In-flight and laboratory evidences of ESD triggered anomalies and secondary arcs

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Abstract. At least two in-flight anomalies have been identified as related to event-triggered discharges, one of the initiating cause beeing photoemission and the second a local sudden pressure pulse due to a thruster firing. Triggering events such as photon illumination, micrometeorid impact, plasma and/or pressure pulse have been identified. On an other side, when a primary dielectric discharge occurs in the vicinity of biased electrodes, a full insulation breakdown or a damaging secondary arc is likely to be triggered. This phenomenology has now been clearly expertised as the cause of power losses having recently occured on geosynchronous satellites. Past and more recent experimental results are presented.

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 refered 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).

There is however an alternative process : the sample might be charged not to the so called threshold level, and the discharge still happens, caused by an external event, a "trigger". The trigger might be an event due to the normal operation of the satellite (thruster firing for instance) or a totally external event (micrometeoroid impact) or simply a specific condition as for instance the satellite sun aspect. After anomalies were recorded in flight and after some "triggers" had good reasons to be suspected, experiments were conducted in the laboratory : "events" were created on previously charged samples (or in their vicinity). The precharge level was set just under the spontaneous (so called threshold) discharge level, or, when the event was a very efficient trigger, well below. Many of the suspected triggering events eventually ended as rather (and sometimes very) efficient mechanisms (*Levy et al*, 1991a, 1996) .

In the course of this research, unexpected secondary arcs happened to settle between biased vacuum isolated plates : a primary dielectric discharge could bridge the plates and cause their full vacuum breakdown (*Frederickson et al*, 1990). This article is also dedicated to *secondary arcs*. But what is an "arc" with respect to a dielectric "discharge" ?

The difference is that the dielectric discharges we mean in the "ESD" context are generally energy limited. A charged dielectric is only likely to dissipate the energy it has accumulated (as a charged capacitor). And the consequence of such a discharge is "only" to induce a so called anomaly, generally an uncommanded switching event. Fortunately, most often, a dielectric discharge does not cause any harware damage. On the contrary, an arc implies a permanent available energy dissipated within a formerly insulating medium -for instance vacuum- that has suddenly been made conductive. It often implies also material heating, melting, unreversible and severe hardware damage. Secondary arcs occur between conductive electrodes biased with power supplies. They are an obvious example of triggered (arc) discharges, and moreover, they are "arcs", different in nature from the dielectric discharge they were triggered by. In this article, the terminology is the following : a dielectric discharge is a discharge on an electron bombarded dielectric, an arc is a discharge between metallic plates (or electrodes) biased by means of a power supply. A primary dielectric discharge may trigger either a secondary dielectric discharge (same nature) or a secondary arc (different nature). Secondary arcs have recently been diagnosed as the most likely failure mode of the solar arrays of two geostationnary satellites (*Katz et al*, 1998; *Hoeber et al*, 1998). The failures (power losses) were well correlated with charging environments and occured in the midnight-dawn sector where surface charging is well known to take place during substorms.

Secondary arcs appeared in a number of circumstances as accidents, hampering experiments in their specific objects. In some cases, they were thoroughfully reported well before the recent failures brought them into the news. The purpose of the section on secondary arcs is to show they are generic, not specific. And to suggest they probably still have the potential to jeopardize the nominal operation of future space systems.

2. Secondary arcs on experimental set-ups

Secondary arcs appeared accidently in the course of an experiment dedicated to the study of the dielectric discharge propagation (*Levy et al*, 1991).

2.1 Dielectric discharge propagation

Figure 1 features the basic characteristics of the set-up which is designed to study how a discharge propagates from one sample to the second.

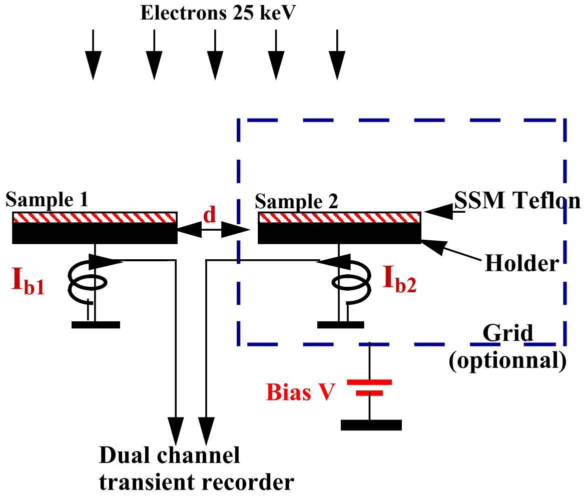

Figure 1 : Experimental set up with two holders

Two samples of (30 x 51) mm2 metallized Teflon (125 µm thick,) used as SSMs on satellites (Second Surface Mirrors) are mounted on two holders and exposed to charging by an electron beam of ≈ 20 keV, 1nA/cm2. One of the samples can be completely enclosed in a grid which provides shielding against electromagnetic fields. The grid can be grounded or biased positively or negatively. It is sufficiently transparent that the charging by the electrons is possible. The distance d between the holders is variable from zero to 50 mm. Each holder is grounded through an induction current probe to monitor a discharge current. The current probes deliver outputs of 1 V/A, both recorded on a dual channel memory scope in a single pulse recording mode. A non contacting surface voltage probe is used to scan the two samples. When a discharge occurs, there are two recorded pieces of evidences: the surface voltage profile modification, and the discharge current transients. Two series of discharges were performed. First, with no grid, the distance d between the samples was set to 7, 16, 36 and 51 mm. The rate of coupled arcing and the time between the onsets of the two discharges were studied versus the holder-to-holder distance. Second, at a fixed distance of 16 mm where the discharge of one of the samples always triggered the discharge of the second (≈ 100 % coupled discharge occurence), a grid was added around one of the two samples. The grid acted as a screen against electromagnetic fields, and, when biased, against the penetration of charged particles from the "free" to the "enclosed" sample.

Without grid, the first very striking result is that most of the discharges propagate from one of the samples to the second. The rate of "coupled discharges" is ≈ 100 % for a distance d as high as 16 mm. This rate is reduced to 90 % at 36 mm, and to 45 % at 51 mm. So, structural continuity is not required for a discharge to propagate. The coupling indicates some form of communication accross the gap, the nature of which might be determined later by the screening action of the grid. The second result is that there is a time delay between the onset of each discharge.

Figure 2 is an example of the discharge transients simultaneously recorded for d= 16 mm.

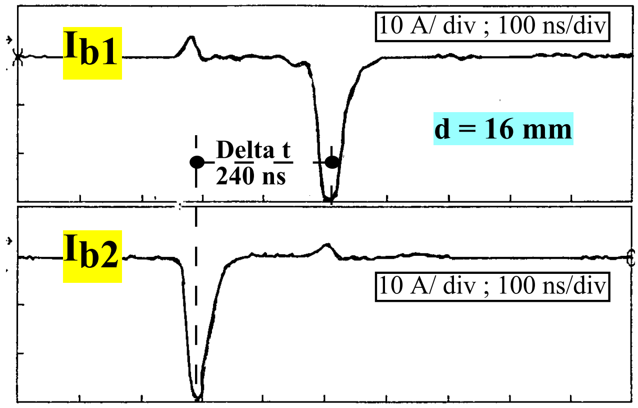

Figure 2 : Blow off transients
(one discharge -sample n°2- triggers a second -n°1-)

The upper part is the current transient (blowoff) of sample 1, and the lower part that of sample 2. A time delay is observed, either positive or negative depending on which of the two samples discharges first and triggers the second. Series of discharges were made in order to study this propagation time, which, for a fixed value of the distance d could vary statistically. From these data, a velocity ranging between 30 and 100 km/s is drawn. This velocity is not the discharge propagation velocity on one sample, however, the two velocities are not very different.

With a grounded or negatively biased grid, there is no notable difference in the rate of coupled discharges. The two samples "communicate" just like when there is no grid. With a distance d = 16 mm, in a series of 11 discharges, 10 were "coupled discharges".

With a positively biased grid, there is a marked difference: the rate of coupled discharges is reduced to 43 % (6 out of 14) at +2 kV, and to 24 % (4 out of 17) at +5 kV. The conclusion was then reached that ions emitted during the discharge were responsible for the propagation, and the expectation was that rising the grid potential to a sufficiently high positive value would completely inhibit the propagation. This hypothesis could infortunately not be confirmed since the rising of the grid voltage resulted in secondary arcs between the grid and the grounded holders. No special attention was paid at this moment to the secondary arcs.

2.2 Interwined biased electrodes

Secondary arcs appeared also accidently in a different experiment aiming at the capture of the plasma emitted by a dielectric discharge (*Frederickson et al*, 1990). Figure 3 is a simplified schematic of a different experiment. Polyethylene terephtalate (PET) foils are exposed to 25 keV electron beams through a set of biased parallel plates. The irradiated surface rises to roughly -15 kV and a discharge spontaneous occurs on the dielectric surface producing a plasma which the electrodes system try to size.

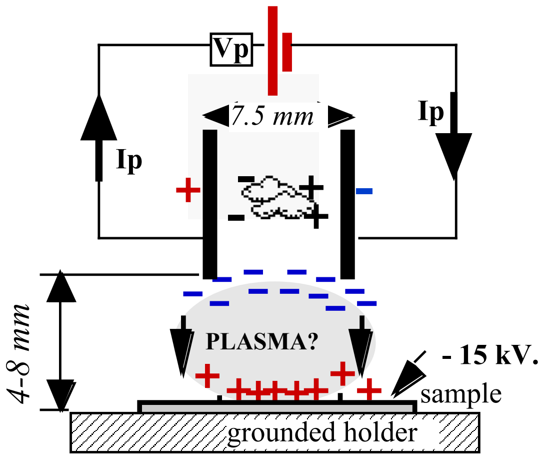

Figure 3 : The basic experiment

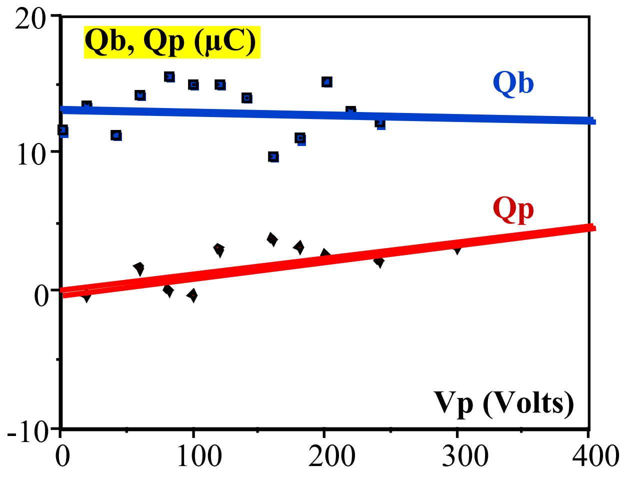

Figure 4 : The total charge collected by the plates Qp versus the bias V. (Qb is the blow-off charge).

It was found that the integral of the plasma collected current Qp was an increasing function of the voltage Vp accross the plates (figure 4). But as Vp was further increased, full breakdown occured between the metal biased electrodes. The lowest value for Vp was 50 Volts, the plates were spaced by 7.5 mm. Figure 5 shows one of these secondary discharges (hundreds were obtained) for Vp = 200 Volts. The discharge dissipates all the charge provided by the supply made of charged capacitors.

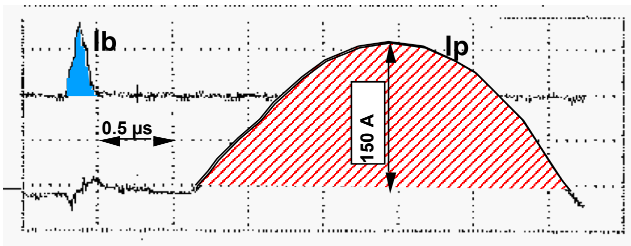

Figure 5 : Secondary discharge Ip(t)
Vp = 200 Volts. Ib = blow-off transient.

The secondary discharges can begin during the blow-off pulse event, but they often began more than a half microsecond after the initial blow-off event had passed. This is evidence that a remnant plasma remains between the plates after the insulator has been discharged. This remnant plasma can have three sources : remains of the blow-off plasma, continued issuance of plasma from the dielectric sample, or secondary ions and electrons from the biased plates.

Other secondary discharges were observed, indicating that the expanding plasma could provide electrical path well away from the sample. Most often, the biased plated connected to the grounded holder. A corrective action was then taken to coat it with dielectric and prevent secondary discharges to settle there. In a few cases, even the electron high voltage power supply protection circuit was tripped. The high voltage (25 kV) was about 20 cm distant from the PET sample and the plates.

3. Secondary arcs between adjacent cells

Secondary arcs have recently been diagnosed as the most likely failure mode of the solar arrays of two geostationnary satellites (Tempo-2 and PAS-6). The failures (power losses) were well correlated with charging environments and occured in the midnight-dawn sector where surface charging is well known to take place during substorms. For about two decades power losses had occured on geostationnary satellites (*Levy et al*, 1991b), but for the first time they appeared in relatevely large number on the same satellite, and with the same kind of typology than ESDs. So, having the precedent section in mind, it was just natural to think the power losses were a consequence of primary discharges occuring on the cover slides and to design an experiment where discharges would be produced on the covers, while having a bias applied between adjacent cells. Different experiments were carried out (*Katz et al*, 1998; *Hoeber et al*, 1998; *Gelderloos et al*, 1998) to assess the scenario. Figure 6 is the schematic of the basic experiment where 20 keV electrons are used to negatively charge the covers with respect to the grounded cells. The cells are layed some 0.9 mm apart on an insulating Kapton layer. A voltage Vp (simulating the solar array nominal voltage) is applied between the cells, accross the gap. The experimental protocol is then to produce the charging and the discharging of the covers (this will be the primary dielectric discharge) for increasing values of Vp while looking after the arc current I_{arc} from cell to cell (secondary arc current).

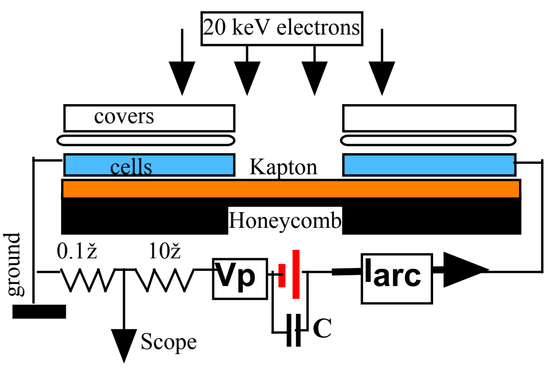

Figure 6 : Basic experiment for secondary arcs on adjacent biased cells

Four samples (N°1,2,3,4) were submitted to the test :

-2 samples (N°1,2) were solar array coupons (SAC) with a standard intercell gap (≈ 0.9 mm)

-1 sample (N°3) was a SAC specially manufactured with an extended gap (3.5 mm)

-1 sample (N°4) was not a SAC, but was made at the laboratory from a printed circuit board : this dummy solar array consisted of floating cupper areas 1 mm apart engraved in the circuit and covered with Teflon simulating the cover slides.

3.1 Arc occurrence versus voltage

Once some -6/7 kVolts are reached on the cover slides, a primary dielectric discharge occurs, and provided that the condition for a secondary arc is met (generaly, a voltage Vp higher than a threshold ≥ 75 Volts), an arc current is detected and measured accross the 0.1 Ω resistor. See figures 6,7,8 and table 1.

Voltage (Volts)	50	75	100	125	150	200
Sample #						
1	0/22	0/20	**3/22**		*	
2	0/10	**1/2**				
3	0/60	0/60	0/60	1?/60	0/5	**1/1**
4	0/4	**2/4**	**2/2**	**1/5**		

Table 1: Number or secondary arcs/primary discharges

Arcs were surprisingly easy to produce under bias voltages between 75 Volts (SACs; 0.9 mm) and 200 volts (SAC; 3.5 mm). Table 1 indicates the number of secondary arcs out of the total number of primary discharges. For the instance of sample #1, no arc was obtained under 50 and 75 Volts. When the voltage was increased to 100 Volts, 3 secondary arcs were obtained out of 22 primary discharges. In short, secondary arcs were relatively very easy to produce, and the voltage applied accross the adjacent cells is apparently governing their onset.

3. 2 Arc characteristics

The arc characteristics obtained on SACs (#1;2) depend strongly on the power supply characteristics, and somehow on the intrinsic physical nature of the arc. Most important are the voltage Vp, the output built-in capacitance of the power supply, the arc "resistance", and anything (resistive, inductive) in series with the arc circuit. For figures 7 and 8, the output capacitance C was 300 µF, the circuit was that of figure 6, and the steady sate current limitation was either 0.5 or 1 A. From the arc peak current at ignition (t= 0), and from the current dyunamics, the arc resistance was deduced and found to be 10-15 Ω. Some of the arc discharges are shown in the figures 7, 8, 9.

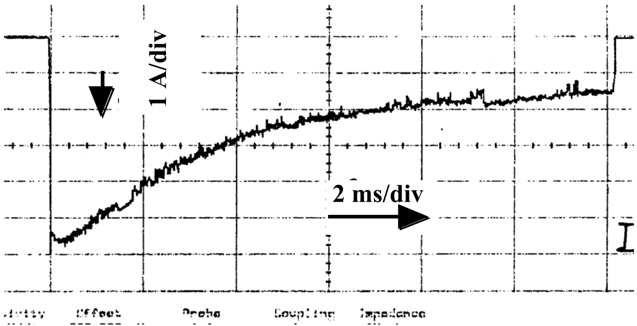

Figure 7 : Arc current on sample #1; Vp = 100 Volts (the first of a train of arcs, for over than 0.9 s)

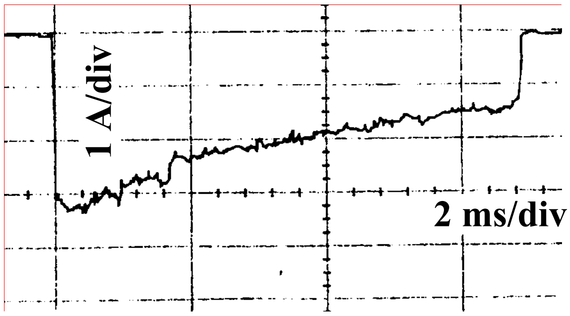

Figure 8 : Arc current on sample #2; Vp = 75 Volts (a unique arc occured; damaged I-V charactersitics)

The figures 7 and 8 have some common characteristics :

-The secondary arc lasts for several ms, much longer than the primary discharge (1 µs). Their duration is clearly dependent upon the value of the capacitance C (fig.6).

-The general shape is that of the current decay of a capacitor through a resistive circuit.

-The arc resistance can be deduced from the time constant (RC) together with the initial current (t=0). It ranges from 10 to 15 Ω for the arcs on SACs.

-The arcs suddenly extinguishe for a current value which is not zero.

There is however a difference between figures 7 and 8 : Fig 8 shows an arc that was unique, but figure 7 is in fact the first of a train of arcs. The signals were recorded with two digitizing oscilloscopes at two different sampling speeds. More than 30 arcs are seen at the lower speed to follow each other over a period of 1 s. The time elapsed between the extinction of one arc and the reignition of the following is the time for the supply to recharge the capacitance C. In brief, the first arc is triggered by the primary dielectric discharge, but all the following are triggered by the previous.

The I-V charactersistics of the cells have nevertheless been damaged, even after a single arc had occured. Visual inspection of the samples revealed dammage and material melting : rather severe dammage for sample #1 which underwent several trains of arcs, and also quite visible damage on sample #2 which suffered only one unique arc. Figure 9 is an arc obtained on sample #4, made of cupper areas engraved on a printed circuit board.

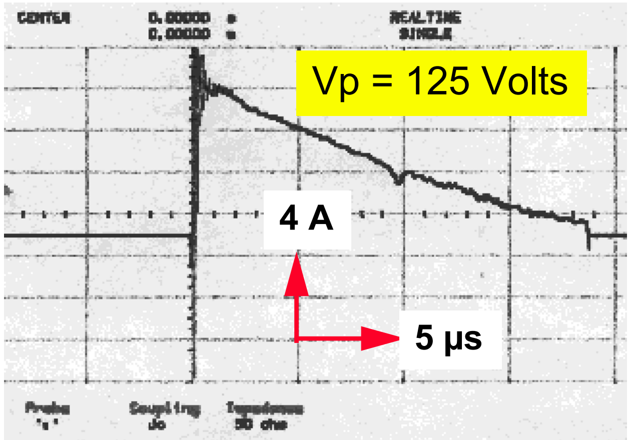

Figure 9 : Arc current on sample #4; Vp = 125 Volts ("dummy sample", C = 1 µF)

The arc duration is shorter due to a lower value of the capacitance. Arc extinction occurs also at a current value different from zero. The arc resistance was found ≈ 5Ω.

3. 2 Arc sustaining condition : Power ?

What causes the arc to end before the current is zero ? Is there a minimum of current or of voltage to maintain the arc ? or on both ? We have computed the power on the arc, product of voltage and current. From our few data, there is an indication that a minimum of power is required : for a standard 0.9 mm gap, this minimum is 25 Watts.

4. Conclusions

Secondary arcs have appeared in a variety of situations, and electrodes : stainless steel, cupper, aluminium, Asga/germanium. Secondary arcs occur whenever a primary discharge is made in the vicinity of biased electrodes, and when there is energy available. It sould be pointed that the solar array structure presents an aggravating characteristic with respect to the risk of secondary arc : the primary discharge source (cover slides, adhesive or the cell itself) is very close to the critical area where the energy is present.

The solar arrays which recently were the victims of this phenomenon cumulated a number of additionnal worsening features : they used cover slides with increased resistivity, and their nominal voltage was also increased and fully present accross adjacent cells. Two thresholds might have been exceeded : one for the onset of the secondary arcs (75 Volts or less), and the second for its sustaining (power availability in arc : ≈ 25 Watts).

This paper has shown a number of circumstances where such secondary arcs have appeared in past experiments. Its main purpose was to focuse on their generic character. And to suggest they probably still have the potential to jeopardize the nominal operation of future space systems.

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