ARC PROPAGATION ON SPACE POWER TRANSFER SYSTEMS: A FIRST APPROACH STUDY

Emmanuel AMORIM[1], Léon LEVY[2], Françoise BOULAY[2], Gérard MIGLIORERO[3], Virginie VIEL-INGUIMBERT[2]

[1] *Centre National d'Etudes Spatiales (CNES),DCT/TV/EL, 18, avenue Edouard Belin, 31401 Toulouse Cedex 9.*

Tel: +33-5-61-28-33-88 – Fax: +33-5-62-28-21-62

emmanuel.amorim@cnes.fr

[2] *Office National d'Etudes et de Recherches Aérospatiales (ONERA), DESP, BP 4025, 2 avenue Edouard Belin 31055 Toulouse.*

Tel: +33-5-62-25-27-48

rene.reulet@onecert.fr, daniel.sarrail@onecert.fr

[3]*ESA-ESTEC– TOS-MMM*

ABSTRACT:
Electric arcs observed between solar cells have been identified as the origin of power losses on orbit. Such arcs have been identified as "vacuum arcs" and have been shown to produce severe damage with functional destruction if the solar array provides sufficient current (1A) under sufficient voltage (20V) to sustain it. In the work presented here, we deal with power transfer systems encountered in equipment like SADM (Solar Array Drive Mechanism) involving many packaged circuits which are designed to carry high current (>5A) under voltages higher than 50 volts. This study is an investigation of vacuum arc propagation from one circuit to another. The experiments were performed on samples made with several metallic tracks and up to three electrical circuits (6 tracks) were used at the same time. The experimental set-up consisted in triggering a first arc between two adjacent tracks while biasing two, three or four more tracks, and to monitor any kind of connection or propagation. The results obtained show that a vacuum arc can propagate from one circuit to another: arcs triggered by propagation between tracks separated by more than 10mm were seen. This propagation is due to the expansion of the arc plasma produced by the first arc towards other tracks. From our experiments we have learned that any kind of connections between the electrical circuits are possible but a vacuum arc would more easily propagate by connecting to one of the tracks where the first arc was triggered. Arc movement on one track has been also observed along several centimetres. The damages produced by such arcs were heavy and destructive: complete vaporization of anode tracks was observed. On cathode tracks, only partial melting and vaporization due to cathode spots of vacuum arcs were seen.

1. INTRODUCTION

Under specific conditions, secondary arcs are currently observed between adjacent and biased solar cells, basically, a kind of static electrode system. The phenomenon, occurring after an ESD occurrence, has been diagnosed as the origin of heavy and costly power losses on orbit. In the laboratory, such arcs on real solar cells have been shown to produce heat, material melting, and ultimately charring of the (initially) insulating layer. The overall resulting effect was severe damage with functional destruction clearly consistent with the observed in orbit power losses. The nature of these arcs is now perfectly identified as "vacuum arcs", a well defined field of fundamental physics. The minimum current and voltage values necessary to sustain such arcs which have been set by laboratory studies are surprisingly low and hence, very frequently found not only on solar arrays, but also on many other spacecraft systems. The minimum current is about 1-2 A, the threshold voltage is about 20 volts.

In this study, we deal with power transfer systems encountered in equipment like SADMs (Solar Array Drive Mechanism) which are designed to carry high current values (>5 A) under voltages (> 50 Volts) in excess of the recognized threshold. Moreover, these power transfer systems are made of "adjacent" slip rings, a structure very close to that of adjacent biased solar arrays. This study is an exploratory investigation of vacuum arc possibility on laboratory made samples, aiming at the reproduction of a SADM system. It is a first effort to assess the risk of damaging arcs anywhere on the satellite where basic conditions for arc ignition are present. More specifically, because SADM systems involve many packaged circuits close one to the other, the possibility of arc propagation from one to the second (and to the third and so on…) has been studied. The reason for the starting first arc was not in the scope of this study, even if the final aim is to develop more robust and reliable spacecraft power equipment for high powered spacecraft.

2. EXPERIMENTAL SET-UP

2.1. EXPLODED WIRE TECHNIQUE

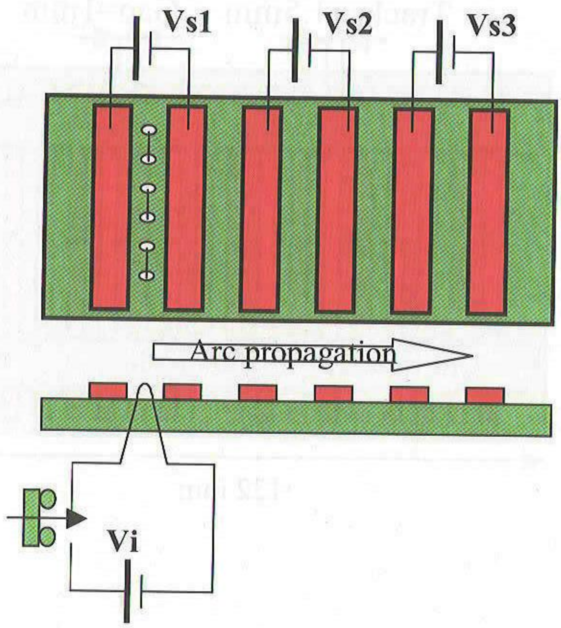


Figure 1: Exploded wire not coupled to any electrode: vaporization is obtained by action of a switch.

The technique of the exploded wire has been used to start the first arc: a piece of thin copper placed in the vicinity of the first circuit (a biased pair of conductors) is very rapidly heated, up to melting by joule heating: the wire is placed between the tracks, goes through the PCB to an ignition circuit which is activated by means of a switch, see Figure 1.

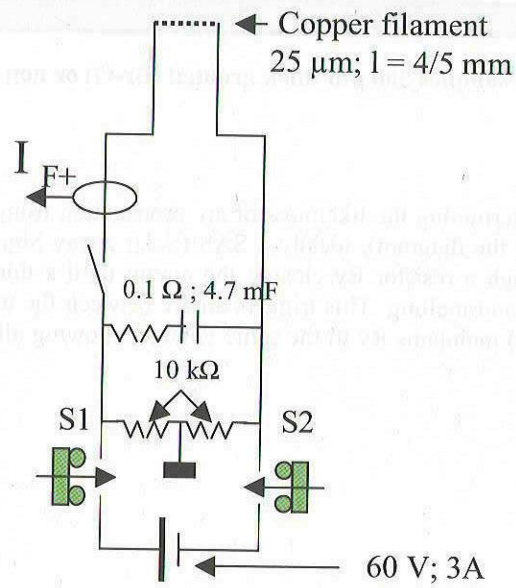


Figure 2: exploded wire circuit

Figure 2 shows the electrical circuit used to vaporize the 25µm copper wire. Switches S1 and S2 are closed just to charge up the 4.7 mF capacitance. When the capacitance is charged, the third switch is closed and the capacitance is loaded with the copper wire. We could easily trigger the first arc in the first circuit, and observe propagation to a second or third circuit almost immediately.

2.2. SAMPLES

Experiments were performed on brass thick traces (0.5 mm) glued on the same support (epoxy glass PCB). The brass samples were either grouted with resin or just non grouted, see Figure 3. The tracks are always 1.5mm large, and they are a gap distance of 1 mm apart. The brass sample is grouted by means of an epoxy resin. The same resin was occasionally used to protect the end of the tracks. Samples are 500 μm thick, grouted and not grouted and their dimensions are 69x122 mm².

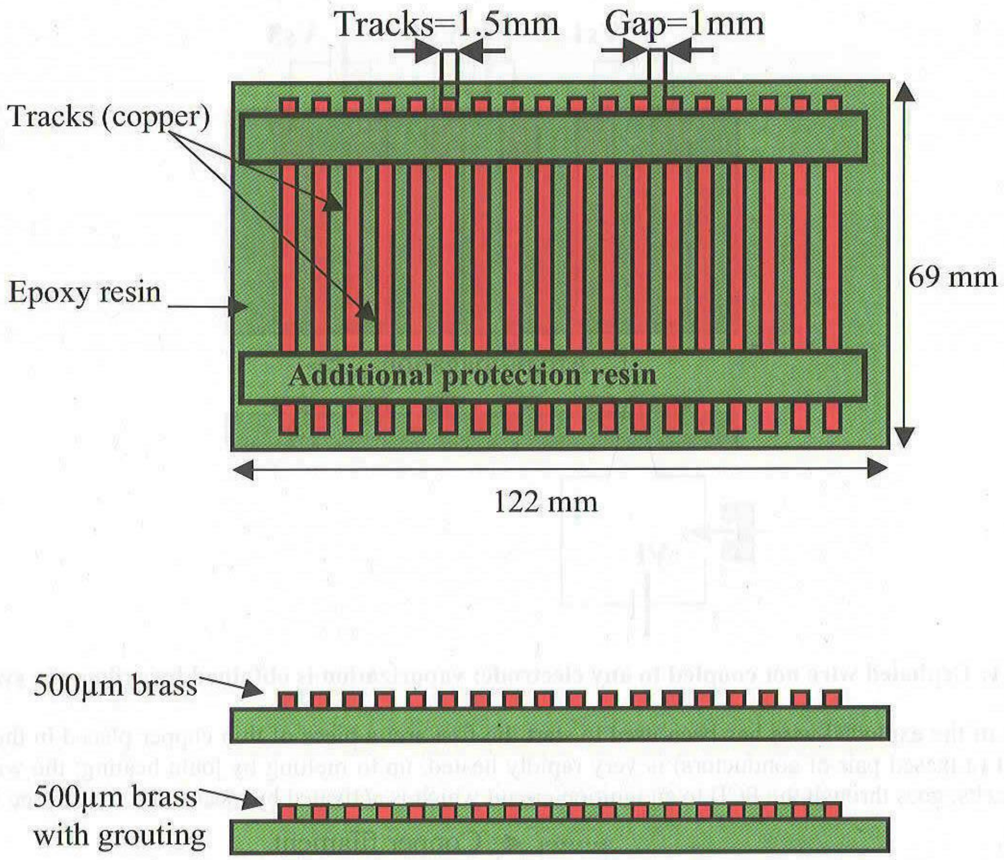


Figure 3 : Brass samples 500 μm thick grouted (Br-G) or non grouted (Br-NG).

3. RESULTS

We are addressing the issue of determining the likeliness of arc propagation from an initial arc to nearby other biased circuits. A power supply (left on the diagram), ideally a SAS (Solar Array Simulator), provide a permanent current Ip+s through the tracks and through a resistor Rv closing the circuit until a thin wire located between the tracks is melted by action of joule heating and melting. This triggers an arc between the tracks and "short circuits" the resistor Rv. Another power supply (right) maintains Rv to the same voltage, allowing all the current from the SAS to flow in the arc.

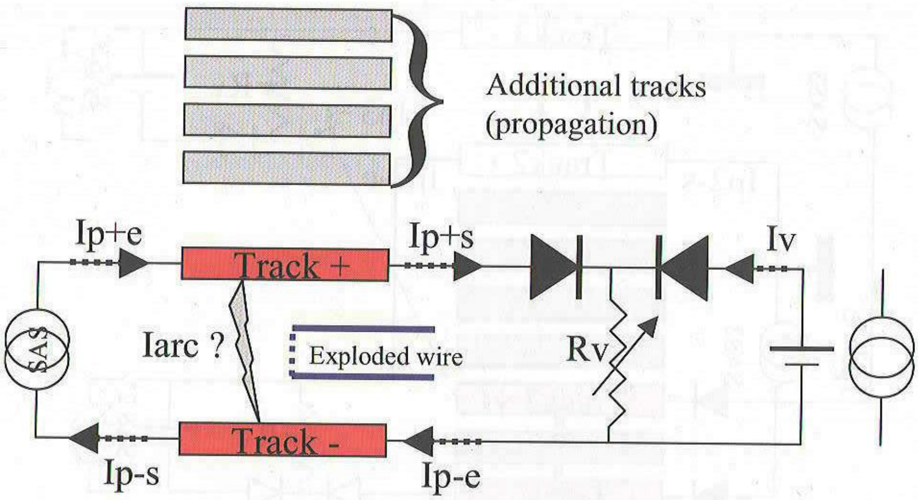


Figure 4: basic experimental circuit. Experimental circuit with a second power supply to have all the SAS current delivered to the arc (left diode in blocking mode due to voltage drop between tracks)

Whenever this occurs, the current will no longer flow through the resistor **Rv** and so, the current measured at the output of the positive track (**Ip+s**) will ideally drop to zero; the current measured at the output of the negative track (**Ip-s**) will keep constant and equal to its previous steady state value. A further consequence is that another arc might be triggered in any adjacent second or third circuit. This is what we call "propagation". Propagation is the focus of this study. Two propagation types were observed (Figure 5): an arc triggered on one circuit could jump from one circuit to another adjacent circuit and using the video, the arc could be seen moving (red arrow) towards the connecting wires. Moreover, when propagation has occurred in our experiments, it did not simply ignite an arc localized on an adjacent circuit, between its pair of tracks. Instead, the (propagated) arc could connect a track of one circuit with a (distant) track of another circuit. This means that the medium between the tracks is not anymore an insulating medium and that arc propagation results and creates connections between previously isolated conductors.

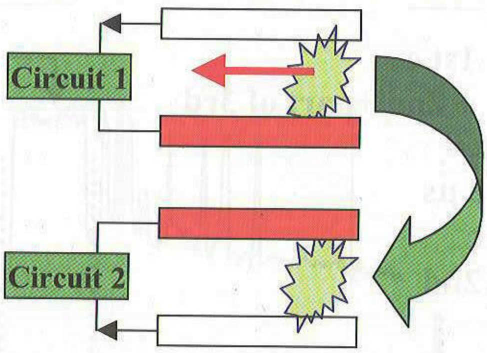


Figure 5: Propagation from circuit to circuit and along the tracks.

Figure 7 shows results obtained on a brass sample without grouting with the experimental circuit shown on Figure 6. On Figure 6, 3 arrows symbolize arcs connecting the lower track to the distant "positive" tracks, Track1+, Track2+, and Track3+. First arc (arrow between Track1+ & Track1-) appears at the melting of the copper wire. A very short time after (900 ns), a second arc bridges Track2+ to Track-, part of the current delivered by SAS2 feeds (Ip-s (t)). See Figure 7. 450 ms later, the total current delivered by SAS2 feeds (Ip-s (t)), and a very short time after (2.2 μs), the 3rd circuit starts also delivering current to (Ip-s (t)). After about 1.05 s, all three circuits are feeding (Ip-s (t)), a plateau current value of 24 A is reached. Notice that 3 such plateau can be seen on Figure 7, at 8, 16 and 24 A, corresponding to the different power supplies providing their current to Ip-s. In order: SAS1 alone (8A), SAS1 + SAS2 (16A), SAS1 + SAS2 + SAS3 (24A). The plateau structure goes on with (Ip-s (t)) dropping from its highest 24A value to 16A when one of the SASs (supposedly SAS1) stops feeding the arc. Then, almost simultaneously, SAS2 & SAS3 stop also feeding the arc. The total arc duration is about 1.4 s.

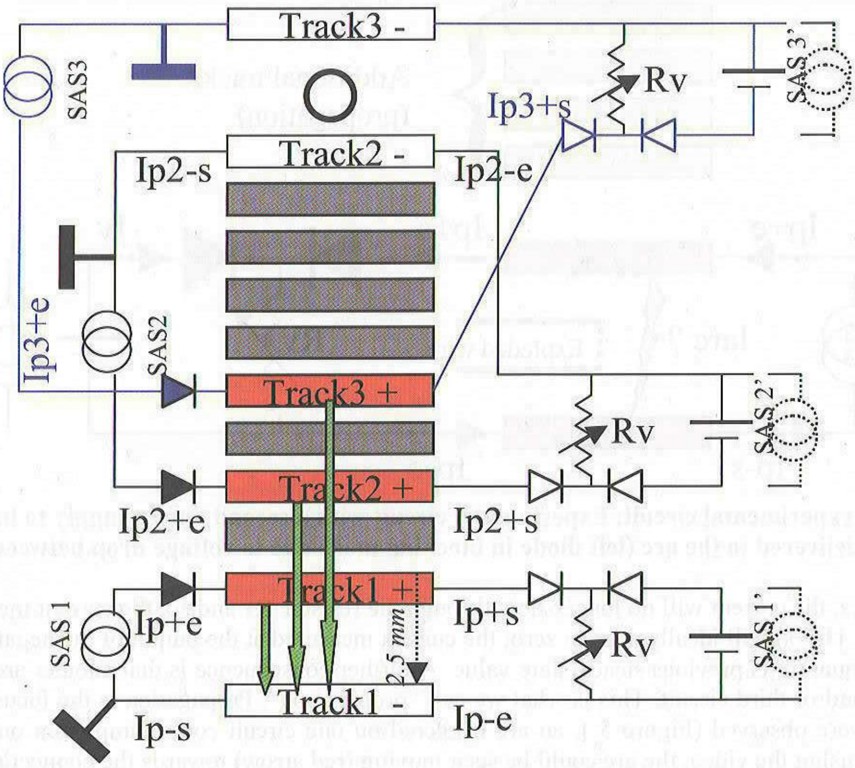


Figure 6 : Brass sample without grouting and distant tracks; 3 circuits. Positive, red colored tracks (Track1+, Track2+, & Track3+), are 3.5 mm apart. 1st , 2nd and 3rd circuit with permanent current flowing; 1st circuit (lower) : 60 Volts – 8A; 2nd circuit (middle) : 45 Volts – 8; 3rd circuit (upper) : 40 Volts – 8A.

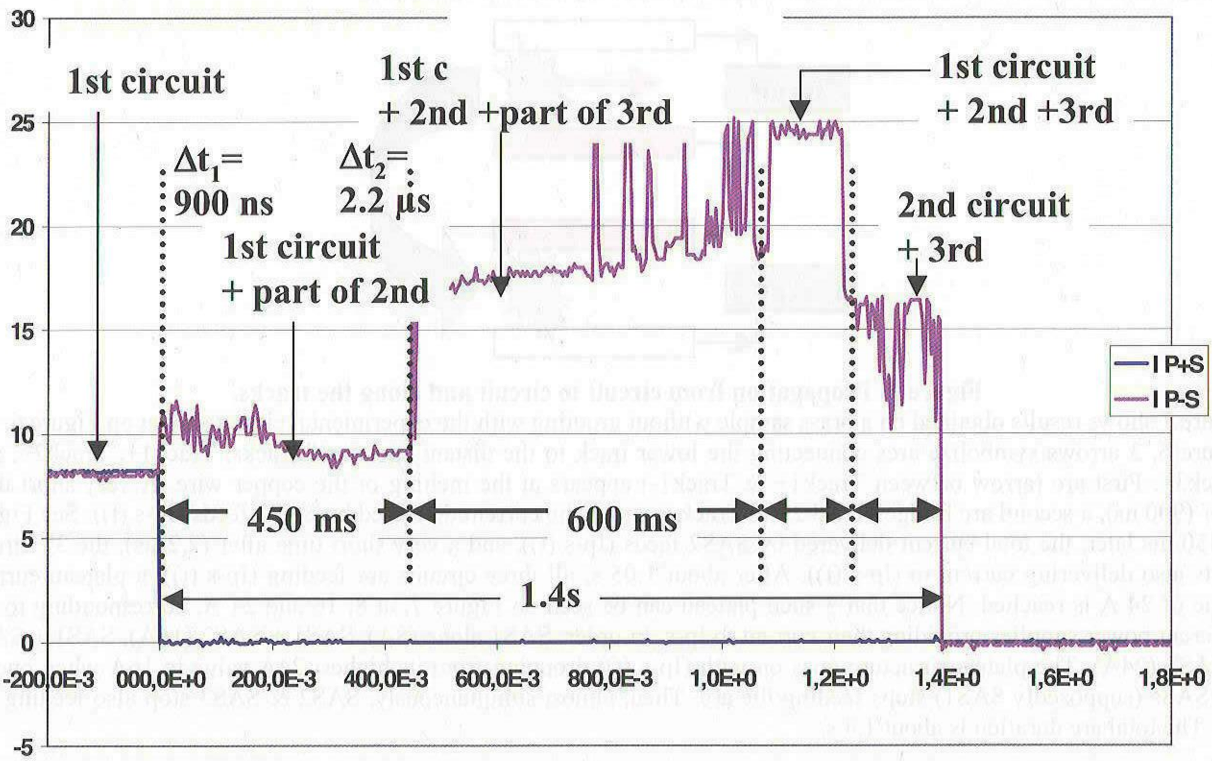
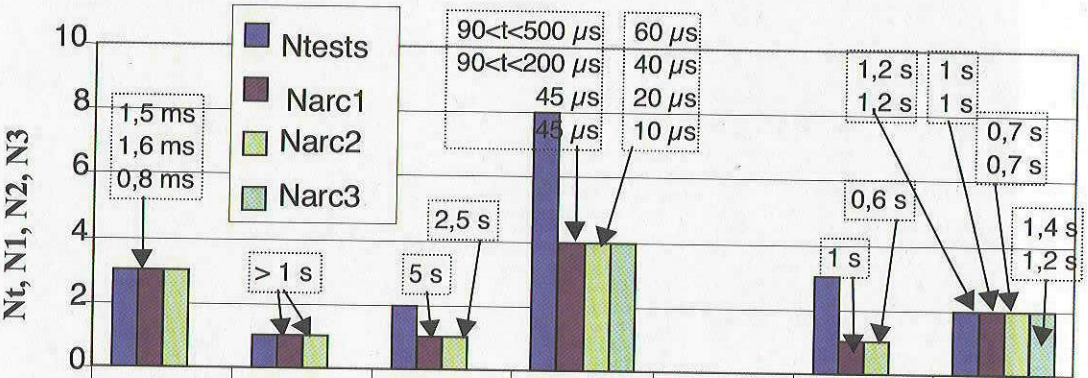


Figure 7 : Arc currents.

One can say that the propagation was complex. Propagation has been observed on a distance up to 11 mm in this case and from the current measurements, we can see two kind of propagation speed. For the 2nd circuit, after 900 ns, one can see partial current contribution. The meantime gives a plasma expansion speed of 0.5 10^4 m/s. After 450 ms, there is total current contribution (8A) from this circuit. The same can be said about the 3rd circuit: after 2.2 µs, one can see partial current contribution and after 1.05 s, there is total current contribution (8A).

Results on propagation are summarized on Figure 8 . Together with the number of tests, we find the number of arcs on the first, second and third circuit, depending on the test condition. On the last column, we find that on the non grouted brass sample, there is a remarkable series of arcs induced on all the 3 circuits. Even on the grouted brass sample, there is a large number of propagated arcs observed.



	Br-G; C1;C2(1)	Br-G; C1;C2(2)	Br-G; C1;C2(3)	Br-G; C1;C2;C3(4)		Br-NG;C1;C2 (5)	Br-NG;C1;C2; C3 (6)
Ntests	3	1	2	8		3	2
Narc1	3	1	1	4		1	2
Narc2	3	1	1	4		1	2
Narc3				4			2

Figure 8: Propagation efficiency (2 & 3 circuits; Grouted & non grouted Brass samples).
(1) : Circuit 1 : 65 V-8A; Circuit 2 : 60V-8A; (2) : Circuit 1 : 85 V-8A; Circuit 2 : 90V-8A; (3) : Circuit 1 : 60 V-8A; Circuit 2 : 60V-8A; (4) : Circuit 1 : 56 V-8A; Circuit 2 : 46V-8A; 40V-8A; (5): Circuit 1 : 60 V-8A; Circuit 2 : 45V-8A; (6) : Circuit 1 : 56 V-8A; Circuit 2 : 46V-8A; 40V-8A

4. DISCUSSION AND CONCLUSIONS

The completely static procedure together with its insulated arrangement has proven efficient on "dummy" samples. Our though is that dummy samples will always remain good test vehicles in order to experiment innovative technologies and mitigation techniques.
The issue of propagation was the bulk of this study. There is no doubt that arc can propagate from one circuit to another. The (arc) plasma expansion speed that was deduced from the time propagation was very close to that known in the literature (10^4 m/s). From our experiments we have learned that arc would more easily propagate by connecting to one of the tracks where the first arc was triggered. It happened also that a "propagated" arc occurred between the two tracks of a distant circuit but this is definitely not the most observed scenario. All connections are possible, but some are more likely than others. The plasma expansion speed that was deduced from the time propagation was very close to that known in the literature (10^4 m/s). However, if a current was effectively flowing between tracks after this very short time (some 100 nanoseconds), this current wasn't always the total available current (0.5 or 1A). In this case, we call the propagation a "partial propagation". We've seen another propagation where the current flowing between the tracks was equal to the maximum current available (8A). We call this propagation a "total propagation" and the time propagation was as long as some hundreds of milliseconds.

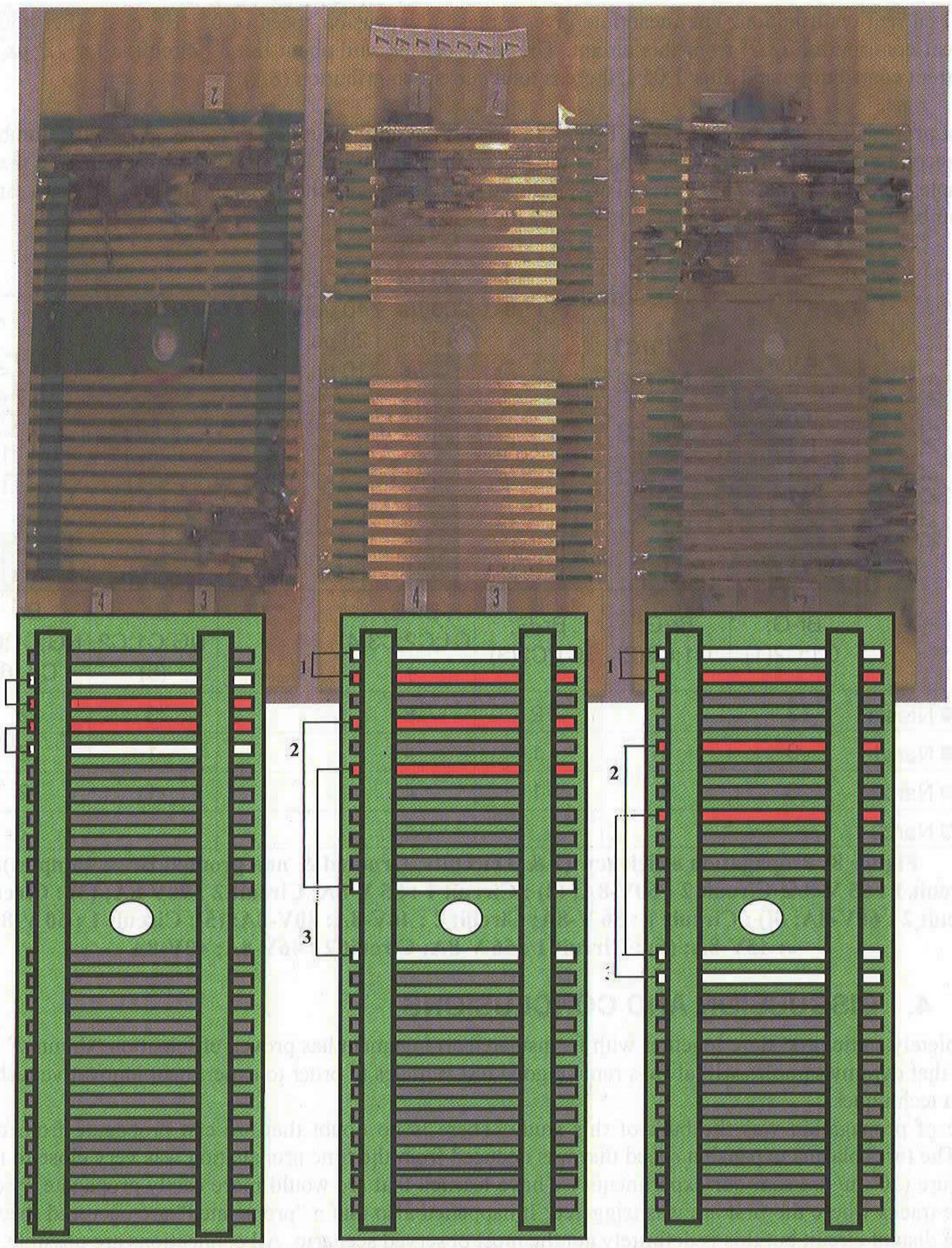


Figure 9: damages produced on samples.

Several conditions are necessary to ignite and sustain a vacuum arc and the most important condition is the arc current: several amperes are needed. The duration of vacuum arcs is statistical, varying from one test to another even for identical circuit conditions. This can be explained by the fact that in vacuum arcs, the current is provided by tiny surface on the cathode called cathode spots. Each spot has a surface of some micrometers, lasts some microseconds and can provide several amperes. After a spot extinction, another spot is ignited on another area of the surface (generally just next to the first one). If the arc current is higher than some amperes, there are several spots providing the current at the same time: when one spot dies, there is always another one to maintain the arc. In our case, the arc current is around 10A and there is probably only one spot at the same time: in the meantime between the end of the first spot and before the ignition of the next one, the arc is more unstable. The arc lifetime, apart from the current, depends on the surface state, the surface temperature, the material, the external circuit, the electrode geometry and the external magnetic field.

On the dummy samples the damage is obvious, heavy and destructive (see Figure 9). This is a feature which will be governed by the arc lifetime and by thermal laws involving the electrode mass, its thermal coupling to the rest of the equipment, etc. It will be easier to melt thin electrodes with no thermal coupling to the rest of the equipment. On the dummy samples and their specific geometry, one can see complete vaporization of some tracks: all these tracks were anodes. One can see damages on cathode tracks, but in this case, only alteration of the surface (melting and partial vaporization due to cathode spots of vacuum arcs).

Arc movement has been seen along the tracks of a single circuit, (and this has caused the melting of the soldered connection of the wires). In case this would this occur in real hardware, the thermal (and damage) issue will propagate from the track (the slip ring) to its connector (brush). This is an important issue that makes a video system mandatory for these studies.

REFERENCES

[1] Boxman R. L., Sanders D. M. and Martin P.J., '*Handbook of vacuum arc science and technology. Fundamentals and applications*' 1st ed., pp49-50 and pp114-118 Noyes Publications.
[2] E. Amorim, L. Lévy, S. Vacquié, J.-P. Gardou, K. Bogus, *Vacuum arcs: literature review and common characteristics with secondary arcs on solar arrays,* 7th Spacecraft Charging Technology Conference. Noordwijk, The netherlands, 23-27 April 2001.
[3] L. Levy, E. Amorim, R. Reulet, D. Sarrail, V. Viel, G. Serrot, R. Gardou, S. Vacquié, P. Degond, R. Talaalout, M.H. Vignal: Solar array triggered arc phenomena studies and modeling (EMAGS), ESA contract 13607/NL/SB, ONERA report RF/4748.00 Octobre 2000.
[4] L. Levy, D. Sarrail, V. Viel, E. Amorim, G. Serrot, K. Bogus : Secondary arcs on solar arrays : occurrence, thresholds, characteristics and induced damage, 7th Spacecraft Charging Technology Conference. Noordwijk, The netherlands, 23-27 April 2001.
[5] Levy L., *Vacuum Arcs and Space Systems Reliability,* ESA Contract 17553/03/NLK/PA, ONERA report N°2/08366, July 2004.