LABORATORY TEST OF ARCING ON SATELLITE POWER CABLES

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Abstract

In Low Earth Orbit, cracks are often made at the power cable of a satellite by debris, heat cycle, etc. Triple junctions are formed from these cracks. Then arcs may occur. On a satellite, the cables of HOT and RTN are placed close to each other in many cases. Therefore, secondary arc may occur if arc tracking is formed. If permanent sustained arc takes place, the cable is carbonized and burned out. At the worst case, it will spread to neighboring cables. If it becomes so, the satellite may lose power from the solar panel. The purpose of this study is to investigate the conditions by which self-sustained electrical discharge is generated on cables. An experiment was carried out in a vacuum chamber which simulated Low Earth Orbit environment. A substrate made of CFRP (Carbon Fiber-Reinforced Plastics) was used. The experiment was carried out by placing the cables with cracks on the CFRP surface or on Kapton facesheet over the CFRP. Many secondary arcs, even permanent sustained arcs were observed in both environments. In the test of simulating front surface, permanent sustained arc occurred when the condition of the string voltage was 200V and the line current was 2.7A. In the test of simulating back surface, because the CFRP substrate was exposed, primary arcs occurred frequently. The arc plasma led to the permanent sustained arc between the cable and the substrate.

1. Introduction

At the end of October 2003, a LEO satellite, ADEOS , suffered an accident where the generation power by solar panel decreased to about 1kW from 6kW in about three minutes. This was because of the sustained arc phenomenon on cable bundles [1].

The mechanism of sustained arc is shown in Fig.1. Under the Low Earth Orbit (LEO) environment, the space plasma, whose density is of the order of 10^{10}~10^{12}m^{-3}, can charge the spacecrafts to a negative potential with respect to the plasma, because of electron's higher mobility than ions. When the spacecraft employs high voltage power generation and metallic/dielectric triple junction is exposed to plasma, an arc occurs. An arc on cable bundles is usually a pulse of current whose energy is supplied by the electrostatic energy stored on nearby dielectric material due to charging via positive ions. Such an arc is often called primary arc. Moreover, a single arc might shorten momentarily the adjoining cable and the current flows for a much longer time than a trigger arc by receiving energy from the array circuit. Such an arc is called secondary arc especially, non-permanent sustained arc. A secondary arc might lead to permanent short-circuit in the array circuit and the arc current keeps flowing until thermal breakdown of insulative layer occurs. Such an arc is called permanent sustained arc. In Fig.2 we show the definition of each arc. We report the test result regarding secondary arcs in this paper.

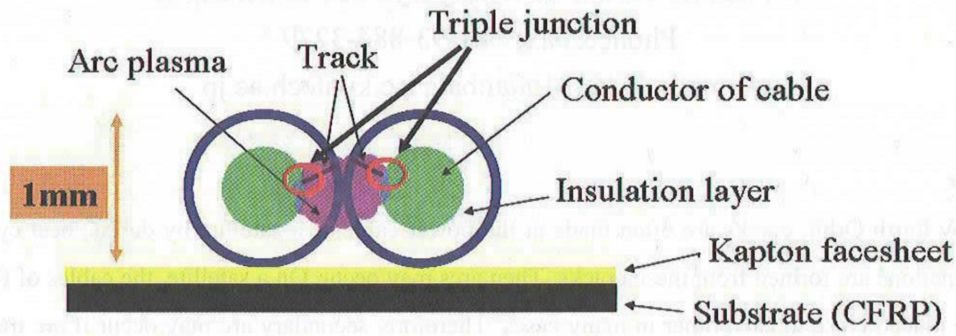

Figure1: Structure of cable on satellite

2. Experiment

2-1 Test sample

The cable used in experiment is the same as that of actual spacecraft. The conductor type of cable is a silver coated copper, and the insulation layer is made of ETFE. AWG (American Wire Gauge) of the cable is 22. We carried out two tests. The first test is to simulate the front surface of the solar panel. The second test is to simulate the back of it. At the front surface, the CFRP/Aluminum honeycomb substrate is covered with the polyimide insulation sheet. At the back surface, the CFRP/Aluminum honeycomb substrate is bare. We prepared two kinds of samples as shown in Fig.3 and Fig.4. The sample of front surface has ten pairs of cracks. All the pairs have two cracks facing each other with separation distance ranging from 0.1mm to 0.5mm. The sample of back surface has three pairs of cracks facing with separation distance of 1.1mm at maximum. On the back surface there are also six cracks on single cables without pairing cracks.

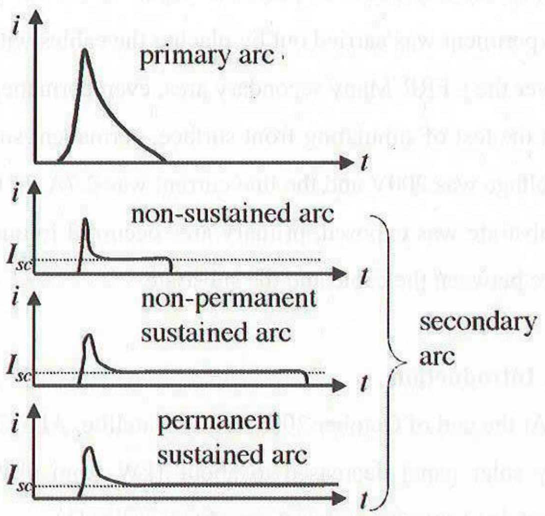

Figure2: Definition of each arc

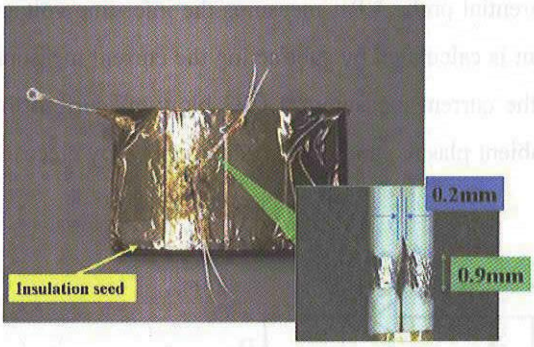

Figure3: The sample of front surface

Figure4: The sample of back surface

2-2 Measurement system

A schematic picture of experimental set-up is shown in Fig.5. The experiments were performed in a vacuum chamber, which was 1m in diameter and 1.2m in length. The pressure in the chamber could reach up to about 5×10^{-6}Torr, and was 1.2×10^{-4}Torr during the experiments. The plasma was produced by an ECR plasma source. The plasma density around the coupon was about $1\times10^{12}m^{-3}$ and the electron temperature was about 1eV with xenon gas of 0.3sccm.

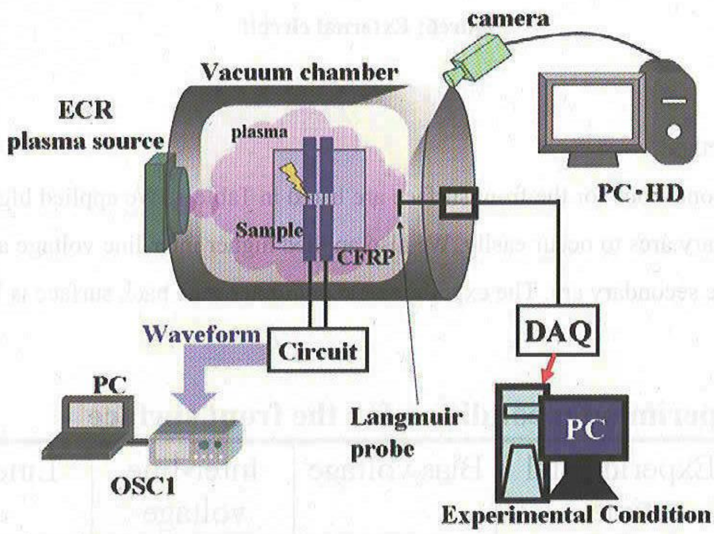

Figure5: Schematic picture of experimental set-up

The external circuit is shown in Fig.6 [2]. The direct current source in Fig.6 is SAS (Solar Array Simulator: Agilent: E4351B) which simulates solar array while generating power. SAS is different from other ordinary DC power supplies, with high speed of recovery time within five microseconds, and the output capacitance less than 50nF. It has a suitable characteristic to respond to a high-speed primary arc phenomenon. The resistance R_L simulates the load of the satellite, and $C_1 \sim C_3$ are associated with a solar cell string. The voltage V_{bias} simulates the charging potential of the satellite. Because a primary arc occurs frequently, the value has been changed. The current probes CP1 and CP2 (HIOKI: 3272) distinguish secondary arc from primary arc. The differential probe VP1, measures the inter-line voltage. When a primary arc becomes secondary arc, arc current is calculated by subtracting the current measured at CP2 from the current measured at CP1. We call the current measured at CP3 blow-off current that simulates the current between spacecraft body and ambient plasma, and the current supplied by electrical charge stored on spacecraft insulator surface.

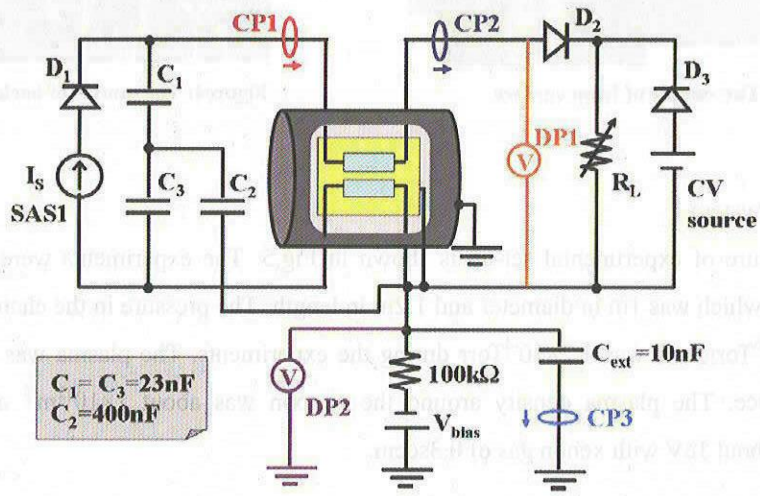

Figure6: External circuit

2-3 Experimental method

The experimental conditions for the front surface are listed in Table 1. We applied higher bias voltage in order to induce primary arcs to occur easily. We also applied higher inter-line voltage and the line current in order to induce the secondary arc. The experimental condition of the back surface is listed in Table 2.

Table1: Experimental condition for the front surface

Test No.	Experimental time	Bias voltage	Inter-line voltage	Line current
1	6m20s	−400V	100V	1.3A
2	5m45s	−400V	200V	1.3A
3	10m52s	−800V	200V	1.3A
4	15m07s	−900V	200V	2.7A

Table2: Experimental condition for the back surface

Test No.	Sample	Experimental time	Bias voltage	Inter-line voltage	Line current
1	3	45s	−400V	100V	1.3A
2	3	1m	−300V	100V	1.3A
3	3	4m39s	−200V	100V	1.3A
4	1 &2	24s	−200V	100V	1.3A

3. Result

3-1 Result of the front surface test

The arc positions of the front surface test are shown in Fig.7. The primary arcs occurred on the triple junctions where the conductor of the cable was exposed. The typical current waveform of primary arc is shown in Fig.8. The experimental result of front surface is shown in Table3. The ratio of the secondary arc to the primary arc increased with the increased inter-line voltage or line current. In each condition, the ratio was 36%, 62% and 92%, respectively. This result shows that secondary arc occurs easily when the inter-line voltage and line current become large.

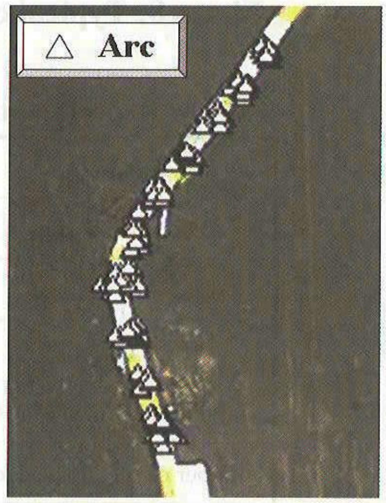

Figure7: Arc position of front surface test

The typical current waveform of secondary arc is shown in Fig.9. Arc current has the waveform of short circuit current, when the gap between the cables is connected by the low-resistance arc plasma. We defined secondary arc as an arc event that lasted longer than corresponding primary arc. We also defined the secondary arc duration as the time difference between the time width of blow-off current and the time width of arc current. The change of the arc resistance shown in Fig.10 was calculated by the ratio of the inter-line voltage to the arc current. The minimum value was defined as the minimum arc resistance. We plotted all of the secondary arc (non-permanent sustained arc) durations in the horizontal axis, and arc resistance in the vertical axis of Fig.10. When the secondary arc duration became long, the arc resistance became small. This arc resistance has approached to the value of the arc resistance observed when permanent sustained arc occurred.

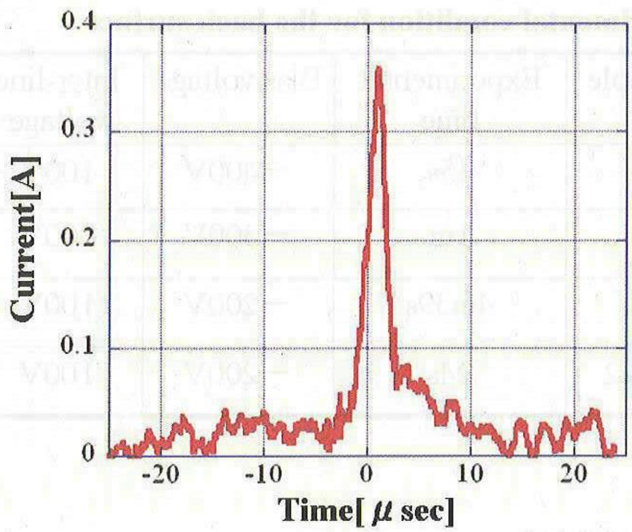

Figure8: Typical current waveform of primary arc

Table3: Experimental result of front surface

Test No.	1	2&3	4
Experimental time	6m20s	16m37s	15m07s
Inter-line voltage	100V	200V	200V
Line current	1.3A	1.3A	2.7A
Number of primary arcs	78	167	24
Number of secondary arcs	28	103	22
Secondary/Primary	36%	62%	92%
Permanent sustained arc	×	×	○

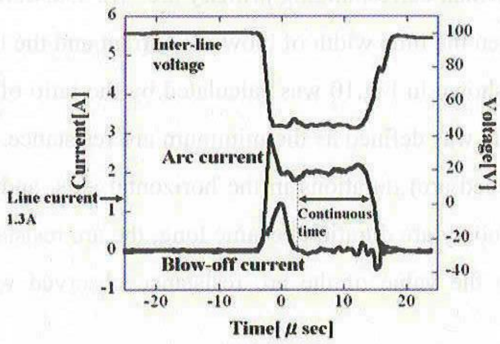

Figure9: Typical current waveform of secondary arc (non-permanent sustained arc)

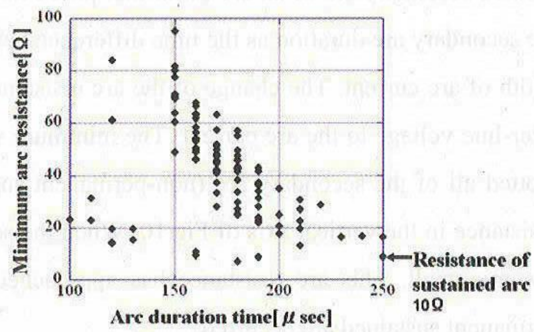

Figure10: Relation of arc duration time and minimum arc resistance

3-2 Result of the back surface test

Primary arcs occurred much more frequently on the bare CFRP substrate in the back surface test. About 2000 primary arcs occurred for about 15 minutes in this test. The arc positions of the back surface test are shown in Fig.11. When primary arc occurred frequently at the crack or near the crack, the sustained arc occurred easily. Table4 lists the number of primary arcs within 1mm from the crack whose locations were confirmed by the CCD video image.

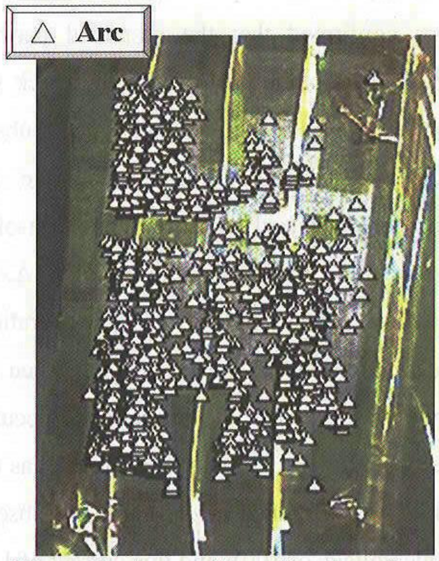

Figure11: Arc position of back surface test

If permanent sustained arc takes place, the cable is carbonized, burned out and arc spreads to neighboring cables. The appearances before and after the permanent sustained arc are shown in Fig.12. The permanent sustained arc occurred at HOT side in Fig.12, and the cable burned out. A part of the cable carbonized also on the RTN side.

Table4: Experimental result of the back surface

Crack	Experimental time	Width of crack [mm]	Primary arc	Permanent sustained arc
3−1−A	6m48s	8.3	149	×
3−1−B	6m48s	10.2	255	○
3−1−C	6m48s	8.1	408	×
3−1−D	6m48s	11.3	369	×
3−1−E	6m48s	11.3	320	×
3−2−A	6m48s	7.1	16	×
3−3−A	8m57s	5.3	115	×
3−3−B	8m57s	4.3	106	○
3−3−C	8m57s	27.1	119	×

4. Summary

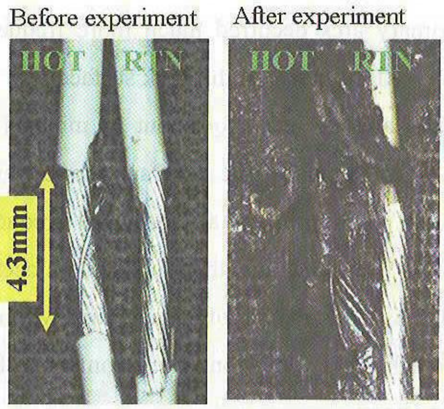

Figure12: Photographs of before and after sustained arc

It was confirmed that the sustained permanent arc occurred between the cables with the crack when they are on the solar panel. Because the substrate was insulated in the front surface test, the permanent sustained arc occurred under the condition of inter-line voltage of 200V and the line current of 2.7A. Moreover, there were correlations between the duration of the secondary arc and the arc resistance. When the CFRP substrate was exposed, the primary arc occurred much more frequently on the substrate. If cable has cracks, the probability of sustained arc is high. We observed the permanent sustained arc under the condition of inter-line voltage of 100V and line current of 1.3A. As the next step of this study, we need to carry out test with more realistic samples.

5. References

[1] S. Kawakita, H. Kusawake, M. Takahashi, H. Maejima, J. Kim, S. Hosoda, M. Cho, K. Toyoda, Y. Nozaki, "Sustained Arc between Primary Power Cables of a Satellite", 2nd International Energy Conversion Engineering Conference and Exhibition, August, 2004 (RI, USA)

[2] Payan D., Schwander D. and Catani J. P.: "Risks of low voltage arcs sustained by the photovoltaic power of a satellite solar array during an electrostatic discharge. Solar Arrays Dynamic Simulator", 7th Spacecraft Charging Technology Conference, ESA-ESTEC, Noordwijk, Netherlands, 2001.