Status of ISO Standardization of ESD Test of Satellite Solar Array

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ABSTRACT

Frequent satellite failures due to charging and arcing on solar array surface, there are strong demands for more thorough electrostaic discharge (ESD) ground test before the launch. It is necessary to validate that a given solar array design can withstand repeated arcing in space before the launch. Test conditions, however, differ among countries, as there is no international standard to define the conditions. An international research project started in 2005 to establish International Standard Organization (ISO) standard on ESD test. In the first year, test coupons of the international round robin tests were produced and the preliminary experiments were carried out. In September 2006, the team members gathered at ONERA, Toulouse France. Demonstration experiments were carried out and in-depth discussion was done regarding the preliminary test results of KIT. In November 2006, the First International Workshop on ISO Standardization of Electrostatic Discharge Test of Satellite Solar Array was held in Kitakyushu. The first version of the working draft of ISO document was discussed in the workshop and the participants agreed to seek the ISO standard by as early as Fall 2008.

1. Introduction

Since the accident on Tempo-2 in 1997 where the satellite suddenly lost 15% of the total power due to sustained arc[1], various research institutions carried out the ground tests to verify that a given design of solar array has sufficient immunity against the secondary arc phenomena. The test methods, however, were not necessarily the same among the different institutions. Series of malfunction of satellite solar array calls for more careful tests and international atmosphere surrounding GEO telecommunication satellites calls for common international standard regarding the test methods.

Since 2001, the need of the international test standard has been recognized among the experts of spacecraft charging. The experts from all over the world met at 9th Spacecraft Charging Technology Conference (SCTC) in 2005 at Tsukuba Japan to define a roadmap to make an ISO (International Standard Organization) standard regarding the test method. At 9th SCTC, a resolution was passed, where the experts agreed to fully cooperate and make best efforts as experts to draft an ISO standard on solar array ESD ground test by 10th SCTC in 2007 and establish the standard within 3 years. At 9th SCTC, the experts also identified issues remaining to reach agreement on the standard ESD test method. The NEDO-grant research project “ISO Standardization of Electrostatic Discharge (ESD) Test of Satellite Solar Array” started under these circumstances. The team members are made by 13 members from 11 organizations, namely KIT, JAXA, Sharp Corp. Mitsubishi Electric Corp., NEC-Toshiba Space Systems, Ltd., CNES, ONERA, Alcatel-Alenia Space, EADS Astrium, NASA and Ohio Aerospace Institute.

The purpose of this research project is to establish International Standard Organization (ISO) standard on ESD test. We will carry out the following items;
(1)Find an effective test method that simulates the charging and arcing phenomena in space in a physically correct manner via international round-robin experiments.

(2)Exchange information via mutual visit exchange of test facilities
(3)Write an ISO document via international workshops.
During the first year of the project, the test coupons for the round-robin experiments were made and preliminary experiments were carried out. Visits to the test facility at OENRA, France and KIT, Japan were organized. During the visits, a demonstration experiment was carried out and the discussion on the ISO standard was held. In this report activities of the first year are summarized.

2. International Round Robin Experiment

2.1 Test coupons

Three types of test coupons were prepared. They are named as Type-A, Type-B and Type-C and their pictures are shown in Fig.1.

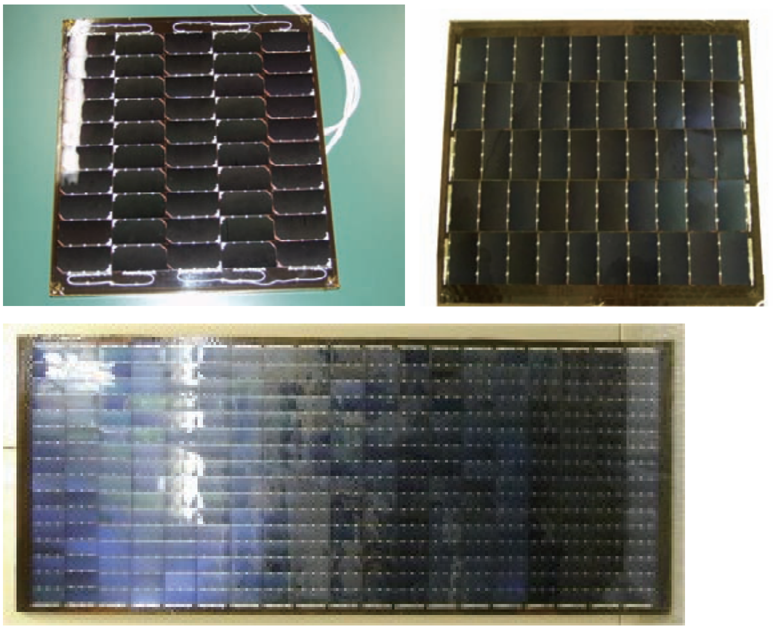

Figure 1-a: Photopgraph of Type-A coupon. GaAs coupon (upper left), small Si coupon (upper right) and large Si coupon (bottom)

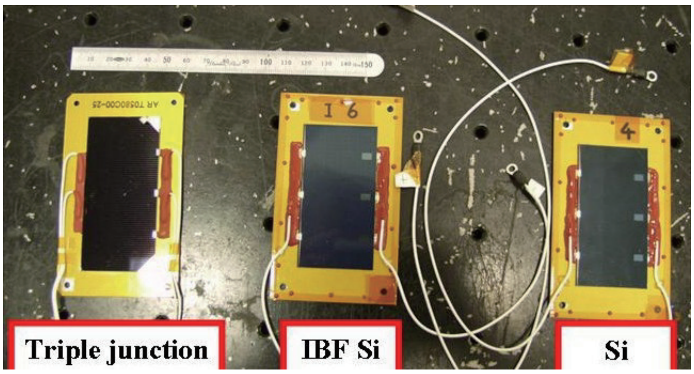

Figure 1-b: Photograph of Type-B coupons.

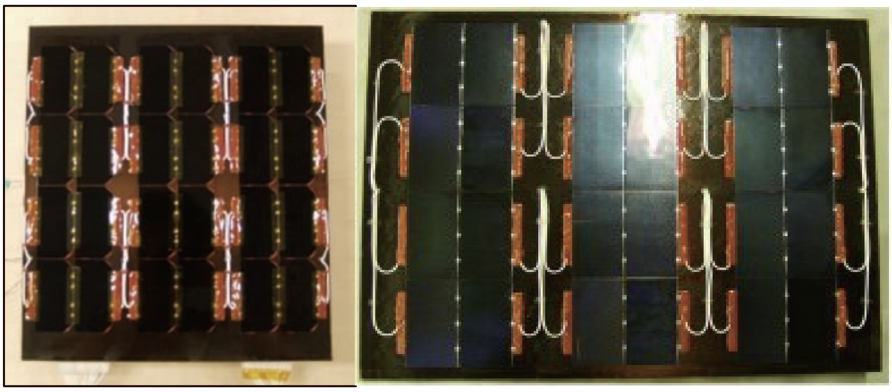

Figure 1-c Photrograph of Type-C coupon. TJ cells (left) and Si Cells (right)

The purpose of the type A coupon is to investigate energy and current injection to primary arc plasma via coverglass charge. When a primary arc occurs, arc plasma expands over the solar array surface like surface flashover. The plasma makes current path between the coverglass surface and the arc inception point and the charge of coverglass is released like a RC discharge where R is the resistance of arc plasma and C is the capacitance of coverglass.

There has been controversy over how far this arc plasma bubble expands, because the area covered by the arc plasma determines the total capacitance and energy involved in the RC discharge. Because the solar array ESD tests are carried out in a finite volume of a vacuum chamber, the size of solar array coupon is limited, which is often much smaller than the area that the arc plasma will cover. Therefore, we usually adjust the external capacitance C_{ext} to make the energy injected to the arc plasma the same as the one in orbit.

The energy supplied by the external capacitance C_{ext} is important from two points of view. They are the following;

- The arc energy may determine the primary arc conductivity and likelihood of a primary arc becoming a secondary arc.
- The arc energy determines likelihood of solar cell performance degradation.

Various institutions carried out experiment to measure how far arc plasma expands over solar array[2,3,4,5]. So far, we have not seen the limit of the plasma expansion. In Refs.2 and 3, coverglass of entire solar panel of 1m size lost charge due to a primary arc. At present the majority of opinion is that we have to prepare for the case where arc plasma expands over a full panel or even a full paddle. Then the energy supplied by the external plasma will become of the order of 1J. Although the energy supplied by coverglass might be very large, it is not injected instantaneously as the arc plasma expands with a finite velocity. The expansion velocity measured by the various institutions vary from 0.7×10^4 m/s to 1.4×10^4 m/s for the case of inverted potential gradient under electron beam irradiation[2,4,5].

The remaining issues are to agree on the limit of plasma expansion, if any, and to agree on the expansion velocity. With the agreements, we can propose a model of appropriate current waveform that simulates the primary arc current that would occur in orbit. Once the current waveform is fixed, the external circuit connecting the capacitance C_{ext} should be modified to reproduce the waveform.

The type A coupons shown in Fig.1-a were originally made during a joint research project of KIT/MELCO/Sharp/ONERA/CNES/Alcatel. The NEDO-grant research project started based on the previous collaboration of the six parties. The six parties research members agreed to use some of the results obtained using the type A coupons shown in Fig.1-a, as making additional sets of type-A coupons were very expensive. The type-A coupons consist of mechanical solar cells that do not necessarily have flight quality electrical output. But the way the solar cells are laid down and the substrates are the same as typical flight solar arrays. The TJ coupon has MgF2 AR coating so that luminescence associated with expanding plasma can be easily detected by a high speed camera. The TJ coupon and the small Si coupons has been tested at KIT. The large Si coupon was tested at ONERA and will be shipped to NASA/OAI for further test in late 2006.

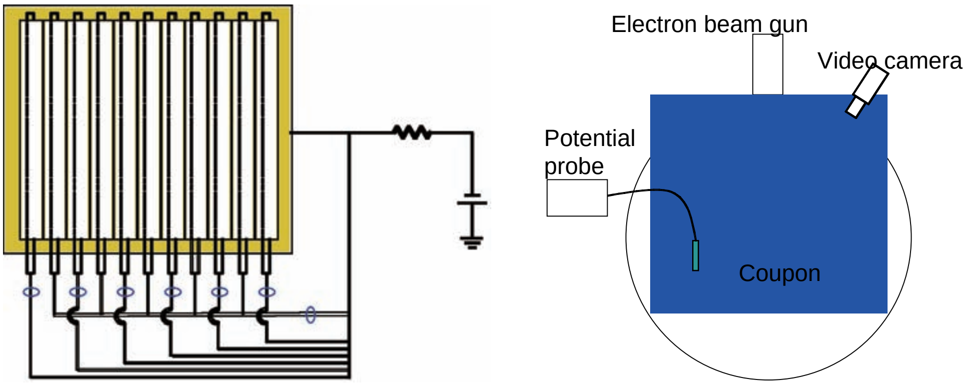

Figure 2: Circuit diagram of Type-A coupon test and test set-up..

In the type-A coupon tests, we bias the coupon without any external capacitance. The current to/from every solar cell strings (5 strings for the small Si and theTJ coupons) is measured by a current probe (see Fig.2). When an arc occurs at one string, the coverglass of the unarced string will provide charge to the arced string. By measuring the current, we can know from how far away unarced string can provide the charge. Also by measuring the time-delay among the currents, we can deduce the propagation speed of the expanding plasma. The expansion can be directly observed by a low-light video camera if coverglass emits luminescence (Fig.2). Non-contacting surface potential probe is also used to measure the change of surface charge distribution before/after each arc.

The purpose of type B coupon is to investigate Solar cell degradation due to repeated primary arcs. During the past ESD tests at KIT, we found solar cell electrical performance degraded due to a primary arc alone. There are two types of degradation mechanism. One is contamination of coverglass surface. The other is short circuit of PN junction due to arc tracking. Short circuit of PN junction occurs both for electron beam experiment and low temperature plasma environment. Because primary arc inception is unavoidable in GEO unless entire solar array surface is made conductive or rigorous active charging control is done, the power degradation due to primary arcs should be included in power design to leave a margin in satellite power at EOL.

As the previous tests were carried out using solar array coupons which had series-connected solar cells, it was often difficult to do detailed analysis of the damaged cell. Each type-B coupon was made with only one solar cell, so that the individual coupons can be analyzed easily. The tests of type-B coupons are carried out in the following manner. First we bias a coupon with an external capacitance, C but without the resistance R. After each arc, the I-V characteristics under dark condition are measured connecting a DC source power meter. If a solar cell degrades, the degradation manifests as decrease in the shunt resistance of solar cell. The external capacitance is increased from a small starting value until we see degradation. Once degradation is noticed, we now fix the external capacitance and insert the resistance in the external circuit. The resistance works to decrease the arc current peak and widen the pulse width.

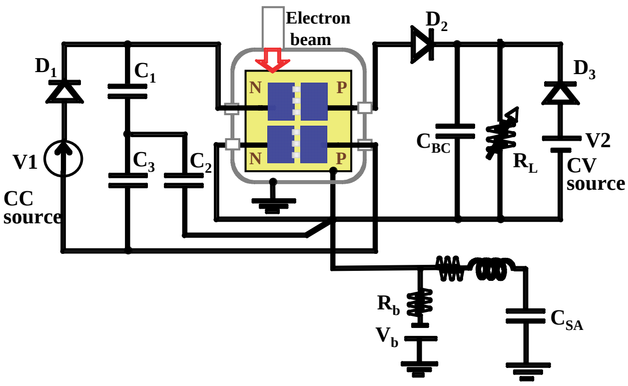

Figure 3: Circuit diagram of type-C coupon test for inverted gradient condition.

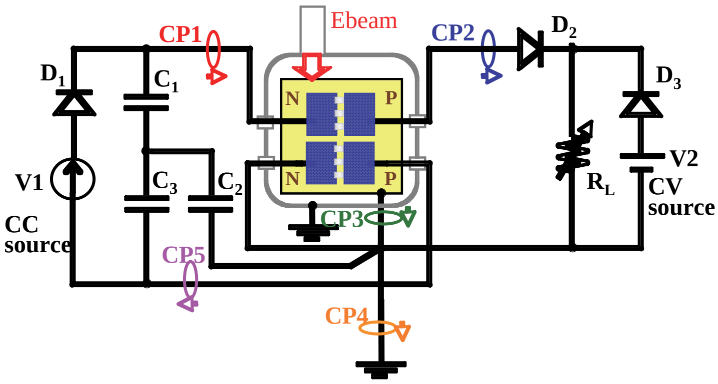

Figure 4: Circuit diagram of type-C coupon test for normal gradient condition.

The purpose of the type C coupon is to investigate dependence of secondary arc occurrence on primary arc inception method. One of the major purposes of ESD test is to examine whether a primary arc that occurs between the HOT string and the RTN string becomes a secondary arc or not. Usually test coupons are made according to the design specification and we seek the combinations of string current and string voltage that can have secondary arc. If those combinations are well below the in-orbit operational condition of the solar array being tested, the design is declared as safe from secondary arc.

A serious problem associated with this kind of ESD test is that we have to wait for a primary arc to occur at the point where we want it occur. Primary arcs can occur anywhere around a solar cell as long as triple junction along the edge is exposed to space. It is difficult to control the timing and the position of primary arc inception. Experimenters always want to do a controlled experiment. If the transition probability is the same regardless the way we produce the primary arc, we can use the most efficient and controlled method to produce primary arcs between the strings to save the test time that is sometimes a determining factor of test cost.

Up to now several methods have been tried to induce primary arcs. Most often, those methods are based on the inverted potential gradient because the threshold voltage is lower. In the inverted potential gradient set-up, the solar array circuits are biased to a negative potential

with respect to the chamber ground. The coverglass is charged more positively either by
(1) Emission of secondary electrons due to impact of an electron beam
(2) Attraction of low energy (typically a few eV) ions produced by a diffusive plasma source
(3) Attraction of energetic (typically 1 keV) ions from an ion beam
(4) Emission of photo-electrons due to irradiation of UV ray

Normal potential gradient condition is also used because we can avoid the use of a high voltage power supply. The power supply V_b, rsistance R_b, the capacitance C_{ext} are removed and RTN string of solar array circuit is connected to the chamber ground. The coverglass is charged negatively by
(5) Attraction of electrons due to irradiation of an electron beam
It is rather easy to focus an electron beam at a high energy and concentrate primary arcs to a desired point.

Among the five methods mentioned above, the methods (1) or (4) give the best simulation of the charging situation in GEO. The method (2) gives the best simulation of LEO. The best simulation method, however, is not always the most efficient method to induce primary arcs.

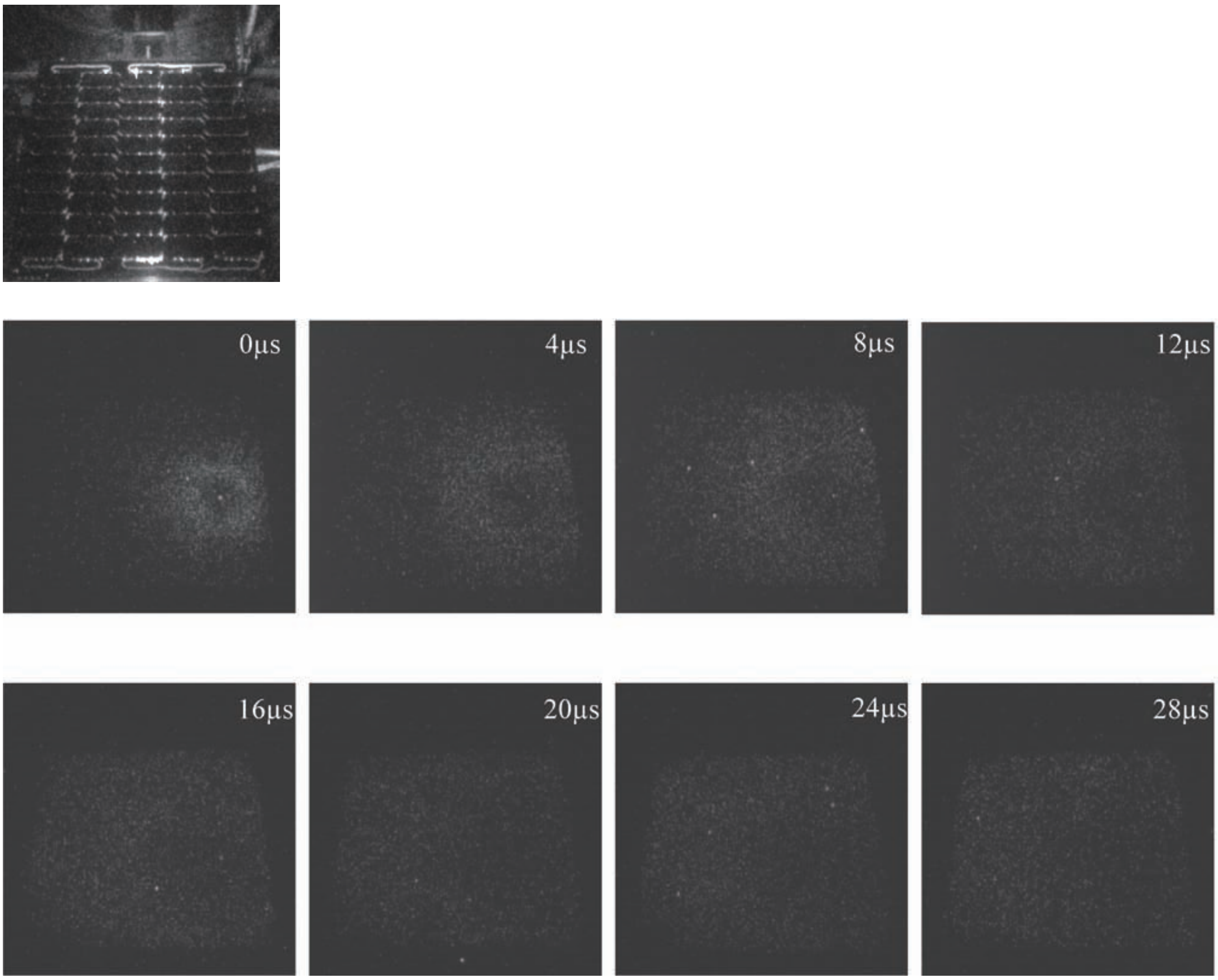

Figure 5: Video image of high speed image intensified camera. The top picture indicates the type-A coupon in the frames of the video sequence. Exposure time of each frame is 2μs.

The length scale of secondary arc phenomenon is usually less than 1mm. In this length scale, the plasma environment surrounding the solar array is probably irrelevant to whether a given primary arc becomes a secondary arc or not. If this statement is true, we can use a method that produces a primary arc most efficiently regardless the orbital situation we are testing. Before to do so, we need more evidence to support the validity of the assumption. The best way to investigate the validity is to test identical test coupons in different environments and see whether the thresholds of secondary arc formation are the same among the environment.

In total six type-C coupons were made. Three coupons use triple junction cells and the other three use silicon cells. Each three coupons are identical. Each set was distributed to KIT, NASA/OAI and ONERA for testing. Each institution plans to carry out secondary arc test using the method (1), (2) and (5) and compares the results with others. Figures 3 and 4 show circuit diagrams used at KIT for the type-C coupon tests.

2.2 Preliminary results of round robin experiments

In Fig.5 we show high-speed image-intensified camera images taken just after inception of a primary arc. A donuts-shape luminescence is clearly seen, which indicates plasma expanding radially from the arc spots. In this case the neutralizing plasma covered all of the coupon surface (40cmx40cm) and the propagation velocity is estimated as $3x10^4$m/s. Currently we are planning to use an image intensified camera to take many snapshots of the expanding plasma to accumulate the statistical data about the propagation of the expanding plasma.

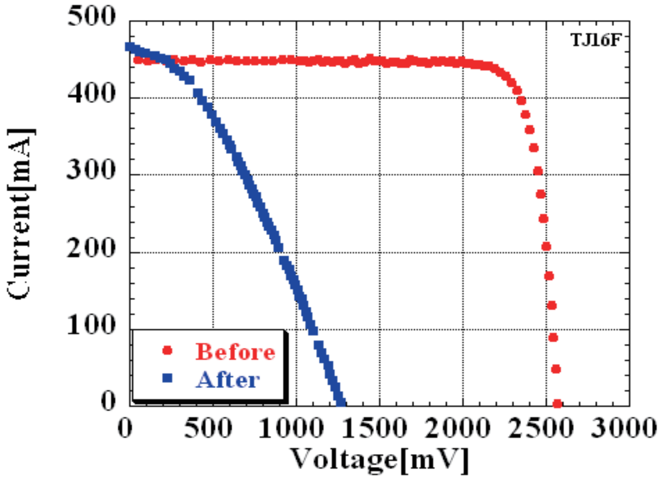

Figure 6: VI characteristics of a TJ coupon after experiments.

In Fig.6 we plot the VI curves measured after the experiments of a TJ type-B coupon. One TJ type B coupon was exposed to series of arcs. The parallel resistance of the coupon decreased significantly and the peak power dropped from 970mW to 208mW. The arc current that caused the largest degradation had a peak of 50A and the total arc energy was 30mJ. Figure 7 shows a magnified photograph taken by a microscope after the experiment. It is shown that arc track runs from the N electrode the P electrode, which suggests short-circuit of the solar cell PN junction.

The results shown in from Figs. 6 and 7 are taken at KIT. During the visit to ONERA in September 2006, a similar test was carried out as a demonstration. The type B coupons sent from Japan were used. Similar behavior of the solar cell degradation was observed. Because there were also American members present at the demonstration experiment, we confirmed that solar cell degradation due to ESD was real and the subject should be studied further.

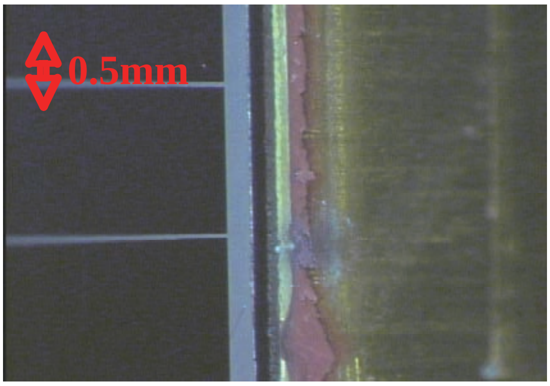

Figure 7: Example of arc spots left on the type-B coupon.

At KIT we tested three different test environments for a type-C coupon. The results are summarized in Fig.8. The inverted gradient condition, either plasma or electron beam gave more or less the same result. The normal gradient condition produced by electron beam, however, had a completely different result from the other two cases. Because the primary ESD current was too small to induce a secondary arc, it would give misleading and underrepresented results if the normal gradient condition were used as the ESD test method. The similar tests were carried out at ONERA in 2005. Their results were contradictory, where the beam normal gradient condition gave secondary arcs as easily as the other two methods. This discrepancy should be investigated further.

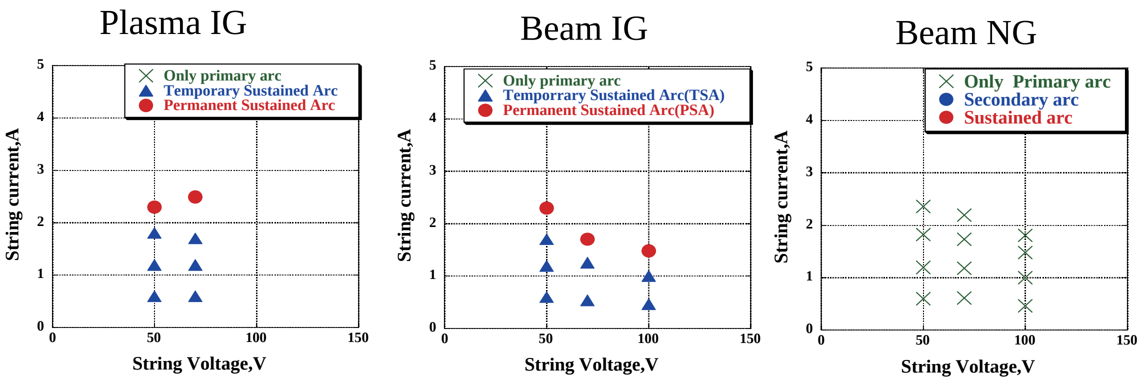

Figure 8: Results of type-C coupon secondary arc test under different charging conditions.

3. Other activities

In September 2006, the visit to the research facility of ONERA at Toulouse, France was organized for one week. A representative of European Space Agency was also invited as an observer, because ESA plays an important role defining European Common Standard for Space (ECSS). Demonstration experiments were carried out at ONERA using JONUS chamber and framework of the ISO documentation was discussed.

In November 2006, the First International Workshop on ISO Standardization of Electrostatic Discharge Test of Satellite Solar Array was held in Kitakyushu. In conjunction with the workshop, the visit to the research facility of KIT was organized. More than 30 participants attended the demonstration experiments that were carried out using the round robin experiment coupons. In the first workshop, the first version of the working draft of ISO document was discussed. 40 people from Japan, US, Europe and China participated. The working draft was reviewed line by line.

Figure 9: Group photos of visit to ONERA (left) and KIT (right)

4. Conclusion

Since the start of the project in October 2005, the research has progressed significantly. The first workshop held in November was an important milestone toward the establishment of the ISO standard. In February, the new work item proposal regarding “Space Systems - Space Solar Panels - Spacecraft Charging Induced Electrostatic Discharge Test Methods" has been submitted to ISO. The official process has now begun. The next important milestone will be the second international workshop that will be held at Biarritz, France on June 22nd, 2007 following the 10th Spacecraft Charging Technology Conference.

5. Acknowledgement

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6. References

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