# SECONDARY ARCS ON SOLAR GENERATORS – EMAGS 2 TEST CAMPAIGN

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## Abstract

For few years, many tests have been performed on solar array samples around secondary arcs in order to validate a theoretical model, to determinate the arcing conditions and to conceive some mitigating techniques.

EMAGS 2 (Solar Array Triggered Arc Phenomena Study - ESA contract) is the continued effort of ESA to try to better define how tests should be performed. This study consists in an extensive test campaign on different solar array samples issued from actual EADS ASTRIUM programs as on dummy SA samples.

In this paper are then presented the five different tests that will be performed from June 2003 to June 2004 in JONAS vacuum chamber at ONERA DESP – Toulouse.

## Introduction

In 1997, it has been reported that 2 commercial satellites solar arrays suffered power losses in geostationary orbit, probably due to some destructive arc [RD1]. The reality of this phenomenon (low voltage self-sustained arc), linked to the fact that a satellite in GEO orbit tends to charge negatively because of the environment, has been demonstrated by ground tests.
Basically, self-sustained arcs between adjacent cells can be triggered if:

- the surface potential of coverglasses is less negative than the absolute potential of the satellite (this situation is called Inverted Voltage Gradient and allows the creation of ESDs between coverglasses and solar cells).
- a primary discharge (ESD) occurs in the gap between adjacent cells

- the voltage between these adjacent cells and the current available in case of secondary arc are sufficient to sustain the arc. The current available is at least the current of a string.

Self-sustained arcs can then result in a permanent short-circuit between adjacent cells or between cells and solar panel structure. The whole phenomenon theory is detailed in [RD2], [RD3], [RD4], [RD5] and [RD6]. Ground tests have also allowed to define some mitigating techniques (such as the installation of blocking diodes on each string) (eg [RD2]). Many tests are still performed on this subject to improve the theoretical model, to find new mitigating techniques or simply to check the immunity vs secondary arcs of new solar arrays. These tests can be performed either under electronic irradiation or in plasma. Contrary to tests in electron, tests in plasma allow to trigger more easily primary discharges but, on the other hand, are not representative of the GEO charging environment.

The first objective of EMAGS 2 is then to compare both methods by tests on dummy solar array samples using similar set-ups.

The second objective is to assess the voltage / current threshold for secondary arc triggering according to the cells type (GaAs triple junction or Si) and to the inter-cells gap (0.5 mm, 0.9 mm, 2 mm).

And finally, the last aim of EMAGS 2 is to determine the possible effects of repetitive primary discharges and secondary arcs on solar cells.

## <u>Comparison Between Tests in Electron and in Plasma (Test 1)</u>

### Introduction

During the first step of EMAGS 2, tests in inverted voltage gradient conditions have been performed on dummy solar array samples, first in an electronic charging environment and then in plasma. Tests on solar array samples under electronic irradiation, contrary to tests in plasma, are representative of the phenomenon but present some difficulties to trigger easily primary discharges in the gap between cells. A comparison of the results (occurrence and characteristics of primary discharges and secondary arcs) can then allow to validate the representativity of a test in plasma and also to determine the satellite capacitance to be used in plasma test. These tests have been performed on dummy samples (Cu) because the triggering of primary discharges is easier to control on such samples than on real solar array samples.

### Test conditions

Tests in IVG under electronic irradiation (energy of about 6 keV and current density of about 1nA/cm$^2$) as tests in plasma (Argon with a density of 10$^4$/cm$^3$) have been performed in JONAS vacuum chamber (ONERA DESP) on identical samples. These samples consisted in an epoxy plan with two copper surfaces (about 5 x 5 cm) simulating solar cells. One of these surfaces was partly covered with a teflon SSM to trigger the primary ESD (see Figure 1).

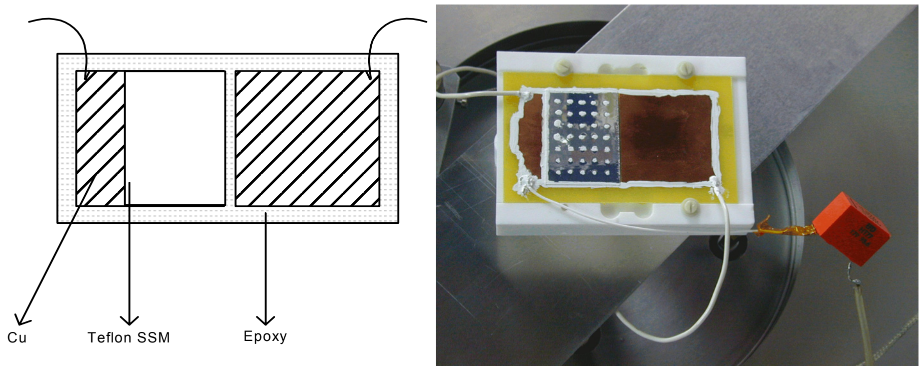


**Figure 1. Dummy samples**

The gap between both copper surfaces was about 0.9 mm, which is representative of SA samples.

## Test set-up

The test set-up in electron was the following:

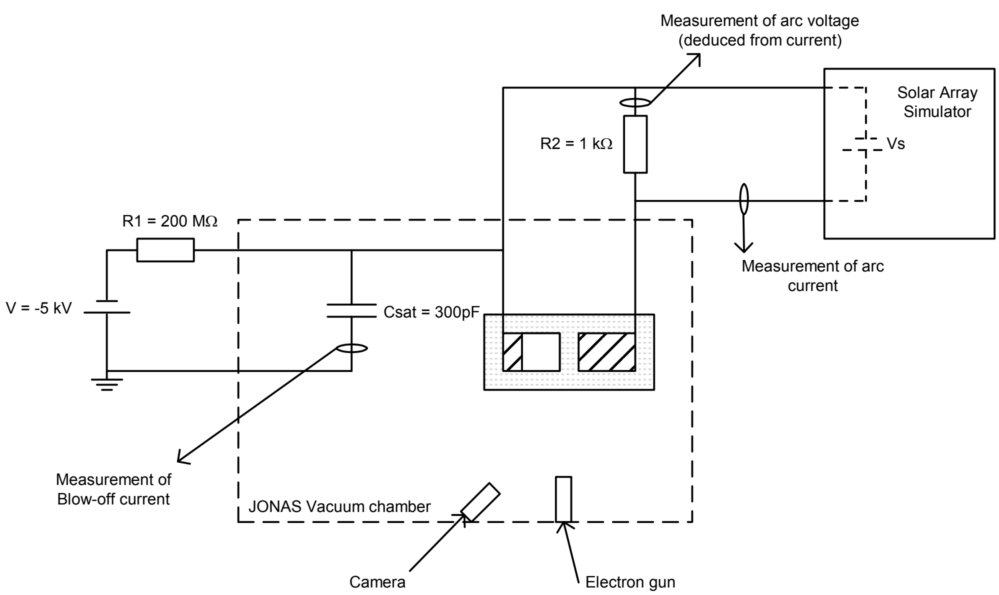


**Figure 2 – Set-up for electron irradiation (Test 1)**

During the tests, the following measurements were performed:

- blow-off current (Pearson current probe placed on the satellite capacitance)
- secondary arc current (current probe placed on the output of the solar array simulator)
- secondary arc voltage (current probe placed on the 1 kΩ resistance)

The whole circuit is floating with regard to chamber structure (except for the high voltage supply for which the return wire is connected to the chamber structure). The satellite capacitance is placed as close as possible to the sample.

Csat (about 300 pF) represents the absolute capacitance of a satellite wrt to the GEO plasma (assessed between 100 pF and 300 pF depending on the satellite). This capacitance is biased by a high voltage supply to –5kV through a decoupling resistance of 200 MΩ. In case of a primary discharge, the blow-off current is provided by Csat and also by a spurious capacitance of about 500 pF brought by the set-up (so a total capacitance of about 800 pF - the physical capacitance placed inside the vacuum chamber is nevertheless expected to have a prevailing influence wrt the blow-off current as the harness length wrt the sample is much shorter for this capacitance).

The solar array simulator (power supply with a current limiter at its output) allows to apply a voltage between the adjacent copper cells. In the case of a secondary arc triggering between these cells, the current is limited by the SAS. The used solar array simulator has the advantage to produce an acceptable current overshoot in case of secondary arc (duration < blow-off rise time and limited amplitude), which is an important aspect with regard to the representativity of the test.

For tests in plasma, the set-up is the same than the previous one except that the cells are biased to -1.5 kV instead of -5 kV. Indeed, at higher bias voltage values in plasma, we constate that most of the primary discharges are not triggered in the gap (so no risk of secondary arc).

Moreover, in order to obtain more easily primary discharges in the inter-cells gap, a conductive mask is placed between the plasma source and the sample.

In the test under electron irradiation, the satellite capacitance used was about 800 pF (total). The bias voltage being 3.3 times lower in plasma tests, the satellite capacitance to be used is then necessarily different.

To determine the value of Csat which allows a test in plasma to give results close to those obtained in electron, tests in plasma were performed with 3 different capacitance values:

- 3 nF to be representative of the charges amount (Q=C.V ; 800pF.5000V = 2.7nF.1500V)
- 10 nF to be representative of the total energy ( $E=C.V^2/2$ ; $800pF.5000^2V^2/2 = 9nF.1500^2V^2/2$)
- 300 nF (worst case approach)

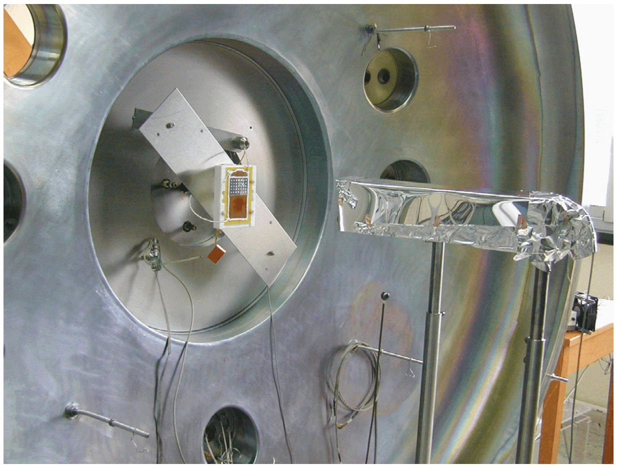

**Figure 3. Installation of the dummy sample in JONAS vacuum chamber**

Tests have been performed at 5 voltage values between cells (set at SAS level): 30, 35, 40, 55 and 70 V.

The different limits of the available current in case of secondary arc were:

- 0.6 A (representative of the max current in a triple junction GaAs cells string)
- 1.1 A (representative of the max current in a Si cells string)
- 2 A

So, for each of the 4 test set-ups (electron with a capacitance of 800 pF, plasma with 3 nF, plasma with 10 nF and plasma with 300 nF), 15 voltage/current configurations have been tested (with at least 3 primary discharges in the gap in each case).

**First results**

No self-sustained arc has been observed during these tests probably because the current available in case of arc was limited to 2 A max.

Nevertheless, many secondary arcs with duration of few 10 µs (for low voltage / current configurations) up to few 100 µs have been measured.

In any case, tests in plasma don't give results very different from those obtained in electron, which tends to validate the representativity of such tests.

With regard to the arc occurrence rate (secondary arc triggering with respect to the number of primary discharges in the gap), the 10 nF capacitance in plasma (with a bias voltage of -1.5kV) allows to obtain results similar to the tests in electron (especially for currents of 1.1 A and 2 A).

With regard to the secondary arc average durations, the results in plasma are close to those in electron, for a capacitance value of 300 nF.

Before setting the capacitance value to be used in the next tests of EMAGS 2 (in plasma), many other comparisons between results have still to be done (arc voltage characteristics, arc impedance, primary discharge characteristics...).

## Tests on solar array samples

The other tests of EMAGS 2 will be performed in plasma (Argon) in JONAS vacuum chamber at ONERA DESP on solar array samples issued from actual EADS ASTRIUM programs. All these tests will be based on the same test set-up including the satellite capacitance that will be determined after the complete review of the results of the first test.

These tests aim to assess the:

- influence of the cell type wrt secondary arcs triggering
- influence of the gap length wrt secondary arc triggering
- effect on solar cells of repetitive primary discharges
- effect on solar cells of repetitive secondary arcs (not self-sustained)

**Test set-up**

For all the next tests, the set-up will be the following:

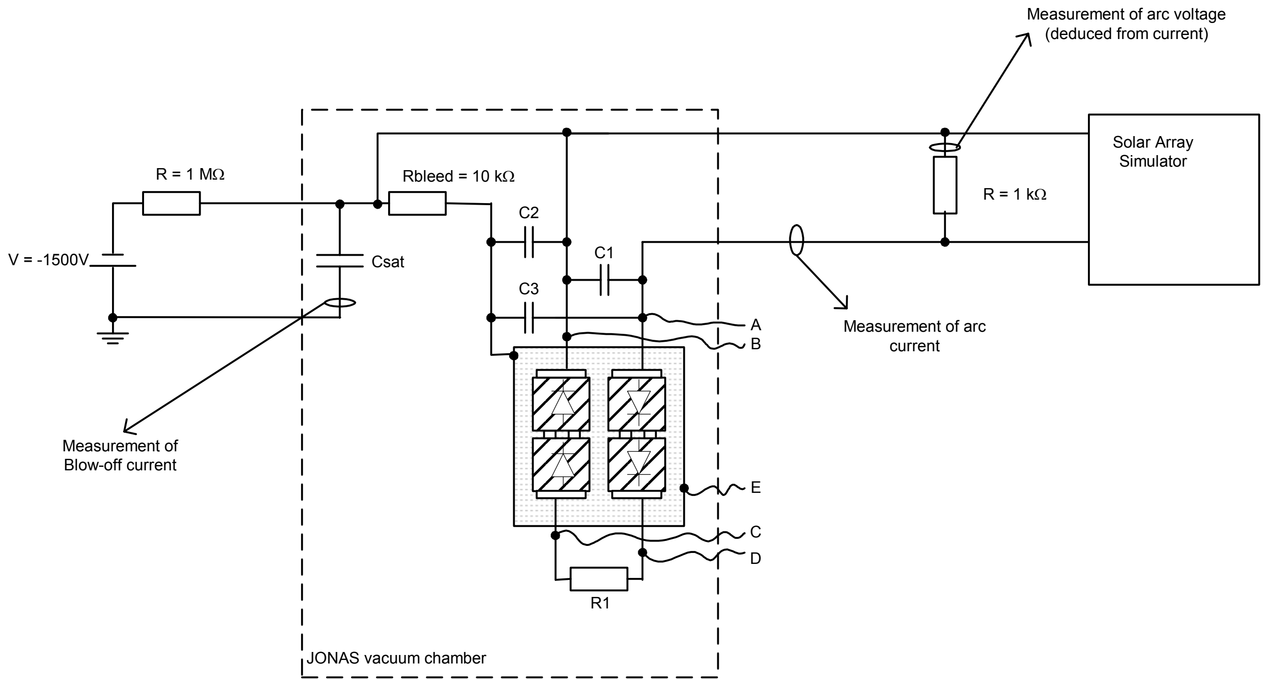


**Figure 4. Test set-up**

Csat will be determined according to the results of the first test (comparison electron / plasma).

R1 will be about 5 kΩ in order to create a steady state current in solar cells of about 10 mA.

C1 represents the junction capacitance of a whole string and will be set to about 300 nF for a GaAs string and 100 nF for a Si string (approximation based on the cell junction capacitance at the functional point and on the number of Si and GaAs cells by string).

C2 and C3 aim to represent the capacitance of the whole string wrt panel structure (kapton capacitance) and are then assessed considering the surface of a solar cell, the thickness of kapton and glue under a cell and the number of cells in a string. C2 and C3 values will then be set to about 15 nF in case of a string of GaAs cells and to about 50 nF in case of a Si string.

The test set-up used for a Si solar array sample will then be slightly different from the one used for a GaAs sample (C1, C2, and C3 necessarily different to be representative).

A, B, C, D and E wires will allow to perform the good-health check test on solar cells i.e. the measurement of the I(V) characteristic of both solar cells rows in darkness (between A and D or between B and C) and the isolation measurements between solar cells and structure (between A, B, C or D and E).

In order to obtain more easily primary discharges in the inter-cells gap, a conductive mask will be placed between the plasma source and the sample.

During all tests, arc voltage and current as blow-off transient current will be measured.

**Influence of the cell type (Test 2)**

The aim of this test is to assess the influence of the cell type in the secondary arc phenomenon. Comparative tests will then be performed on two solar array samples with either Si cells or triple junction GaAs cells and in each case, the voltage / current thresholds for secondary arc (and/or sustained arc) triggering will be determined.

The samples are similar: on each sample, 2 rows of 2 solar cells in serie (similar sizes and CMX coverglass in both cases) are bonded on a kapton layer. The support is a NIDA with two carbon fiber layers (see next figure).

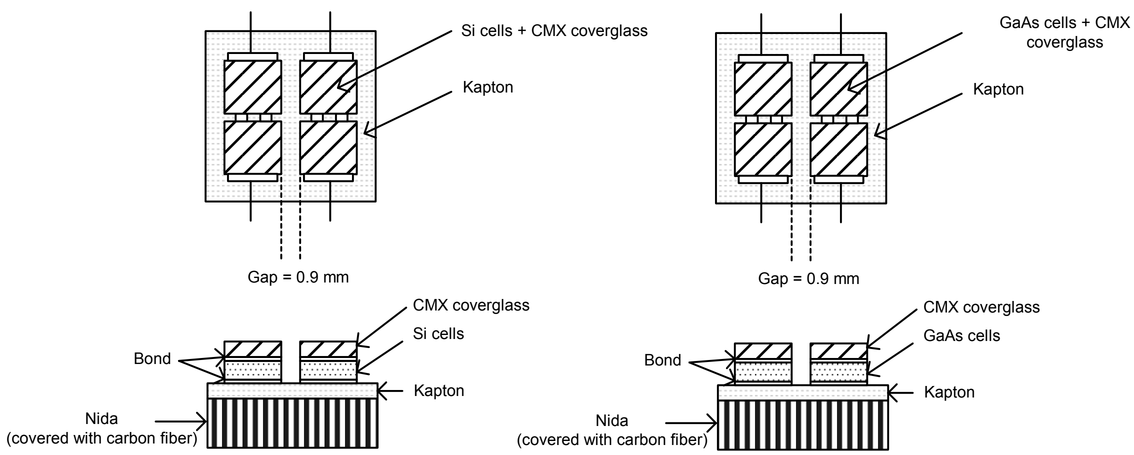


**Figure 5. Samples definition (comparison Si / GaAs)**

In both cases, the inter-cells gap is of 0.9 mm and the coverglass position on the cells doesn't present an overlapping in the gap.

Tests will be done for SAS current limits of 0.6 A (representative of the max current in a triple junction GaAs cells string), 1.1A (representative of the max current in a Si cells string), 2 A and 3 A. For current limits of 0.6 A and 1.1 A, tests will be performed only at 50 V, 70 V and 90 V because such current limits are not expected to present a high risk of self-sustained arc triggering.

For current limits of 2 A and 3 A, tests will be done at SAS voltage values from 30 V to 90 V (by step of 10 V).

So, for each of the 2 sample types, 20 voltage/current configurations will be tested (for each configuration, a minimum number of 3 primary discharges in the gap is required).

The following data will then be determined for each cell type:

- maximum values of voltage between cells and current limit for no secondary arcing (wrt GaAs coupon, this data is an input for the test of primary discharge cumulative effect)
- thresholds (voltage / current) for aborted secondary arcs (wrt GaAs coupon, this data is an input for the test of secondary arc cumulative effect)
- thresholds (voltage / current) for self-sustained arcs

The secondary arc sensibility to the solar cells material will then be assessed.

**Gap sensitivity characterization (Test 3)**

The aim of this test is to assess the influence of the inter-cells gap in the secondary arc triggering. Comparative tests will then be performed on three solar array samples (Si cells) with different gap values. In each case, the voltage / current thresholds for secondary arc (and/or sustained arc) triggering will be determined. On each sample, 2 rows of 2 solar cells in serie (Si with CMX coverglass in any case) are bonded on a kapton layer. The support is a NIDA with two carbon fiber layers (see next figure).

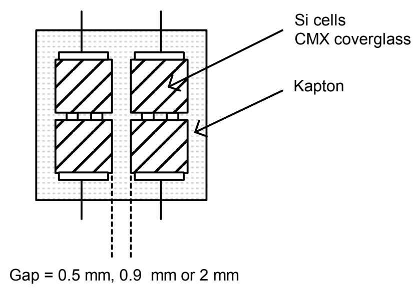


**Figure 6. Samples definition (gap sensitivity)**

The three samples are identical except with regard to their inter-cell gap:

- 0.5 mm (worst case gap)
- 0.9 mm (nominal gap value between adjacent cells of a same string for solar arrays)
- 2 mm (nominal gap value between adjacent cells of different sections for solar arrays)

In all cases, the coverglass position on the cells is identical (no overlapping in the gap).

Test will be performed for SAS voltages between cells from 30 V to 90 V (by step of 10 V) and for the current limits of 1.1A (representative of the max current in a Si cells string), 2 A and 3 A.

So for each of the 3 sample types (gap of 0.5mm, 0.9 mm or 2 mm with Si cells in any case), 21 voltage/current configurations will be tested (for each configuration, a number of 3 primary discharges in the gap, with or without secondary arc triggering, is required), which will allow to determine in each case:

- thresholds (voltage / current) for aborted secondary arcs
- thresholds (voltage / current) for sustained secondary arcs

The secondary arc sensibility to the gap distance can then be assessed.

**Primary discharges cumulative effect (Test 4)**

The aim of this test is to characterize the cumulative effect of primary discharges on a same solar array sample (triple junction GaAs cells with CMX coverglass and gap of 0.9 mm). This test will then be performed at a unique SAS voltage / current configuration (voltage between cells/ current limit) chosen with regard to results of tests 2 (configuration for which only primary discharges were observed on a GaAs sample). A solar cells characterization (measurement of I(V) cells characteristics) will be performed before and after the test (in full darkness) to check that repetitive primary discharges don't affect the solar cells performances (which is expected because of the low energy contained in primary discharges).

**Secondary arcs cumulative effect (Test 5)**

The aim of this test is to characterize the cumulative effect of aborted secondary discharges on a same solar array sample (triple junction GaAs cells with CMX coverglass and gap of 0.9 mm). This test will be performed for a unique configuration of voltage between cells/ current limit chosen with regard to results of tests 2 (configuration for which aborted secondary arcs only were observed on an identical sample). The possible effect of aborted secondary arcs on solar cells will be checked comparing the I(V) characteristics (in darkness) of the solar cells before and after many secondary arc (not self-sustained).

## Conclusion

The tests performed in the frame of the second phase of EMAGS 2 (ESA study) will then allow to:

- compare with regard to secondary arcing, tests under electron irradiation (most representative) with tests in plasma (discharges more easy to obtain) in order to define a representative set up in plasma
- assess the sensibility of secondary arc triggering with regard to the solar cells material (Si, GaAs)
- assess the sensibility of secondary arc triggering with regard to the inter-cells distance (Si)
- determine the effect of repetitive primary discharges on solar cells (GaAs)
- determine the effect of repetitive secondary arcs on solar cells (GaAs)

A summary of the EMAGS 2 test campaign is given in the following table :

| Test | Environment | Sample | Output |
|---|---|---|---|
| Set-up validation (Test 1) | - Electron irradiation<br><br>- Plasma | - Copper cells covered by teflon SSM | - Comparison of secondary arcs and primary discharges<br>- Determination of the satellite capacitance to use in plasma tests (input for tests 2, 3, 4 and 5) |
| Material comparison (Test 2) | Plasma | - Si cells / CMX / 0.9 mm gap<br><br>- Triple junction GaAs cells / CMX / 0.9 mm gap | - Thresholds for aborted secondary arcs and self-sustained arcs (input to tests 4 and 5 wrt GaAs cells)<br>- Secondary arc sensitivity to solar cells material |
| Gap sensitivity (Test 3) | Plasma | Si cells / CMX /<br>- 0.5 mm gap<br>- 0.9 mm gap<br>- 2 mm gap | - Thresholds for aborted secondary arcs and self-sustained arcs<br>- Secondary arc sensitivity to the gap between cells |
| Primary discharges cumulative effect (Test 4) | Plasma | Triple junction GaAs cells / CMX / 0.9 mm gap | Cumulative effect of primary discharges on solar cells (SAS voltage / current defined according to results of test 2) |
| Aborted secondary arcs cumulative effect (Test 5) | Plasma | Triple junction GaAs cells / CMX / 0.9 mm gap | Cumulative effect of aborted secondary arcs on solar cells (SAS voltage / current defined according to results of test 2) |

**Acknowledgement**

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