VACUUM ARCS: LITERATURE REVIEW AND COMMON CHARACTERISTICS WITH SECONDARY ARCS ON SOLAR ARRAYS

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Abstract : *In this paper, a description of a very particular discharge, the vacuum arcs will be made. A vacuum arc is a low voltage, high current discharge, which produces its own the conducting medium by electrode vaporisation. The dedicated literature will be reviewed in order to describe the fundamentals of vacuum arc science. We will first be interested on the arc ignition, then we will describe the cathode spots responsible for electron emission and metal vapour plasma production. The great current densities on the cathode spots produce electrode vaporisation and melting by Joule heating, creating craters on the cathode surface, electrode erosion, and the inter-electrode plasma. After that, we will describe the arc lifetime, the erosion rate and the arc voltage (nearly constant for each electrode material). Then we will compare the vacuum arcs found in the literature with a phenomenon observed on satellites in a GEO orbit. During its lifetime, a satellite might be charged by the space environment up to a discharging threshold level, resulting in electrostatic discharges (ESD) and finally in satellite. A new phenomenon has appeared which produces permanent damages has been described: secondary discharges triggered by a primary ESD localised in the vicinity of two adjacent solar cells are the most probable cause of short-circuits and power losses. As a major outcome of the EMAGS (acronym for Etude of Modelisation of Arcs on Solar Arrays granted to ONERA/CERT by ESTEC), it is clear now that secondary discharges are vacuum arcs: all the characteristics voltage, current, spectroscopic data, craters observed on the cathode, show that secondary discharges are vacuum with some particularities.*

1. Vacuum arcs

"vacuum arcs" are electric arc discharges burning in metal vapours. they are low voltage, high current discharges, and provide themselves the plasma medium by a strong vaporisation of the cathode material. The cathode spots are the main characteristic of the vacuum arcs: they are responsible for the electron emission and the production of the metal plasma.

1.1. *General characteristics*

Arc discharges are low voltage, high current discharges. Arc current I_a varies between one to thousands amperes and the voltage drop V_a is concentrated within a cathode fall zone and is typically in the range of the first ionisation potential of the cathode material. The vacuum arcs are particular arcs: in this case, the discharge provides itself the conducting medium. The electronic current emission is concentrated in very small areas (few micrometers) creating a strong Joule effect and leading to melting and vaporisation of the cathode material. So, the vacuum arcs doesn't really take place in the vacuum but in metallic vapour plasma.

1.2. *Arc ignition*

The interaction between the electrodes and the plasma is important in understanding the discharge behaviour. The interaction includes the emission of electrons from the electrodes into the plasma.

<u>Thermoionic emission (emission T):</u> a plane, homogenous metallic surface at temperature T emits an electron current which density is given by the Richardson-Dushman equation:

$$J_{RD} = \frac{4\pi k_b e m_e T^2}{h^3} \exp\left(\frac{-\Phi}{k_b T}\right)$$

with :
- k_B : Boltzmann constant
- e : electron charge
- m_e: electron mass
- h : Planck constant
- ϕ : work function

Field emission (emission F): applying an external electric field, electrons have a finite probability of tunnelling through the barrier of potential. The field emission current density is given by the Fowler-Nordheim equation (available for tip cathode geometry):

$$J_{FN} = \frac{e^2F^2}{8\pi h\Phi}\exp\left(\frac{-4\sqrt{2m_e \times 3\Phi}}{3h\ e\ F}\right)$$

with F : applied electric field

But the calculated emission current calculated by this equation is order of magnitude smaller than the measured one for cathode having extended areas: the field is in fact enhanced by microscopic "whisker like" surface protrusions, inclusions, presence of triple junction (confluence of 3 materials –vacuum, insulator, conductor- due to insulator inclusions on electrode material or to the presence of bulk insulator, distorts and enhances the electric field).
The transition from field emission to electrical breakdown is due to the increase in current density: a tip (or a micro-protrusion) submitted to an increase of field emission is heated by the Joule effect, the tip is melted and vaporised, creating a conducting plasma.

In vacuum arcs, there is both elevated temperatures and external field, so a combination of thermoionic and field emission occurs: the T-F emission.

We describe here some experimental methods of initiating vacuum arcs.

- Breakdown to arc: one common method is simply forcing a breakdown and promoting the continuation of the breakdown as an arc
- Drawn arc: this method utilise surface imperfections of the two contacts. Separating two contacts, the current pass through very limited areas: the current density reach very high values, leading to Joule heating and strong vaporisation of the contacts.
- Fuse wire: a very thin wire is placed between the electrodes: when the current pass through the wire, the high current density vaporise it, creating a plasma.
- Triggered arc ignition: for spatially fixed electrodes arcs can be triggered by a breakdown initiated between an auxiliary electrode and the cathode, then the resultant plasma bridges the main electrodes gap where a discharge can be established
- Laser ignition: a laser is focused upon the cathode and vaporises it, creating a plasma (5.10^{+8} W/cm^2 are necessary)

In the case where two power supplies are used (one for ignition, one for sustaining the arc) the arc stability depends greatly on the circuit impedances.

1.3. *Cathode spots*

In vacuum arcs, the current emission is concentrated in small areas (size: ten micrometers): the current density reach very high values, thus creating strong Joule heating, producing melting and vaporisation of the cathode material. These areas are called cathode spots and are a striking feature of the vacuum arcs. The cathode spots are small, luminous and move over the surface. They are responsible for electron emission, metal vapour plasma production (ions, metallic vapour, droplets) and their number is proportional to the arc current. As one can see in Figure 4, craters can bee easily seen on the cathode surface after the arc extinction: the pressure due to the dense plasma in front of the spot deforms the cathode surface (Figure 1) (that sudden plasma pressure produce also ejection of molten droplets).

Cathode spots characteristics greatly depend on surface (electrode geometry, electrode material, micro-protrusions, inclusions, grain boundaries…). Several spots can exist simultaneously (number of spots and arc stability decrease with decreasing current). The spot diameter is few µm, the spot lifetime is in the µs region, the ions are in several charge states.

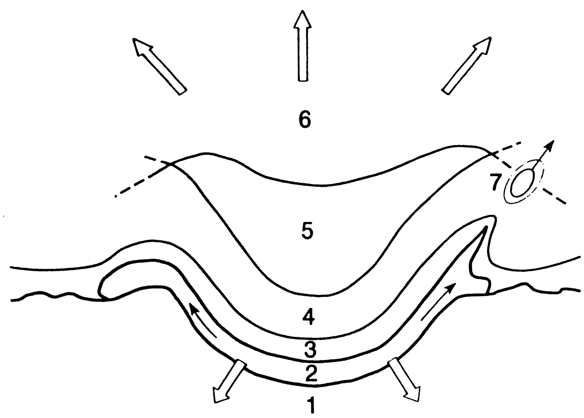

Figure 1: spot structure: 1- solid metal cathode below the spot; 2- molten metal layer (0.2-0.5µm); 3- space charge layer (0.005-0.01µm); 4- ionisation and thermalisation layer (size 0.1-0.5 µm); 5- dense central spot plasma (5-20 µm); 6- plasma expansion region; 7- ejection of molten droplets (size: 0.1-100µm). Ref: Farral, Lafferty: Vacuum arcs

1.4. *Inter-electrode plasma*

The inter-electrode plasma in vacuum arcs, at low and medium currents, is constituted by metallic vapours emitted from the cathode. The plasma moves away from the cathode and a part of it condenses on the structures surrounding the electrodes. Its main function is to conduct the arc current but it interacts also with the electrodes. For the low current vacuum arcs, a single spot produce a plasma jet directed away from the cathode. The plasma characteristics depends on the cathode material. The electron density is proportional to the current density which varies generally from 10^{E+20} to 10^{E+22} m^{-3}. The ion current fraction is nearly constant (from 0.07 to 0.12 of the total arc current). The electronic temperature varies with the cathode material (from 3 to 9 eV).

1.5. *Characteristics*

Erosion - Damages: the erosion rate is defined as mass loss per transported charges (g/C). In a low current vacuum arc the erosion is localised at the cathode and is due to emission from the spot of ions, neutrals and molten droplets. Generally, erosion is due mainly to emission of ions (95%) and to the ejection of droplets (the evaporation of neutrals can be neglected). The dominant erosion rate due to the ions can be evaluated by:

$$E_{ri} = \frac{m_i}{Z\,e}\;\frac{I_i}{I}$$

with: m_i ion mass
Z: charge number of the ions flowing out of the spot
I_i / I: fraction of the current of ions flowing out of the spot (nearly constant)

The erosion rate depends on the arc current, the cathode material, the cathode temperature… Typical values of the erosion rate is some 100µg/C.

Arc lifetime: the arc lifetime is different than the spot lifetime: while the mean lifetime of a cathode spot is typically shorter than 1µs, a vacuum arc can be established permanently. But the vacuum arcs aren't stable and their lifetime depends on many parameters. The most evident parameter is the arc current: the higher the arc current, the higher the number of spots exist and the higher the arc lifetime (when many spots exist simultaneously, the extinction of one of them has less influence on the arc than when a single spot exists). The average lifetime depends also on the surface state (rough surface mean longer arcs because there are many sites with local enhancement of the electric field), on the surface temperature, on the material (higher vapour pressure mean higher arc lifetimes), on the external circuit (higher circuit voltage mean higher lifetime, capacitors, inductance) and on the electrode geometry.

Arc voltage: the arc voltage depends greatly on the cathode material: the voltage drop V_a between the two electrodes, is concentrated within a cathode fall zone and is typically in the range of the first ionisation potential of the cathode material. Typical values vary from 15V (for zinc electrodes) to 25V (for Mo electrodes). A striking feature of the vacuum arc voltage is its noisy character: the voltage consists in a dc signal with peaks. These peaks correspond to cathode spot motion or to the formation or death of a spot. The vacuum arc characteristics $V_a(I_a)$ show a relatively flat resistive-like evolution over a large current range (**Figure 2**).

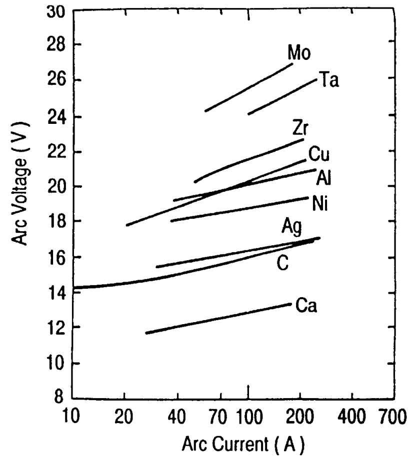

Figure 2: V(I) characteristic of vacuum arcs for many cathode materials. Ref: Farral, Lafferty: Vacuum arcs

2. secondary arcs on solar cells: atypical vacuum arcs

During its lifetime, a satellite on a geo-stationary orbit is charged by particles of the magnetosphere (mainly electrons) and dielectrics are differentially charged to a point where a spontaneous discharge may occur. This is a well-known phenomenon called electrostatic discharges (ESD) which produce temporary anomalies, unwanted switching mainly due to electromagnetic interferences. A new phenomenon was however observed recently producing permanent damages as observed on several satellites. It has been described as "secondary discharges" triggered by a primary electrostatic discharge localized in the vicinity of available energy. These secondary discharges occur particularly on solar arrays between two adjacent and biased solar cells. Cover glasses covering the solar cells are typically proved to charging and discharging in a geo-stationary environment.

2.1. *Secondary arcs are vacuum arcs*

From laboratory experiments done on dummy zinc and copper samples and on real solar cells samples, the following observations are made: the duration of secondary discharges; the arc current and arc voltage; the spectroscopic data; the SEM recordings showing erosion craters on the surface and molten droplet ejections.

For instance, the recorded experimental current values between 1 to 5A typically fall in the electric arc domain. The discharge voltage measured between 15 and 40V are clearly along vacuum arc characteristics. The experimental data also shows the very characteristic voltage noise associated with cathode phenomena.

The spectroscopic data indicates that the secondary discharges produce a large amount of metal vapour plasma. The plasma radiation clearly indicated strong zinc lines for the zinc electrode samples and strong copper lines for the copper samples. Strong silver lines were also found for the real solar cells, but in this case there are also another spectral lines not clearly identified (maybe produced from the solar cell components and/or adsorbed gas).

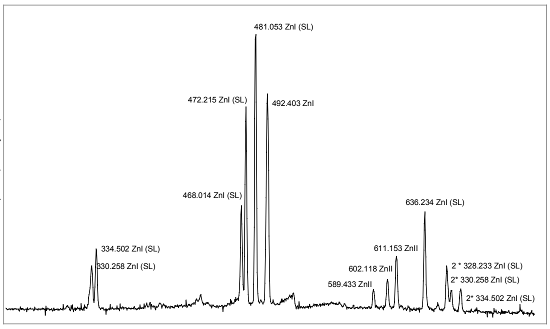

Figure 3: spectroscopic data obtained during a secondary discharge on a zinc sample: all the identified lines are zinc lines.

The SEM recordings (**Figure 4**) show erosion craters very typical in shape and size (~ µm diameter) to spots described in the literature for all the samples observed (copper, zinc, solar cells). These zones are the site of strong melting and vaporisation of the cathode material resulting in important electrode material erosion and degradation.

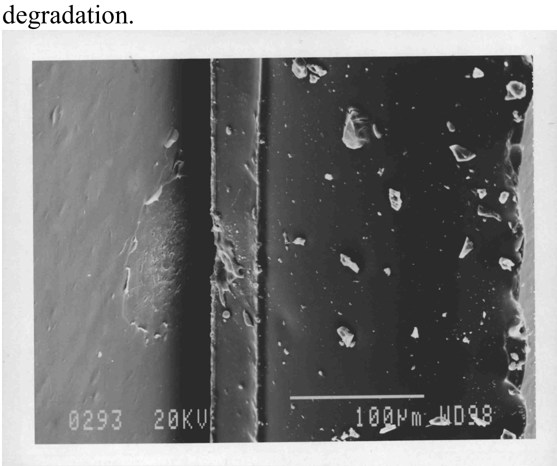

Figure 4: SEM recording of a solar cell sample (left part: kapton, middle: silver interconnect, left part: cell and cover-glass)

The liquid metal droplets emitted from the spots during the discharge is another vacuum arc characteristic. These metal droplets may in fact form an important fraction of the total erosion loss of the surface.

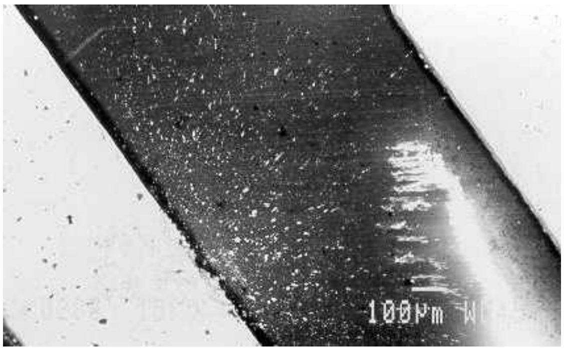

Figure 5: SEM recording of a zinc sample (dark layer in the centre : epoxy insulator, white layers on both sides are the zinc cathode –left- and anode –right. The large white cloud with striations on the bottom right of the epoxy layer is an artefact from charging effects of this surface under the SEM.

We see clearly a large number of the metal particles being splashed away from the erosion craters within the gap area (**Figure 5**). The size of the particles varying between 0.1 and 100 µm in diameter is consistent with the vacuum arc literature data.

Thus, all the experimental data effectively show that secondary arcs have the same characteristics than the vacuum arc discharges.

2.2. *particularities of the secondary arcs*

Arc ignition: the experimental study shows clearly that secondary arc ignition is triggered by a primary ESD taking place in the active gap i.e. between the two electrodes: no secondary arcs was observed when ESDs take place elsewhere. In the solar cell samples, all the damages observed were located on the silver electrode beneath the solar cell itself (**Figure 4**); sometimes the damages were also observed on the kapton film and on the solar cell. One can therefore believe the secondary discharge ignition on the solar cell occurs only on the metallic connector and not on the solar cell itself.

Electrode geometry: another secondary arc particularity is its uncommon geometry. In both zinc, copper and solar cell samples, two thin electrodes (some 10µm) are facing each other, while in the vacuum arcs literature at least one massive electrode is used. That particularity may affect the secondary arc characteristics like the lifetime (lower lifetime for thin electrodes than bulk electrodes) and the erosion rate.

Currant domain: the vacuum arcs found in the literature are studied for currents higher than ten amperes while the secondary arc current domain was restricted from one to five amperes. This current is high enough to identify the secondary discharges as vacuum arcs but it induces some little differences like the $V_{arc}(I_{arc})$ characteristics.

2.3. *characteristics*

Erosion: The surface material erosion rate values range typically in the hundreds of micro-grams of metal removed per Coulomb of electric charge transferred, this value being around 215 µg/C for zinc cathodes [ref: Kimblin]. Integrating the secondary discharge current of a typical discharge lasting 40-60µs to yield the total charge transferred (4.77×10^{-4} C) results in a mass eroded of 0.1 µg. Such metal removal is first in the form of metal vapour that eventually condenses on the surrounding surfaces, and more particularly within the inter-electrode gap.
Important visible damages observed on zinc, copper and solar cells samples (**Figure 6**) resulted from long duration secondary discharges of more than 100µs.

Figure 6: photo of a solar cell sample. One can see clearly visible damages (molten metal between the two adjacent cells (scale: gap=1mm).

On other samples damages appeared clearly in the microscopic scale, for example in **Figures 3&4** where one can see the craters created by the cathode spots. Such tiny damages were observed also in locations where no secondary discharge was clearly identified, i.e. where both the current and voltage variations lasted no more than the electrostatic discharge duration

Depot: chemical analyses of the surface composition in local gap regions where no particles are seen indicate clearly the presence of zinc on dummy zinc samples. Such thin metallic films clearly degrade the gap insulating properties as observed through electrical resistance measurements between the electrodes. The inter-electrode resistance is seen to decrease from more than 500×10^{9} Ω on new samples to 20×10^{9} Ω after a few discharges, and even to some hundreds of ohms for samples on which important visible damage is seen following destructive arc discharges.

Lifetime: The secondary arc stability is showing a clear dependence with both the current and voltage alimentation (**Figure 7&8**).

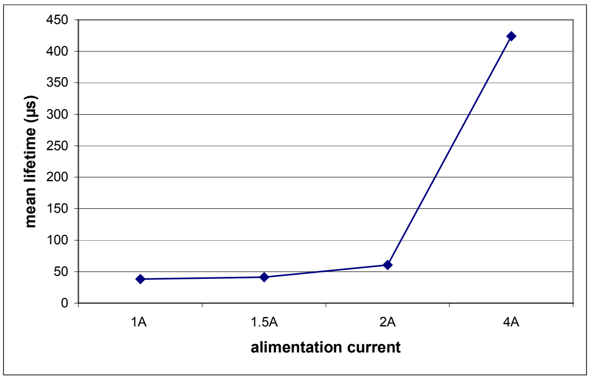

Figure 7: lifetime as a current function (zinc sample). Applied voltage=40V

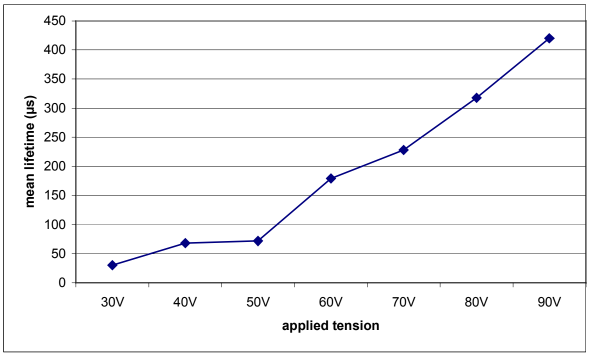

Figure 8: lifetime as an applied voltage function (copper sample). Current=4A

3. Conclusions

All experimental results presented in the present paper converge to a very specific type of electrical discharge referred to as “vacuum arcs”. The cathode arc foot is the source of very important fluxes of both metal vapour eventually condensing on nearby surfaces and of liquid droplets splashed away from the emitting sites. As such, the cathode spots are not only the location of important local degradation of the metallic electrode, but the source producing a metallisation of the surrounding surfaces. Electrical resistivity measurements effectively indicated a degradation of the gap insulate property with the number and/or duration of such discharges.

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