on those samples, there is material melting, burning, and loss of functionality. Nearly 200 arcs were obtained and analyzed : the laboratory findings, combined with the observation of satellites power losses in orbit, put the reality and the harmfulness of such arcs in space beyond any doubt. The study has produced lot of information about the nature of the secondary arcs, their voltage and current thresholds, the dependence of the voltage thresholds on the gap. The study has definitely improved the knowledge of the test procedure to be used in order to ascertain the solar array immunity against secondary arcs.*

1. Introduction

The most usual understanding of the process of ESD discharges related anomalies is that a dielectric is differentially charged by the environment up to a point where a spontaneous discharge occurs. This "limit point" is referred to as the threshold level, and according to laboratory experiments, ranges in the 5-10 kVolts for negatively charged samples, and to 0.5-1.5 kVolts for positively charged samples (inverted gradient voltages). Most usually, the damage caused by the ESDs is limited to disturbances and upsets which corrupt the nominal status of the logic circuits onboard satellites. Most of the time also, the corrupted systems are just upset, not broken, the disturbance is reversible and only corrective actions (ground telemetry) are required to restore the systems. In brief, ESDs are generally the sources of electromagnetic interference, but not of hardware damage.

On the contrary, secondary discharges or " triggered arcs" following ESDs have a much larger potential to cause considerable and definitive hardware damage due to the fact that they are fed by a renewed available energy. Vacuum arcs imply a permanent available energy dissipated within a formerly insulating medium (vacuum). They cause material heating, melting, non reversible and severe hardware damage.

This is specifically the case of solar arrays made of adjacent and biased cells covered with dielectric glasses: a primary discharge (ESD) triggers a subsequent arc, provided that certain conditions (reported in this paper) are met. Secondary arcs on solar arrays have received a sudden interest since they have been diagnosed as the most likely (power) failure mode of two geo stationary satellites (*Katz et al*, 1998; *Hoeber et al*, 1998). The failures (power losses) were well correlated with charging environments and occurred in the midnight-dawn sector where surface charging is well known to take place during sub storms. In the past, many other satellites suffered power losses, most probably from secondary arcs, although this was not completely understood at the moment.

This paper reports on a study entrusted by the European Space Agency (ESA) to the authors. The conditions for the initiation of secondary arcs, for their maintenance, and for their damaging potential was to be investigated. The influence of a series of parameters was explored : the nominal voltage and current, the gap distance, the cell material and technology, the primary discharge location. The investigation allowed many findings related to the arc initiation and characteristics, and also to the understanding of the basic processes involved. Consistently with this basic understanding, mitigation techniques appear very clearly.

2. The experimental approach

Figure 1 displays the basic test configuration. The samples (real or dummy cells) are electrically biased while submitted to charging by electrons in the inverted gradient mode.

Whenever an arc occurs, it is detected with a variety of electrical and optical signatures which are the **experimental outputs** :

-A current (Iarc) flows between the biased cells
-The biasing voltage drops from the pre arc value (Vs) to the arc voltage value (Va)
-Light is emitted from the primary discharge location and recorded by a video camera

-Light is picked up (in situ) by use of an optic fiber (in line with the gap axis) and fed to a spectrometer (to analyze the species contained in the arc vapor)
-Photographs are taken (ex situ) to show macroscopic or microscopic defects
-The (gap) insulation between the cells is measured
-These outputs are recorded for each discharge (see figure below) while a series of parameters supposedly critical to govern the occurrence and characteristics of the arcs are investigated.

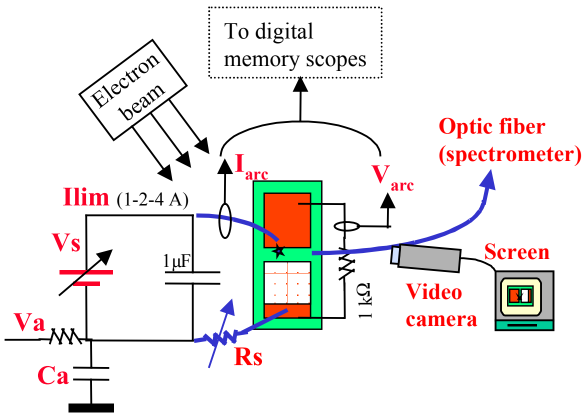

Figure 1: The basic experimental set up

The outputs displayed in the figure 1 (above) are recorded for each discharge while a series of parameters supposedly critical to govern the occurrence and characteristics of the arcs are investigated. The inputs for the experimental study were related to the sample (nature of electrodes, gap distance), to the external biasing system (voltage Vs; limit current Ilim, resistance in series Rs), to the primary discharge (magnitude and location) :

-The gap distance (0.5 –6 mm); the cell technology (AsGa/Si/Other :copper, zinc),
-Nominal voltage Vs (30-100 Volts) applied between adjacent cells,
-Nominal current I_{lim}(1-2-3-4 A): authorized to flow between adjacent cells to feed an arc.
-Resistance in series in the arc circuit Rs (2-20 Ω)
-The primary discharge magnitude (Va, Ca) and location (distance to "active" gap). (most usually Va = -3000 Volts; Ca = 10 nF; duration ≈ 25 µs ; location in the active gap).

The experiments dealt with real solar arrays and with dummy samples simultaneously.

The *dummy solar array* samples were made of copper (or zinc) plates simulating the cells, covered with insulating SSM Teflon (simulating the cover slides). Dummy samples made of copper (70 µm) have been made out of printed circuit epoxy boards. The gap distance was a "standard" 0.9 mm apart for a specific study where it was varied from 0.5 to 6 mm. Zinc samples were manufactured differently: 75 µm thick plates were glued on epoxy holders. *Real solar arrays* were made of AsGa and silicon solar. Each sample was specific with respect to its gap condition (see Figure 2).

• "**variable gap**" (DSS#1;5): the two cells are mounted on separate holders
• "**standard**" (DSS#2;4): the gap is ≅ 0.9 mm
• "**grouted**" (DSS#3;6): same as the standard with grouting added in the gap.

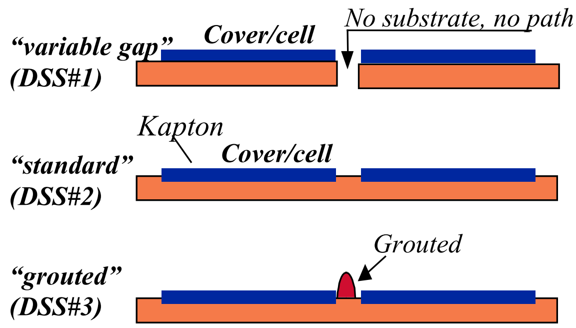

Figure 2: Solar array samples cut off.

3. Experimental results

3.1. Generalities

An extensive data basis was built, rich of 191 secondary arcs (Ns) that were triggered by 639 primary ESDs (Np) under a variety of biasing conditions.

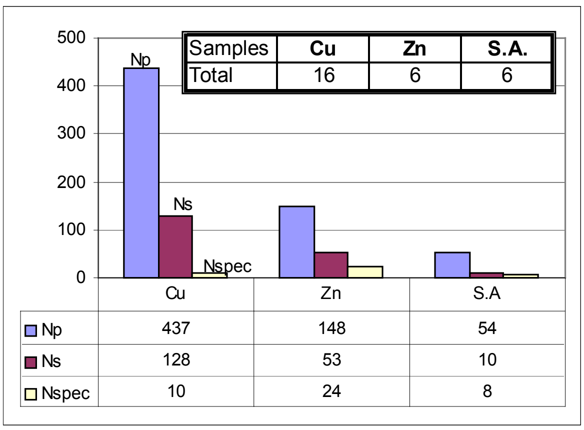

Figure 3: Overview of the data basis :
Np; Ns : primary and secondary discharges
Nspec : optical spectra **(**for all 28 samples).

28 samples have been studied, most of them being "dummy" samples (see figure 3b). A technique was used (treating the samples) to force the primary ESDs in the active gap where the bias is applied, and as a consequence, it has been very easy to obtain a lot of secondary arcs.

-A first very clear result is found : *In order to get a secondary arc, the first condition is to get a primary*

ESD in the "active gap" where the bias is applied. Then only after come additional conditions for the voltage applied and the current allowed to feed the arc.

-The primary ESD was kept constant by using an absolute voltage Va = - 3 kVolts and a Ca capacitance of 10 nF. In some cases a much lower value for Ca was used (330 pF) and secondary arcs were also obtained for Vs values of 100 Volts. But the incidence of Ca was not systematically investigated.

-A technique was successfully tried for the measurement of the arc voltage : it was indirectly derived from a current measurement across a resistor (1 kΩ; see figure 1) in parallel with the gap.

-The results found on dummy samples and on real solar arrays were very identical, but it has been much easier to obtain primary discharges on dummy samples (where we could do anything to favor the start of an ESD). On some real solar cells, it has been impossible to get primary ESDs (although the inverted gradient voltage was quite important and higher than 1800 Volts). As a consequence, we have much more arcs on dummy samples than on real cells.

-All of the 191 secondary arcs present in the data basis are those triggered by primary arcs in the gap.

3.2. *Arc current and voltage characteristics*

Figures 4a and 4b display a typical example of arc voltage and arc current characteristics : The voltage (measured across the gap) drops from the initial voltage value Vs (90 Volts) to a value Varc ≈ 40 Volts. The current starts from "0" to a value limited by the power supply. The remarkable features are the following :

-The secondary discharge current and voltage (red colored) duration is much longer than that (black trace) of the primary discharge alone (the arc "survives" after the ESD has gone).

-A peak in current (lower figure "b") is always associated with a pit in voltage (upper "a"; do not be misled by the aspect of the voltage where the voltage pits look like peaks).

-This shows very clearly the **unstable** nature of the arc made of successive ignitions and extinction. Only when the current is high (near the supply limited value 4A) and the voltage low (here ≈ 40 Volts) do we have an arc. In the 120 µs duration, we can identify very easily about 30 ignitions and extinction, but there can be more at a lower time scale. The fact is that such arcs are noisy and made of a series of short duration arcs living and dying until a complete extinction occurs (in a following section, we will see that the total duration of the arc is a direct function of the arc limited current). An other example of arc current and voltage is given in the following figure for a series of 6 arcs on real solar arrays.

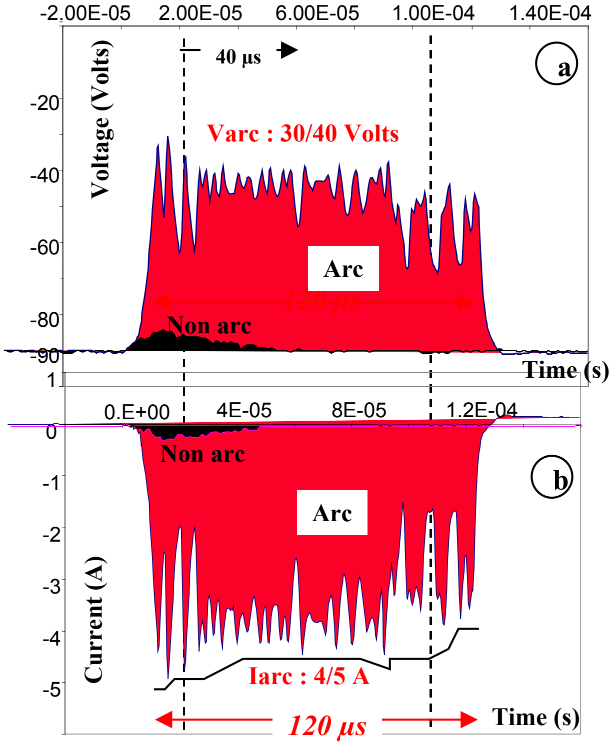

Figure 4 : Arc voltage Varc(t) upper(a) and **Arc current Iarc(t)** lower(b)

Dummy copper sample 70 µm; gap 2 mm ;
Vs = 90V; Ilim = 4A ; Rs = 10ohms; Ca = 10nF

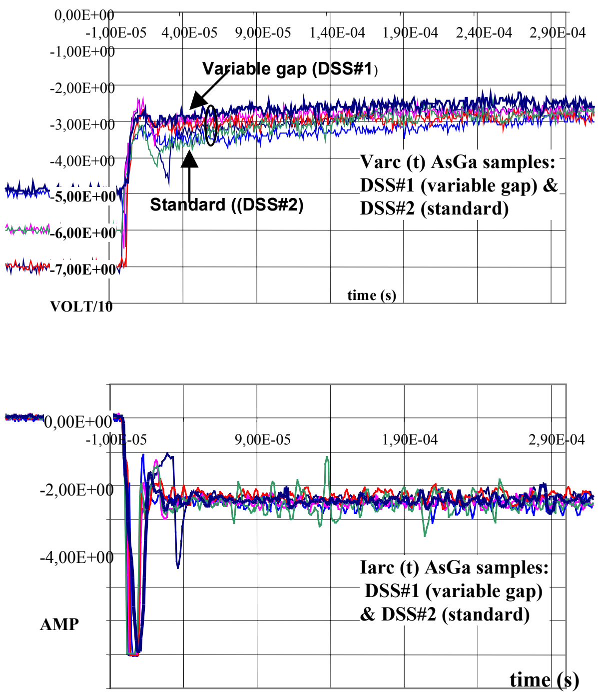

Figure 5 : Varc(t) & Iarc(t) (6 discharges)
(for samples DSS#1&#2; 50-60-70 Volts; 4.5 Ω; 3A)

Records from two AsGA cells samples have been accumulated on figure 5. Five of these discharges were obtained on the "standard" sample (gap 0.9 mm), and one on the "variable gap" sample set at a gap of ≈ 1.1

mm (See previous section §2). The six accumulated records are remarkably identical, although they were obtained with different initial voltage values : 50-60-70 Volts. Not shown on the records is the total arc duration which ranges from 1 to 9 ms. The current limit was set at 3 A. Some noticeable features are listed:

-Although the records of the arc voltage start at different values (depending on Vs), when the arc is set, the arc voltage drops to a value that seems a constant ≈ 25Volts. The arc vacuum theory states for such "constants" specific for a given material.

-There is no difference between the samples, indicating that the arc process does not depend on the substrate (insulating Kapton). In the case of the "variable gap" sample, there is no substrate, at least not in the gap area.

-The arc current is about 2.5 A, lower than the setting of the current limit 3A, excepted at the start of the arc.

-The current and voltage records are noisy, although it seems less obvious than in figure 4.

Damage has resulted from these discharges to both samples, and hence also to the "variable gap" sample which underwent only one arc.

3.3. *Voltage threshold*

The **voltage threshold** depends on the gap. See figure 6 for gaps from 0.5 to 6 mm on Cu samples.

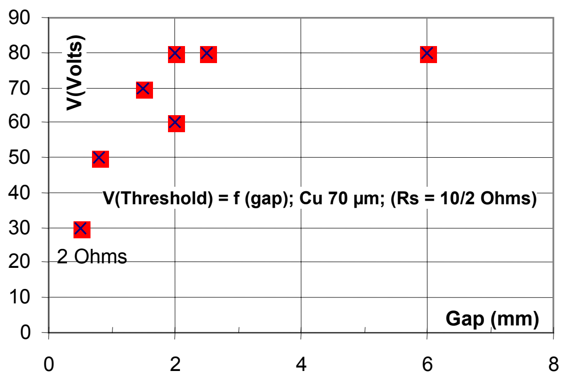

Figure 6: Voltage threshold (for initiation) as a function of the gap (copper 70 µm; Ilim 4A)

The threshold is as low as 30 Volts for a gap of 0.5 mm. It then increases rapidly with gap distances up to 2 mm, and stabilizes after. Beyond this threshold of 2 mm, and up to 6 mm, there is no further gain in the threshold. In all cases tested, 80 Volts (associated with a current of 4A) **is absolutely not safe**.

3.4. *Arc duration (and damage)*

The **maintenance of the arc, its duration,** and hence the induced damage, depend on the current limitation. The highest the current, the longest the arc (and the more the damage). In **Figure 7** the arcs are sorted by duration against the current limit **Ilim**.

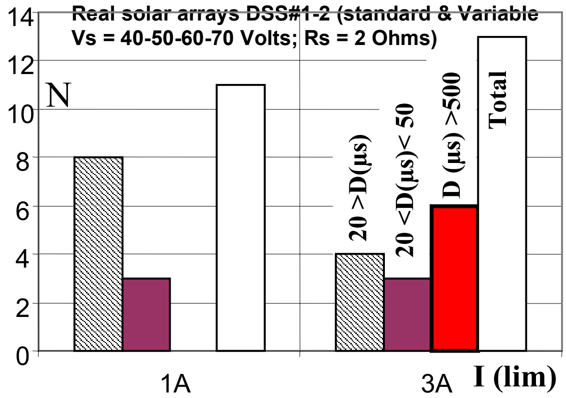

Figure 7 : Number of arcs N (D, Ilim) (AsGa samples DSS#1-2)

On **Figure 7**, (Asga cells), arcs lasting for more than 500 µs are seen only when the current limit is shifted from 1 to 3 A. The same is true with zinc samples : arcs with duration D>60 and D> 500 µs appear only when the current limit is higher than 1.5 A.

3.5. *Damage on samples:*

Photographs have been taken at microscopic and macroscopic scales. Arc induced defects are shown on two different samples below on the figures 8 and 9.
A full series of well documented photographs have been published in the ESA contract report (*ONERA/DESP Ref : TN8; Sept 2000, ESA Under Contract No. 13607/99/NL/SB*).

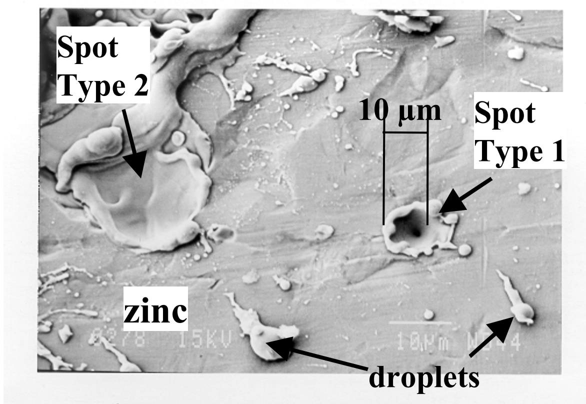

Figure 8: Zinc dummy sample #21 (50-100V - 2A) ;

On figure 8, cathode spots have been photographed by means of SEM microscopy on Zinc dummy samples. These microstructures (cathode spots) are typical of those involved in vacuum arcs where micron (or 10 micron) sized structures are the signature of the melting of the material due to the flow of the current in restricted areas and intense local heating. These microstructures (together with the detection of metal vapor) are one of the most obvious evidences that secondary arcs are vacuum arcs, although the term vacuum arc is not quite adequate since the arc develops in fact in the vapor produced by the electrodes (with high pressures localized on the cathode spots).

On figure 9, obvious damage is shown in the gap between the cells where the gap insulation is not anymore kept at the initial level.

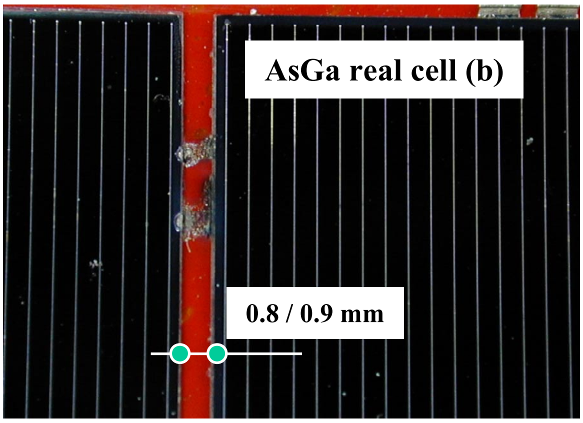

Figure 9 : AsGA sample DSS#2 (50V - 3A)

This kind of damage is caused by these well identified arcs with duration (≥ 60 µs) higher than the primary ESD (≈25 µs). But microscopic damage is also caused by events that were not at the moment recognized as arcs due to their very short duration. The conclusion here is that no ESD in the active gap should be considered harmless.

3.6. *Optical spectra* :

Optical spectrums (42 in total) were obtained on all the tested samples when secondary arcs were triggered. Metal vapor from the electrodes was clearly detected : Cu and Zinc "sensitive lines" on dummy samples, Silver, Germanium, Arsenic and Gallium on AsGa solar cells samples (see figure 10 below).

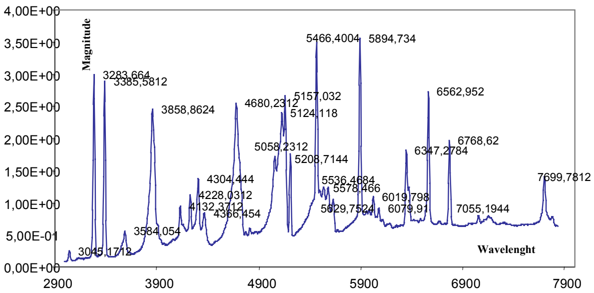

Figure 10: Optical data on AsGa solar cells

4. Summary of results and discussion

4.1. *About the nature of secondary arcs*

Secondary arcs are « **vacuum arcs** ». The appellation « vacuum » is misleading, because such arcs develop in the metallic vapor produced by the electrodes heated by the high density currents on local and tiny microscopic spots called "cathode spots". The vapor is emitted as ionized vapor jets and the optic spectrometer reveals lines (wavelengths) specific of the metal electrode. These specific lines were found on all the studied samples : Copper and Zinc were identified on the dummy solar arrays (made of copper or zinc) , and silver, germanium and arsenide were found on AsGa solar cells. The common characteristics of vacuum arcs are : self sustaining ability; electrode material melting; metal vapor detection, cathode spots, electromagnetic noise. Since vacuum arcs belong to a well identified field of the physics -and is covered with many studies (books, articles, thesis..)- , the finding is full of signification. Nevertheless, the vacuum arcs in the dedicated literature deal with much higher currents than those available from solar arrays. This explains why our records are not quite typical of vacuum arcs. Secondary arcs on solar arrays obtained at low currents are most of the time aborted arcs with limited duration. The arc duration D is precisely a very dependable function of the available current **Ilim**.

4.2. *About the arc initiation and maintenance*

-The initiation depends mostly on the occurrence of a primary discharge at a **specific location** -the active gap- where the voltage Vs is applied, and not anywhere.

-It then depends on a **threshold value** of the voltage **Vs** applied across the gap and of the **current limit Ilim** associated to the supply, and of the value of the **gap**.

-Although the study is not completely conclusive on this aspect, the initiation **does not depend** on the value of the **absolute capacitance Ca** (we have got an example of a secondary discharge triggered with a Ca value as low as 330 pF).

-The arc duration (maintenance) depends mainly on the available current Ilim. The higher the current, the longer the arc duration.

To summarize, for an arc to occur, 3 conditions must be filled simultaneously : (1) the primary discharge must take place in the gap, (2) the voltage bias and (3) the current must be higher than a threshold. Because the investigated range of currents was limited to (1-4 A), most of our secondary arcs were "aborted arcs" with limited duration.

4.3. *About the arc characteristics*

Once an arc was set under a certain voltage bias condition **Vinit**, it required a lower voltage **Varcst** to be maintained. **Varcst** is also lower than the usual nominal voltages of solar arrays. On the contrary, it required a high current (> = 2A) to be maintained –at least to last for hundreds of microseconds- and to show obvious damage visible at naked eye. For currents (<=2A), the arc duration was limited. The table 1 gives a first view of the voltage thresholds (for initiation) and of current threshold (to maintain an arc for a duration > 50 µs). The table gives also a value labeled **Varcst** which is the arc voltage when the arc is set.

Table N°1 : Current and voltage steady state values (after initiation) Voltage threshold (for initiation)

	Copper	Zinc	AsGa
Voltage threshold (**Vinit**)	30-80*	40**	50**
Iarcst (A)	2.4	1-1.5	2.5
Varcst (V)	16	14	24

*= variable gap 0.5 à 6 mm ; ** = gap 0.8-1 mm

Because **Varcst** is a physical constant depending on the electrode material, it can be speculated that it represents an absolute and extreme limit value for the secondary arc prevention. This means that **Varcst** (for instance 24 Volts for AsGa cells) is already too high a value for a safe design.

4.4. *About the induced damage*

There is no question that well identified arcs with duration (D>100µs) are very damaging. Even for those "events" not clearly identified as arcs at the moment, there is damage caused to the sample. The only difference is the scale of this damage, at the scale of the so called cathode spots, in the microns range.

4.5. *About preventing the arcs*

The bias voltage between adjacent cells should be lower than the threshold voltage for initiation Vinit (table 1), and probably also lower than Varcst, the arc voltage constant value. The current allowed to flow should be lower than Iarcst (table 1). Playing with the gap distance should not be disregarded, at least to restrict the allowed tolerances with respect to the nominal value. The grouting technique (tested on sample DSS#2; figure 2) appeared quite effective.

4.6. *About the usefulness of data on dummy cells*

We state that data from dummy and real solar arrays are consistent with each other. All the arcs are governed all by the same physics of "vacuum arcs".

5. Conclusions and recommendations

This study has clearly stated in the laboratory the existence of damaging arcs triggered by electrostatic discharges on biased adjacent solar arrays. The laboratory findings, combined with the observation of satellites power losses in orbit, put the reality and the harmfulness of such arcs in space beyond any doubt. This study contributed to a better definition of how solar arrays should be protected against arcs occurrence and how they should be tested in the laboratory. Testing of solar arrays at the laboratory should comply with a number of conditions : (1) only primary discharges in the gap must be considered; (2) representative solar array simulators should be used rather than power supplies; (3) The solar cells submitted to tests should be selected with the lowest possible gap distance (worst case approach); (4) The cumulative effect of primary discharges (aborted arcs) should be regarded in terms of damage and functionality

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