ARC PHENOMENA IN SPACE ENVIRONMENT AND EQUIPMENTS (APSEE)

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ABSTRACT

The Space mechanisms attached to satellites is exposed to an unfriendly environment that may strongly interact with the material, in particular on the electrical circuits. The solar generators are particularly exposed and were subject to intense research programs to eliminate the risks related to arcing.

Other mechanisms are also exposed to the risk of being damaged by arcing propagating within its structure. The mechanism of such propagation and the initial arc triggering are however not known.

The present study is aimed at getting more insight in these phenomena. It is the continuation of the investigations started on solar generators that will now extend to the full satellite electrical loop.

The SADM is particularly involved in this study as the mechanical structure of a slip ring imposes that inner conductors are exposed.

After a careful evaluation of the most important parameters governing the arcing phenomenon, tests were developed to measure various properties in air and vacuum. The test covered a very large range of dimensions from microscopic arcing in an opening contact to macroscopic arcs triggered and propagating in a mechanical structure representative of actual slip rings.

Thanks to the activity, knowledge on arc generation, stability and propagation could be broadened and the main results are summarized hereunder.

The study conclusions brought interesting and important information to enhance the design rules able to mitigate the arcing phenomena. APSEE has opened the path to a new vision of arc phenomena in space mechanisms. We are now confident that further investigations will unable RUAG Aerospace to bring predictive models and rules to provide a complete immunity of the material towards arcing.

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1. General orientations of the study

The experimental investigation covered phenomena from microscopic to macroscopic sizes.

Three important aspects of the physics of arcs were investigated by three different laboratories:

- Arc ignition (EPFL, Lausanne)
- Arc propagation (ONERA, Toulouse)
- Arc stability (University of Rennes, France)

The first studies the spontaneous apparition of micro-arcs when two electrodes are slowly separated. The scale of these phenomena is micrometric. Fundamental information about material state and the plasma prevailing in micro contact disruption is obtained here.

The second study evaluates the conditions leading to an arc propagation following a local perturbation sufficient to trigger a primary arc between two metallic parts. The primary perturbation was here generated with a laser in order to minimise the interaction between the ignition circuit and the propagating circuits formed by a dummy slip ring representative of current SADM design configurations.

The third study investigates the effects of material, environment, voltage and current on the duration and length of an arc generated between two electrodes separated at high velocity.

The values recorded in these three studies were similar:

- Voltage vs. time.
- Current vs. time.
- Light emission
- Steady state pressure and atmosphere composition prior to arc ignition.

2. Experimental parameters

The arcing is a stochastic phenomenon that requires fast recording, putting severe experimental constraints (record synchronisation in particular).

The behaviour of the arc is also very sensitive to other conditions related electrical architecture. The selection of the electrical connecting circuit, the power sources and the way the measuring instruments are connected must be carefully devised in order to obtain representative results of SADM application. The following elements were selected with this respect:

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2.1. Solar Array Generators (SAS):

The solar arrays of current satellites are usually working under 50 V with characteristic voltage-current dynamics. This is provided by Solar Array Generators (SAS) used in his study. The trend for future satellites goes however towards an increase of the voltage (in order to reduce the current load, and consequently increase the power capacity of the solar array). The risk of arcing has been demonstrated to increase with increasing voltage (discussions occurred during an expert exchange meeting with the participation of the main European specialists). The study under 100 V or more is thus also recommended.

The available SAS had a limited capabilities to generate up to 8 A under 80 V maximum. Testing at higher voltages and currents is foreseen in a more detailed arc characterisation program which is under preparation.

The maximum current of 8 A is compatible with many satellites in function, though higher current transfer is also encountered. Stable arcs have been observed under much lower currents. The limit at 8 A imposed by the SAS has been considered as acceptable in this first study, but extension to higher currents is also envisaged for future investigations.

2.2. Satellite representative configuration

Electrical circuit:

The satellite circuit is composed of solar arrays, cables inductances, diodes, capacitances and resistances. The magnitudes of these elements depend on the size of the satellite (solar panel surface, wing length defining cable length and inductances, filtering capacities, etc.

A typical electrical scheme considered as representative of most satellite situations, has been defined for the purpose of the present study (***Figure 4***).

Other features, switching in particular, are also important when the complete satellite circuit configuration is considered. Limited information was available with this respect and could not be simulated during tests.

Environment:

Chemical composition and pressure influence the arc. Test under air, Nitrogen and vacuum (10^{-6} mbar) have been conducted.

Presence of magnetic field may interfere with the arc evolution. This parameter was considered secondary and has not been investigated.

Presence of ionising radiations may favour arc triggering. No investigation of the sensitivity of this parameter with respect to arc triggering has been made in the present study.

Materials:

The selection of tested materials was essentially similar to those found in slip rings. A few additional materials have been investigated for comparisons.

Experimental conditions:

In a preliminary study (AMAPSEE), interference between the power circuit and the arc triggering circuit could be observed. This latter was composed by exploding wires placed at proximity of the tracks where the primary arc was initiated.

In order to prevent this type of interference, a YAG LASER triggering technique has been developed in the frame of the present study, providing a completely independent energy source for arc ignition.

3. Experimental setups

Three experimental setups were dedicated to each of the measurement campaigns:

3.1. Arc propagation measurement set-up

The test sample was a slip ring mock-up made of the same materials, technology and typical sizes as for actual devices used for SADM applications. No ball bearing were present as they are not participating to the arcing process, but rotating was allowed between tests so that fresh surfaces could be easily exposed.

The design of the mock-up also allowed for easy replacement of wire contacts, rings and insulators between the rings as arcing may generate damages.

The housing surface, metallic at the beginning, was anodised in a later testing phase.

A removable cover was used to allow testing in open or confined configuration. The presence of a window was necessary to initiate the primary arc with the LASER.

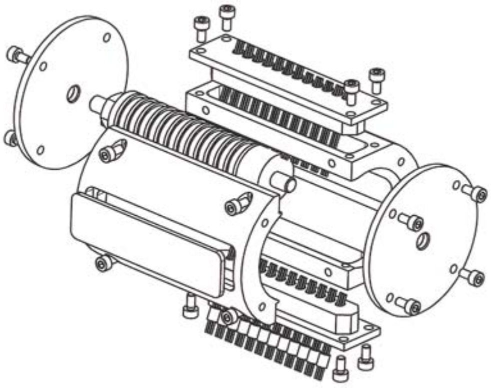

Figure 1: Exploded view of the slip ring mock-up

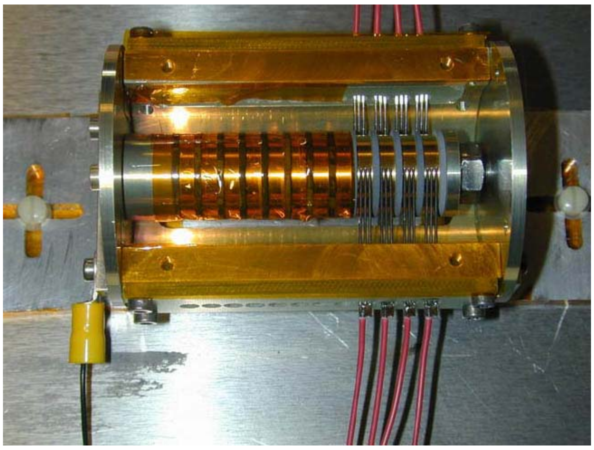

Figure 2: Slip ring mock-up

The mock-up was mounted in a vacuum chamber equipped with a window for the LASER excitation, a camera, and a translation mechanism to modify the mock-up position with respect to the LASER focus point. The equipment sketched and photographed in ***Figure 3*** and the propagation tests were made at ONERA, Toulouse:

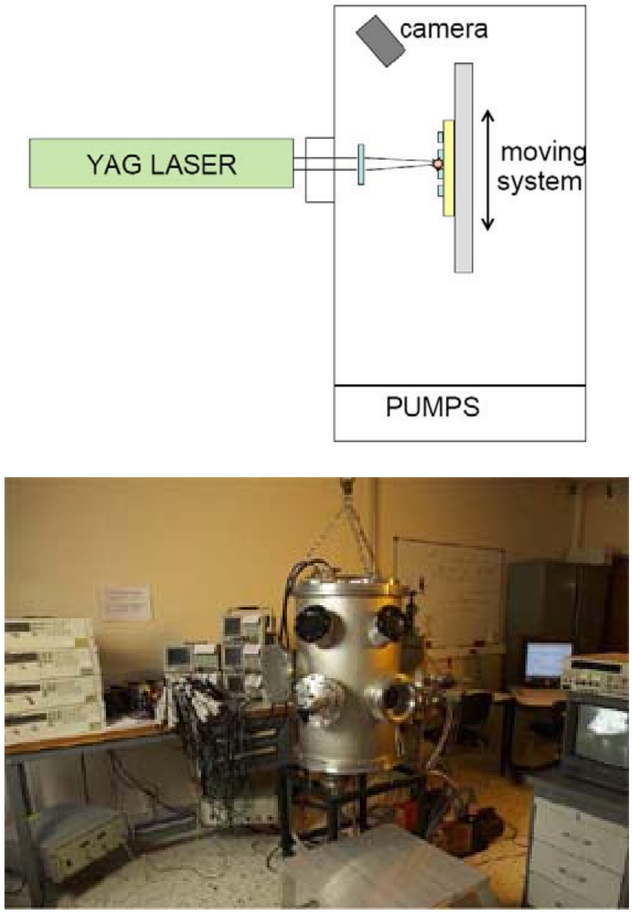

Figure 3: Test equipment at ONERA

Figure 4 represents the electrical test circuit simulating the connections between the Solar Arrrays (SA) and satellite through the slip ring. The currents are sensed with current probes on every circuit branches so that the total current fllow is monitored, included the grounded housing.
SAS are used on the SA side.

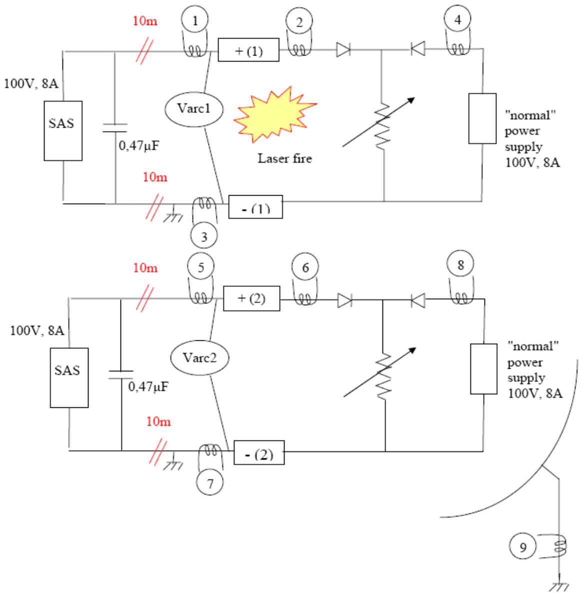

Figure 4: Arc propagation electrical test circuit

The YAG LASER beam is focussed by its associated optics on various parts of the sample.
For adequate LASER power, arcs are triggered on the samples, and occasional propagation observed.
The record of voltage and currents versus time is done by a battery of oscilloscopes coupled by a common trigger.
When an arc propagates, the circuit branches are modified by the arc resistance, modifying also the current flows in the branches. The arc path is deduced from the analysis of the current evolution with time.

3.2. Arc Initialisation measurement setup

The samples were made of two crossed wires of various metals, in particular the gold alloys used for contacts in slip rings. A translation mechanism allows moving the contact position along the wires so that virgin surfaces are always used.

Figure 5: Mounted crossed wires ready for test

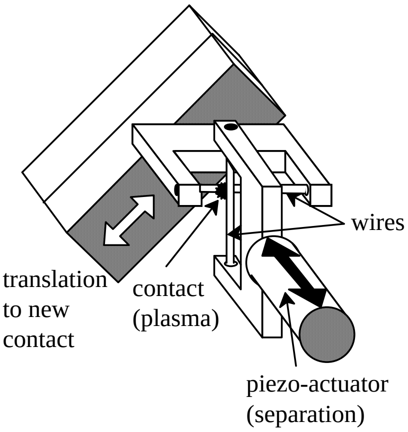

Figure 6: Test equipment for arc ignition study

A piezo actuator mounted on a spring blade controls the slow contact opening movement at a speed of 17 µm/s.

The test was conducted in a facility (***Figure 7***) between atmospheric pressure and $< 10^{-6}$ mbar in air and Nitrogen.

The evaluation of arc phenomena is essentially made by recording the following values in a circuit shown in ***Figure 8***:

- Arc voltage
- Circuit currents
- Light emitted (white and spectral composition have been investigated).

The arc life is of the order of a few nano-seconds. Instruments with very high time resolution are essential to capture the relevant details (250 ps/point); the irregular apparition of arc occurrences also required the use of special triggering techniques to allow the capture of all events.

Figure 7: Test facility at EPFL

A stiff source with very fast time response was used to stabilize the current during the arcing events. The voltage source was set to 30 V in steady state conditions) and limited to 1.5 A (nominal capacity of the wires).

Several load configurations with various resistances, capacities and inductances were tested.

The switch of ***Figure 8*** is used to sense when the contact is established between the two samples before the measurement is started.

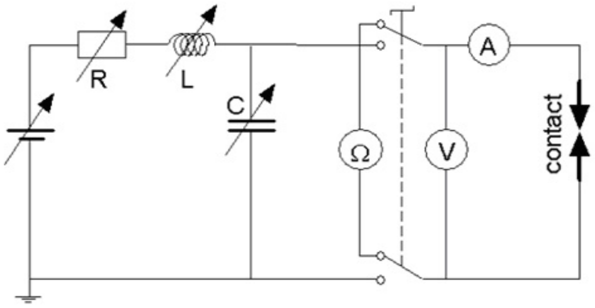

Figure 8: Electrical scheme for arc initiation study

3.3. Arc stability under fast contact opening

Rivets (Ø 4mm) made of identical metals are used as samples. The cathode is convex (R= 10mm) and the anode is flat.

A mechanism opens the powered contacts at high velocity (20 cm/s). An arc is ignited and its life time mainly depends on materials, voltage, current, atmosphere and pressure.

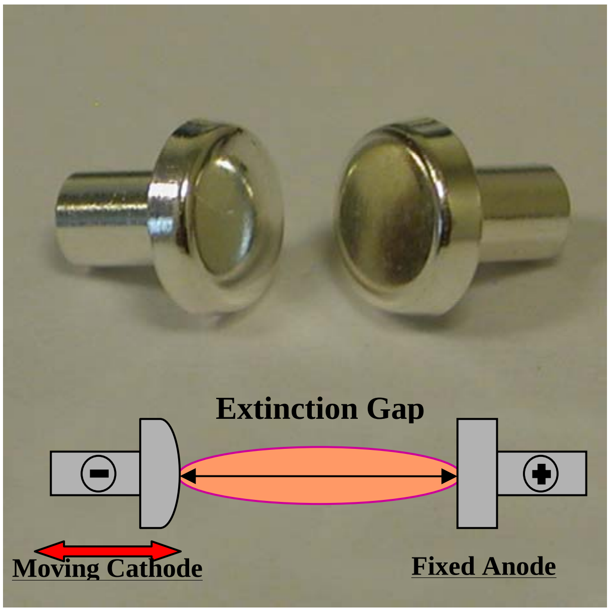

Figure 9: Test samples for arc stability testing

The arc length and duration are related by the electrode velocity. The voltage, current, maximum arc length are recorded in air and vacuum(< 10^{-6} mbar).

The source is a SAS with a capability of delivering 8 A under 60 V, and a capacitor of 0.47 µF is connected in parallel to simulate the SA line capacity. The measurement circuit is represented in ***Figure 10***.

Pure metals (Au, Ag, Cu) have been investigated.

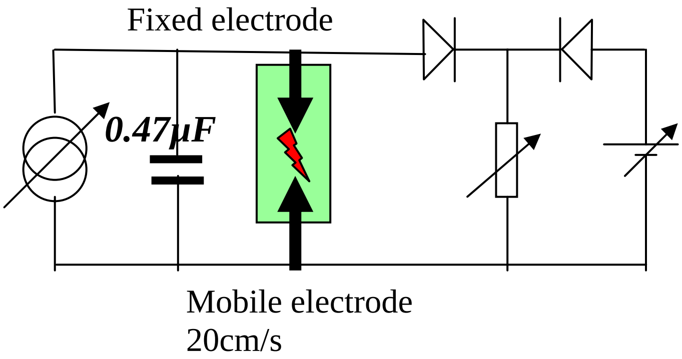

Figure 10: Electric scheme for arc stability measurement

4. Test results

4.1. Arc propagation

The test statistics is summarised on ***Table 1***. The arc duration is a highly variable and unpredictable figure, but is however somehow correlated with pressure and confinement as illustrated by the histogram of ***Figure 11***. Most of the arc, even with propagation, last less than 5 ms ; only 3 arcs lasted a half second , producing some contact distortion due to over-heating.

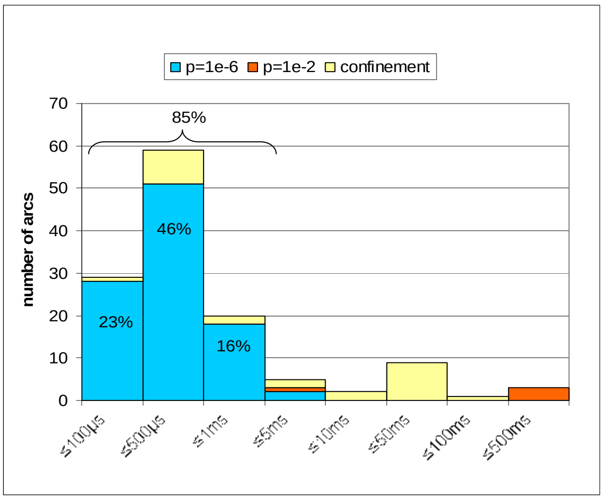

Figure 11: Arc duration distribution

The propagation is illustrated on *Figure 12* :

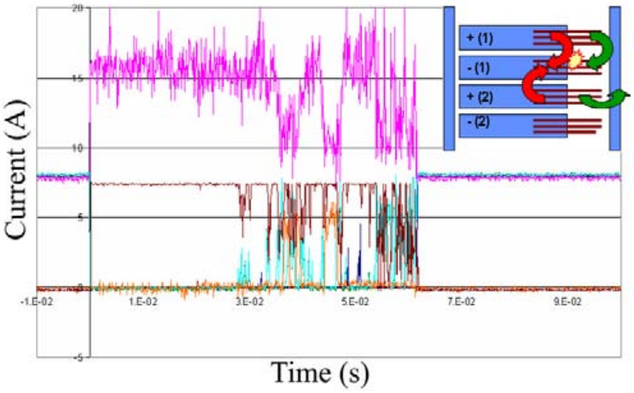

Figure 12: Time record of a complex propagating arc between track and housing

Table 1: Propagation test statistics

Configuration	Pressure (mbar)	N events	n > 1 ms	Percent > 1 ms	n > 100 ms	Percent > 100 ms
High Pressure	Typ.10^{-2}	26	4	15%	3	11%
Low Pressure open	Typ.10^{-6}	258	4	2%	0	0%
Low Pressure confined	Typ.10^{-6}	40	14	35%	0	0%
All	Any	324	22	7%	3	< 1%

The current of several tracks may add up in some legs of the circuit (***Figure 4***).

The insulation of the housing and of the contacts drastically improves the immunity with respect to arc propagation.

4.2. Initiation of arcs with slow contact opening

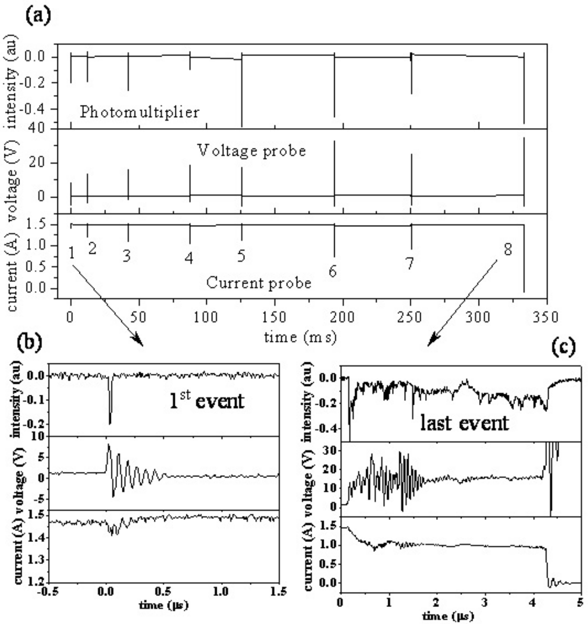

Figure 13: Light, voltage current evolution with time during contact opening

A succession of very short (10-20 ns) discharges appears during contact opening until electrical connection is interrupted. A liquid metal connection maintains the conduction when the distance between the electrodes is small enough.

The analysis of the light emission shows that very dense non-ideal plasma is associated to the short discharges.

The plasma is confined in a very small volume localised around the contact (***Figure 14***). A stable arc is never produced in this case of slow electrode velocity.

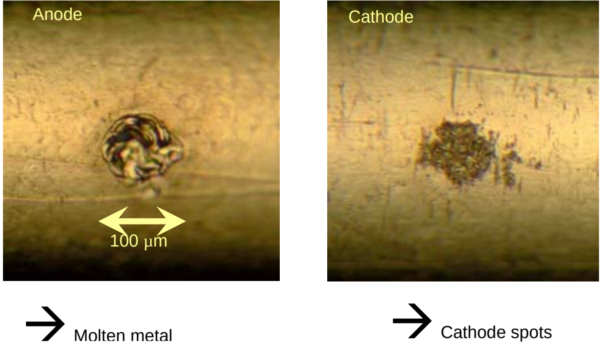

Figure 14: Local surface damages

4.3. Stability of arcs with fast contact opening

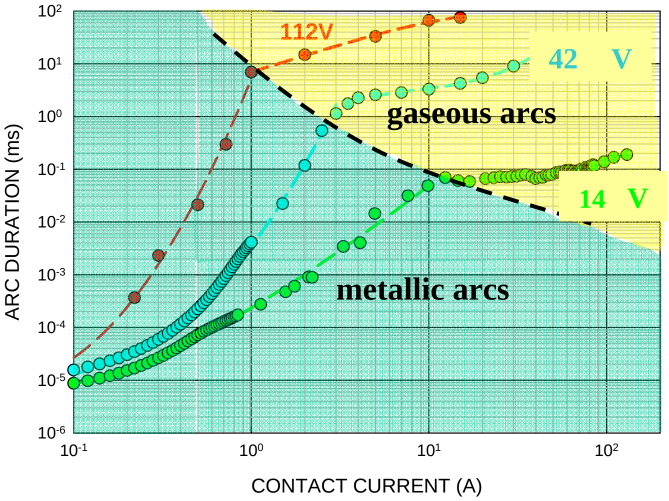

Figure 15: Arc type existence limit in air

The fast electrode separation experimental process allows obtaining a relatively low dispersion of the arc duration recorded under identical conditions.

Several conclusions could be drawn from these measurements:

For long arcs, the contribution of atmosphere (gaseous arc) becomes important in the stability of the arc while metallic plasma (metallic arc) essentially contributes to short arcs (***Figure 15***). The arc duration is significantly related to the electrode material, and the material contribution in air or vacuum may be very different.

An arc is not stable below a threshold related to materials, but typically below 12 V. The arc duration increases very fast with voltage beyond this threshold as shown by ***Figure 16***.

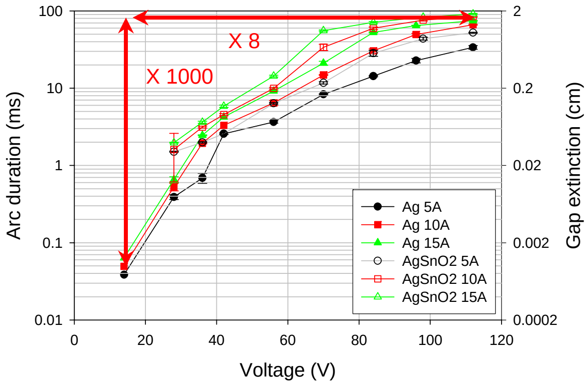

Figure 16: Arc duration relationship with voltage increase in air

5. Summary of results applied on equipments

The set of experiments presented in paragraph 5 brought some insights on the possible occurrences of arc in electrical equipments under vacuum and confirmed the soundness of the general design rules already applied on RUAG AEROSPACE slip rings to increase the immunity to arcing phenomena.

The following points are clear results of the study:

The arc may propagate under vacuum, the probability of long lasting events is low, but increases with the source voltage.

The damages to material are related to the total dissipated power in arcs. Several power supplies may add up in a single circuit when arcs propagate. Higher current transferred through the mechanism at higher voltage increases the potential damages should an arc be initiated. In this study, very little damages were created by the arcs. The maximum current allowed by the sources amounted only 16 A. More energy would be needed to produce large damages.

The influence of the complete circuit connecting the source (Solar Array for example) to the satellite users was demonstrated to be important and should not be ignored when equipment is designed.

The immunity to arcing is significantly improved when the following characteristics are satisfied:

- The conductors are not in direct line of sight
- The housing is insulated
- The insulating barriers between conductors are as high as possible.

These features are standard in RUAG AEROSPACE slip rings.

The increasing demand for high power slip ring connections with lower and lower mass and size also increases the risk of occurrence of hot long arcs. The large number of parameters influencing the arc (voltage, current, atmosphere, pressure, materials, geometrical configuration, number of powered circuits connected in parallel and electrical architecture) was scanned over a limited range.

An extension of the study with multiple circuits and connected to sources above 100 V and delivering 10 A or more is necessary to define the limit where an arc may become destructive.

A model able to characterise the energy necessary to initiate a propagating arc is also missing. Several sources of arc triggers (LASER, exploding wire) were tested and showed that no arc could be produced if insufficient plasma is generated, that is, if insufficient energy is available to start the arc.

The understanding of the representative satellite electrical architecture by the equipment designer needs to be reinforced.

6. Conclusion

The present study opened an innovative way to the understanding of the underlying mechanisms driving a very complex phenomenon: the arc under vacuum. Experimental evidences were obtained to:

- Demonstrate the validity of applied design rules efficient to mitigate the arc occurrence in space equipments.
- Provide information about the underlying physics that favours or inhibits arc initiation and propagation.

The obtain results provide a clear orientation for a further study where a predictive model will be developed to sustain rules able to secure equipment by design.

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