Electrostatic Discharge Testing of Carbon Composite Solar Array Panels for NASA's planned Europa Mission to Jupiter

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Abstract: The next planned NASA mission to visit Jupiter is known as the Europa Mission. The objective of this mission concept is to enter orbit around Jupiter in order to conduct multiple close flybys of the icy moon Europa. After careful trade studies, the mission designers have selected solar arrays as the baseline power system for the proposed mission rather than more traditional radioisotope thermoelectric generators. In order to examine the risk of using solar arrays, a series of tests were devised to determine the response of a typical solar array coupon to energetic electrons. Test coupons were fabricated and exposed to electrons ranging from 10 keV to 100 keV, at 1 nA/cm^2, while being held at both room and cryogenic temperatures and exposed to end of mission radiation levels. While under electron bombardment, electrical discharges were observed and recorded with the majority of discharges occurring with electron energies of 25 keV. The largest effects on discharge size and rate were the decrease in temperature and the reduction of dielectric material on the sample surface. These tests indicate that solar array panels could be used by the planned Europa Mission in the Jovian environment, but that electrostatic discharges could be expected on the carbon composite solar arrays.

Keywords: Europa, Jupiter, electrostatic discharge, ESD, carbon composite, energetic electrons, temperature, radiation

1 Introduction

One of the important considerations for deep mission designers is the power source for the spacecraft. Until the Juno mission's pioneering use of solar arrays, all spacecraft traveling beyond the orbit of Mars were powered by traditional radioisotope thermoelectric generators. With the planned Europa Mission, intended to study Jupiter's icy moon Europa, the design team again faced the choice of which power system to employ. After much consideration, and multiple risk reduction efforts, the decision was made to again utilize solar arrays to power the spacecraft.

One of those risk reduction efforts focused on the effects of energetic electrons on the solar arrays panel structures. In order for solar arrays to be feasible for this mission, the baseline design uses solar structures made of carbon composite facesheets with an aluminum honeycomb core. While these composite structures would be a good functional substitution for the metallic materials they replace, they present unique spacecraft charging challenges when interacting with the harsh Jovian space environment. As a composite material, they would be constructed of more than one material which may show different base properties depending on differing conditions. In the Jovian environment, with temperatures reaching 50K and under the bombardment from energetic electrons, the non-conducting pre-preg binding materials may heavily influence how these materials respond to the space environment. Before the project selected solar arrays as the baseline power system for the planned Europa Mission, the response of the carbon composites to energetic electrons while held at cryogenic temperatures was examined.

The primary issue with these type of solar arrays from a spacecraft charging point of view is the carbon composite. In general the carbon weave, the major portion of the structure, is a conductive material.

Energetic electrons that impact the material can migrate fairly easily into the material.[1] Since the material is a composite, however, it is made from more than one material. In this case, the carbon weave is held together with a non-conductive binder. When exposed to energetic electrons, the negative charges will become embedded in the binder material and will not easily be transported away.[2,3] With sufficient time and continued exposure, these trapped electrons build up large electric fields that can lead to electrostatic discharges (ESD).[4,5] The impact of these ESD events is dependent on their size and rate of occurrence. Small but frequent events can produce background noise impacting sensitive scientific instruments. Large events can potentially lead to damage of the solar array strings or their associated electronic hardware.

A series of tests were performed on sample solar array composite structures to help determine if they would have a significant negative impact on the planned Europa Mission. These tests were performed to better understand the risks of used carbon composite facesheets on the solar arrays in Jovian radiation environment rather than as qualifications tests for the materials. In general, the tests were composed of bombardment of the array coupons with energetic electrons with energies ranging from 10 keV to 100 keV at approximately 1 nA/cm^2. The samples were tested at temperatures of both 298K and 93K to examine the effect of temperature on the production of ESDs. In addition, the sample coupons were tested both before and after receiving an approximate end of mission dose of radiation.

The majority of samples were simply the carbon composite facesheets with an aluminum core as would be used on the back side of the solar arrays with the thought that these surfaces would receive the majority of energetic electron exposure. One set of sample coupons, however, was constructed with a layer of co-cured Kapton. In the construction of solar arrays, the solar cells are attached to a similar Kapton surface to provide electric isolation between each cell. Kapton is a very good dielectric that is known to produce large discharges under exposure to energetic electrons. While the majority of the co-cured Kapton surface will be covered by the solar cells, enough area will be left exposed to the Jovian environment that it was deemed important to include a sample with these tests.

2 Testing

The first question to be answered by this risk reduction effort was if the carbon composite facesheets would produce electrostatic discharges while exposed to electrons. Provided they did, the next effort was to get some understanding of how large these events could be under varying conditions including electron energy, sample temperature, and degree of radiation dose. As the testing progressed, the additional criteria of quantity of binder material on the composite surface was added in an effort to find a relatively simple way to reduce the total number and size of discharges.

Two sample groups were obtained for this risk reduction test. The first was a new panel constructed out of facesheet with M55J conductive carbon weave and RS3 pre-preg binder material. These facesheets were mounted on either side of an aluminum honeycomb piece to create the solar array structural piece. The second was essentially the same panel structure, but one of the facesheets incorporated a co-cure Kapton layer which would be used beneath the solar cells on an actual solar array.

2.1 Measuring Electrostatic Discharges

Measuring the plasma released from a discharge is a difficult prospect, but measuring the image charge movement from a nearby non-conductor is relatively easy. When a non-conductive material is charged by electron exposure, an electric field is formed. In nearby conductors, a reciprocal field is generated by the movement of image charge in the conductor to balance out the induced field from the trapped charges. During a discharge, the electric field caused by the trapped electrons is rapidly reduced in proportion to the size and duration of the discharge. This causes a current of image charge to again balance the remaining

field. By placing a conductor in close contact with the sample, connecting that conductor to ground through a resistor, the size of the image charge can be measured using an oscilloscope.[6,7]

The total energy from each discharge can be difficult to obtain. The energy emitted by each blow off into the vacuum chamber is dissipated throughout the system. What can be measured is the energy dissipated in the measurement resistor. In this case, the resistor chosen was 50 ohms to most closely match the impedance of the coaxial cables used in the test set up.

The energy dissipated in this resistor can be calculated by integrating the area under the resulting curve captured by the oscilloscope. Using a spreadsheet and a rectangle approximation for the dissipated energy, E, given in equation 1 below.

$$E = \sum \frac{V^2}{R} \Delta t \tag{1}$$

In this case, V is the voltage at each point measured on the oscilloscope, Δt is the time increment between each scope measurement, and R is the value of the series resistor. The resulting value is representative of the amount of energy that might be dissipated by a similar resistance at a distance from the spacecraft. The variation of energy measured with this method will scale with the total charge released in the electrostatic discharge from the test material.

2.2 Test Methods

Two separate rounds of testing were conducted. In the first round, an existing test carousel was used to examine small 2”x2” samples exposed to electrons at room temperature. This fixture allowed for the measurement of surface potentials along with discharges. To test the samples at cryogenic temperatures, a new fixture was constructed to cool the samples while still allowing for the measurement of ESD’s. The samples allowed in this fixture were larger 3.5”x6” samples to match the size of the cooling plate. In all cases, testing was performed in a vacuum chamber held at vacuum levels of approximately 1×10^{-6} torr.

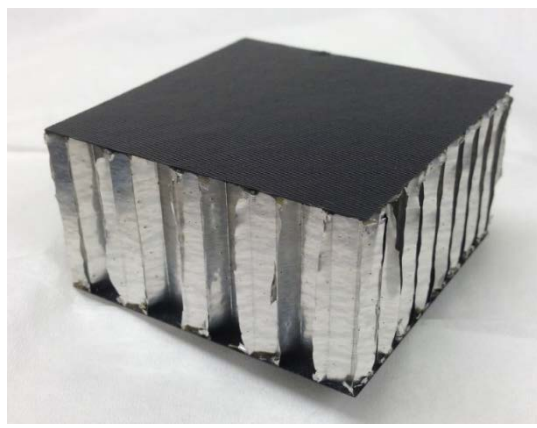

Figure 1. Small coupon showing composite facesheets and aluminum core

Samples were procured in two sizes to fit the two separate test fixtures. One set was cut to 2”x2” and the other to 3.5”x6” and are referred to as “Small” and “Large” samples respectively. A photograph of one of the small samples can been seen in Figure 1.

In order to mount the samples on to the test fixtures, aluminum plates were first adhered to one facesheet with conductive, silver filled, epoxy. In all cases, the aluminum plate was the same size as the sample facesheet. The adhesive was applied in such a way to cover the edges of the bottom facesheet and to make an ohmic contact between the aluminum mounting plate and the aluminum core of the sample coupon.

2.3 Surface Modification

Samples of the simple carbon composite coupons were modified to create three types of surfaces for testing. The first type was tested in an as received condition with no surface modification. The second was abraded with a Scotchbrite pad to remove a part of the outer RS3 layer. The third sample surface was sanded using

220 grit sandpaper to remove the majority of the non-conductive material from the top surface. Figure 2 and Figure 3 below show the modifications to the surface with the increasing amount of surface abrasion.

The white streamers seen in the images are regions of the non-conductive RS3 pre-preg material that have been squeezed to the surface of the facesheet during the manufacturing process. In abrading the facesheet,

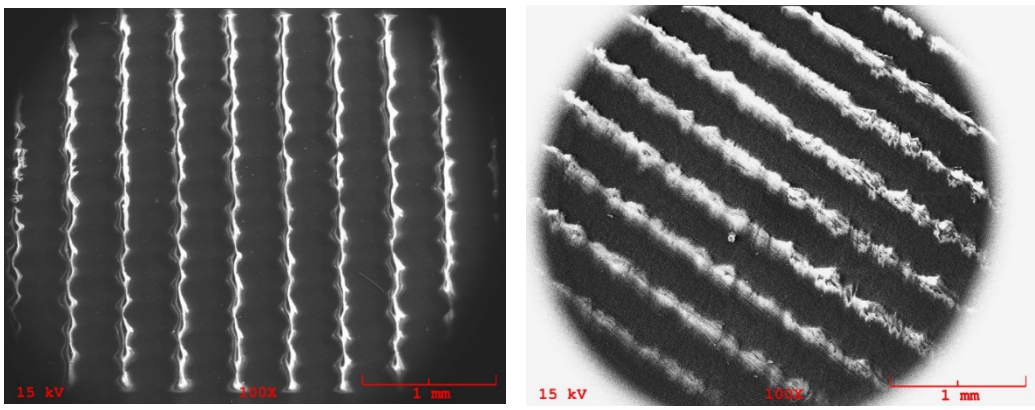

Figure 2. SEM image of the 'As Received' (left) and 'Scotchbrited' (right) sample surfaces

the quantity of the RS3 was reduced. In the case of the sanded surface, Figure 3, the bands of RS3 were completely removed leaving only the carbon weave and small regions of the RS3 between the fibers.

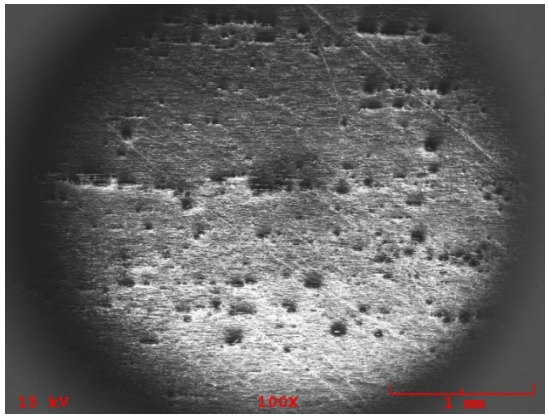

Figure 3. SEM image of the 'Sanded' sample surface.

3 Test Results

3.1 Small Samples

The first round of testing was performed on the small 2"x2" samples at room temperature. The primary purpose of these tests were to determine if ESD's would be generated in the samples while under electron exposure. Once it was shown that discharges did occur, testing continued to determine changes as a function of electron energy, surface preparation, and radiation dose. Temperature changes could not be performed due to the carousel fixture used for testing, but the surface potential for each sample could be measured.

To perform these tests, a set of samples were mounted in the slots of an aluminum carousel and inserted inside of a vacuum chamber. When mounted in the vacuum chamber, a stainless steel disc was attached to

the carousel to block the electrons from all but one sample at a time. Also attached to this steel disk is a floating capacitor sensor that allows the average potential of the sample to be measured by an external electrostatic voltmeter. A schematic of the test setup is shown in Figure 4. The measurement resistance at the scope was 50 ohms.[8]

The first set of testing was conducted with electron energies of 25 keV, 50 keV, and 100 keV. Samples with As Received, Scotchbrited, and Sanded surfaces were tested in turn. In all cases, discharges were observed when exposed to 25 keV electrons, but none were found with the two higher energies. These results indicated that the ESD's are due to the pools of non-conductors on the surface only. More energetic electrons penetrate further into the material. While some of these electrons may still stop in the pools of RS3 on the surface, the majority penetrate into the carbon fibers and are conducted away without forming large electric fields.

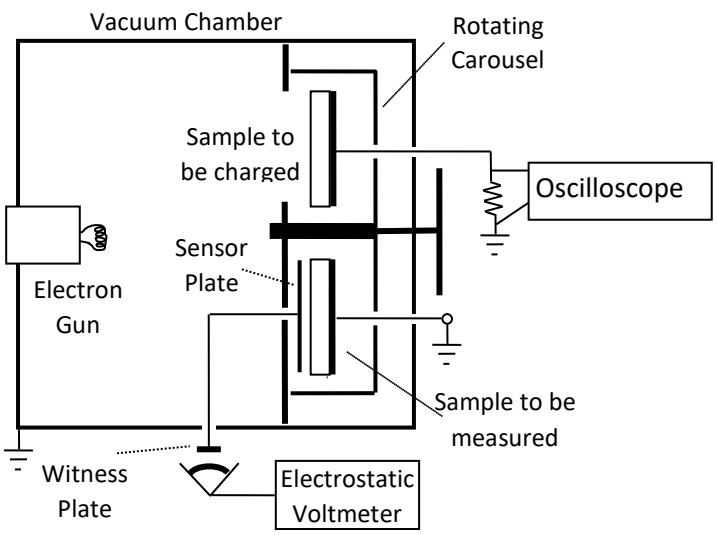

Figure 4. Schematic of the fixture used for small sample testing.

Once it was determined that discharging did occur with 25 keV electrons, the majority of testing continued using this energy. A flux of 1 nA/cm^2 was used as the standard for all testing. This current density is within the range that is expected to be found in the Jupiter system for this energy range. Samples with all three surface types were tested at room temperature with the 25 keV electrons and found to produce discharges.

After completion of the first round of testing, samples were give an approximate end of mission radiation dose to look for changes in the size and rate of ESD production as a function of radiation. The dose used was 6.5×10^{15} electrons/cm^2 of 1 MeV electrons at a flux of 1×10^{11} electrons/cm^2/second. An additional sample with a co-cured Kapton sample was added at this time. No small sample pre-radiation testing of this sample was performed due limited accelerator time coupled with the unavailability of the sample when the initial tests were performed.

Table 1, below, gives the results for all small sample coupon testing. As can be seen, there is a definite drop in the quantity and size of discharges as the surface was modified. The samples abraded with the scotchbrite pad and with the sandpaper show a reduction in the maximum discharge energy. Note that the surface voltage for all samples was non-zero after exposure to electrons. This indicates that charge is retained in the non-conducting portions of the facesheets. For the unmodified surfaces, this potential was quite large. These voltage were measured approximately 30 to 60 seconds after the beam was turned off. Later measurements showed a decrease of this surface potential over time, but the decay was slow.

Table 1. Small Sample Test results. All tests performed at 298K with 25 keV electrons at 1 nA/cm^2.

Sample Name	Elapsed Time	Number of ESD	Discharge Rate	Surface Potential	Current – Average	Current – Maximum	50 ohm Energy – Average	50 ohm Energy – Max
As Received	9000 seconds	258	28.7 mHz 1 per 35 s	-1334 volts	0.187 amps	1.502 amps	46.89 nJ	1.498 µJ
Scotchbrite	11460 seconds	31	2.7 mHz 1 per 369 s	-1051 volts	0.754 amps	2.611 amps	254.4 nJ	1.199 µJ
Sanded	14400 seconds	20	1.4 mHz 1 per 720 s	-20.7 volts	0.120 amps	0.298 amps	4.65 nJ	17.43 nJ
As Received Post-Rad	15990 seconds	286	17.9 mHz 1 per 56 s	-1730 volts	0.234 amps	2.227 amps	163.1 nJ	12.34 µJ
Scotchbrite Post-Rad	17400 seconds	85	4.9 mHz 1 per 205 s	-1162 volts	0.271 amps	2.210 amps	111.8 nJ	2.512 µJ
Sanded Post-Rad	18120 seconds	118	6.5 mHz 1 per 154 s	-19.4 volts	0.250 amps	1.376 amps	36.86 nJ	307.5 nJ
Co-Cured Kapton Post-Rad	14910 seconds	49	3.3 mHz 1 per 304 s	-7975 volts	0.440 amps	1.081 amps	103.9 nJ	1.246 µJ

It is interesting to note that while post radiation samples generally produced ESD with a larger maximum energy, the average did not always change. The post electron surface potential for the pre- and post-radiation samples also stayed relatively constant with a possible slight increase. The co-cured Kapton sample surface potential was substantially higher than that of the other samples, but this may be attributed to the larger dielectric surface area of the Kapton sample. The co-cured Kapton is a continuous piece of dielectric on the surface, with the standard facesheets having a mix of conductive M55J carbon with streaks of RS3 as seen in the images in figures 2 and 3.

3.2 Large Samples

After the conclusion of testing using the small 2”x2” samples, the fixture to examine the impact of temperature on ESD results was inserted into the chamber. This fixture allowed the use of larger 3.5”x6” samples due to the size of the cold plate used in testing.

Using the results of the small sample as a guide, the large sample test was tailored to the test conditions deemed of most interest for the project. The majority of testing was conducted using 25 keV electrons at a current density of 1 nA/cm^2 using sample that had received the end of mission dose of ionizing radiation. To provide additional information, an un-radiated ‘As Received’ sample was testing at both 298K and 93K using both 10 keV and 25 keV electrons at 1 nA/cm^2. Since the small sample tests indicated that post-radiation testing might be a worst case, sample with each of the different surface modifications were dosed with the 1 MeV electrons to an approximate mission ending dose as described above. To further the worst case testing status, these samples were only tested at 93K. Samples with a co-cured Kapton surface were also included in this test. They were tested in both pre- and post-radiation exposed states and at both 298K and 93K to provide some characterization date for a co-cured Kapton surface.

Numerical results from the large sample tests are summarized in Table 2 for the average and maximum energy and current for all discharges recorded during testing.

Table 2. Discharge results for Large Sample testing as a function of temperature and electron energy. All at 1nA/cm^2.

Sample Name	Temp.	Elec. Energy	Current – Average	Current – Maximum	50 ohm Energy – Average	50 ohm Energy – Max
As Received	298K	10 keV	3.969 amps	13.83 amps	103.8 µJ	1.116 mJ
As Received	93K	10 keV	5.257 amps	22.53 amps	258.2 µJ	2.210 mJ
As Received	298K	25 keV	0.709 amps	5.529 amps	1.944 µJ	97.17 µJ
As Received	93K	25 keV	1.518 amps	9.765 amps	12.85 µJ	477.3 µJ
As Received Post-Rad	93K	25 keV	1.423 amps	11.23 amps	12.61 µJ	679.8 µJ
Scotchbrite Post-Rad	93K	25 keV	0.488 amps	4.506 amps	1.020 µJ	41.60 µJ
Sanded Post-Rad	93K	25 keV	0.121 amps	0.391 amps	10.68 nJ	145.3 nJ
Co-Cured Kapton	298K	25 keV	12.52 amps	27.78 amps	1.886 mJ	8.506 mJ
Co-Cured Kapton	93K	25 keV	21.95 amps	61.13 amps	7.023 mJ	20.89 mJ
Co-Cured Kapton Post-Rad	298K	25 keV	8.164 amps	20.10 amps	567.7 µJ	2.245 mJ
Co-Cured Kapton Post-Rad	93K	25 keV	17.48 amps	56.95 amps	5.320 mJ	17.95 mJ

Looking at these results, it is clear that there is a strong increase in discharge current and energy as a function of temperature. In the 'As Received' samples, the total energy of the discharges increased by as much as a factor of 5 with a 200 degree decrease in temperature. Since only two temperature data points were taken, it is not known if this change is a linear response, but it does indicate that during these tests, colder temperatures with the M55J/RS3 material produced larger discharges.

Also of note in this set of data is the continued decrease in discharge size with surface modifications. As was seen on the small samples, the sample abraded with a scotchbrite pad produced smaller discharges than the unmodified 'As Received' sample. In this case, the largest discharge was smaller by more than an order of magnitude. The sample whose surface was sanded showed an even larger decrease with a three order of magnitude decrease in maximum energy when compared to the 'As Received' sample.

For the 'As Received' sample, the effect of lowering the electron energy to 10 keV was also explored. The results indicated that the number of discharges decreased, but the size of discharges increase by a factor of 11 at 298K and a factor of 5 at 93K.

The effects of radiation on theses samples is less clear, partly due to the fact that only two samples were tested both before and after receiving the end of mission dose. These two are the 'As Received' sample and the co-cured Kapton sample. With the 'As Received' sample, the average energy of the discharges remained constant, while the maximum energy increased slightly. With the co-cured Kapton, the average energy decreased, by as much as a factor of two in the 298K case, while remaining very close at 93K. The

maximum energy for the co-cured Kapton also decreased, but only slightly. The differences in the response likely indicate that RS3 and Kapton react differently to electron radiation exposure. The overall effect is minor compared to the larger impact of temperature and surface preparation.

Table 3. Discharge frequency for Large Samples as a function of temperature and electron energy. All at 1nA/cm^2.

Sample Name	Temp.	Elec. Energy	Elapsed Time	Number of ESD	Discharge Rate >1 nJ	Discharge Rate >1 μJ
As Received	298K	10 keV	22297 seconds	266	12 mHz 1 per 84 s	9.9 mHz 1 per 101 s
As Received	93K	10 keV	22024 seconds	139	6.3 mHz 1 per 158 s	5.3 mHz 1 per 186 s
As Received	298K	25 keV	22761 seconds	4202	185 mHz 1 per 5.4 s	51 mHz 1 per 19 s
As Received	93K	25 keV	22340 seconds	2995	134 mHz 1 per 7.5 s	65 mHz 1 per 15 s
As Received Post-Rad	93K	25 keV	22180 seconds	3406	153 mHz 1 per 6.5 s	64.6 mHz 1 per 15 s
Scotchbrite Post-Rad	93K	25 keV	22522 seconds	2690	119 mHz 1 per 8.4 s	21.2 mHz 1 per 47 s
Sanded Post-Rad	93K	25 keV	22003 seconds	123	4.5 mHz 1 per 222 s	none
Co-Cured Kapton	298K	25 keV	22721 seconds	152	6.7 mHz 1 per 149 s	5.8 mHz 1 per 173 s
Co-Cured Kapton	93K	25 keV	22830 seconds	156	6.8 mHz 1 per 146 s	6.0 mHz 1 per 168 s
Co-Cured Kapton Post-Rad	298K	25 keV	22476 seconds	111	4.9 mHz 1 per 202 s	4.5 mHz 1 per 222 s
Co-Cured Kapton Post-Rad	93K	25 keV	22333 seconds	184	8.2 mHz 1 per 121 s	6.5 mHz 1 per 153 s

Table 3 shows the frequency of discharges for each sample. In the tests detailed above, the time allotted per sample was much more constant than in the small sample tests. To help make sense of the gathered data, the pulse rate is given for two thresholds: discharges greater than 1 nanoJoule and those greater than 1 microJoule. Using these results, discharges in both energy ranges occurred in testing on a regular basis.

Reflecting on data presented in Table 3, it can be seen that the frequency of discharges decreased significantly with the reduction of non-conductors on the surface of the M55J/RS3 coupons. This result is in keeping with the overall trend seen through these tests. As the quantity of non-conductor on the surface was reduced, the size, rate, and number of ESDs decreased. Of interest is that fact that the number of discharges, and the rate of their occurrence, also decreased when the electron energy was lowered from 25 keV to 10 keV. The results in Table 2 also showed that the size of the discharged increased with the same change. It can be postulated that the rate decreased while the overall size of the discharge increased with decreasing energy. A similar effect can be seen when looking at the overall change in discharge size and rate when the surface was varied between the standard composite facesheet and the co-cured Kapton. The co-cured Kapton samples did not discharge as often, but the average and maximum energies of the resultant ESD's were substantially larger reaching into the milliJoule ranges across the 50 ohm measurement resistor.

The effects of temperature on the rate of discharge is much less pronounced than on the dissipated energy. In the four cases where the same sample was tested at both 298K and 93K, the total number of discharges reduced somewhat in the 'As-Received' samples and remained fairly constant in the co-cured Kapton samples. The overall discharge rates at both energy levels, however, remained fairly constant.

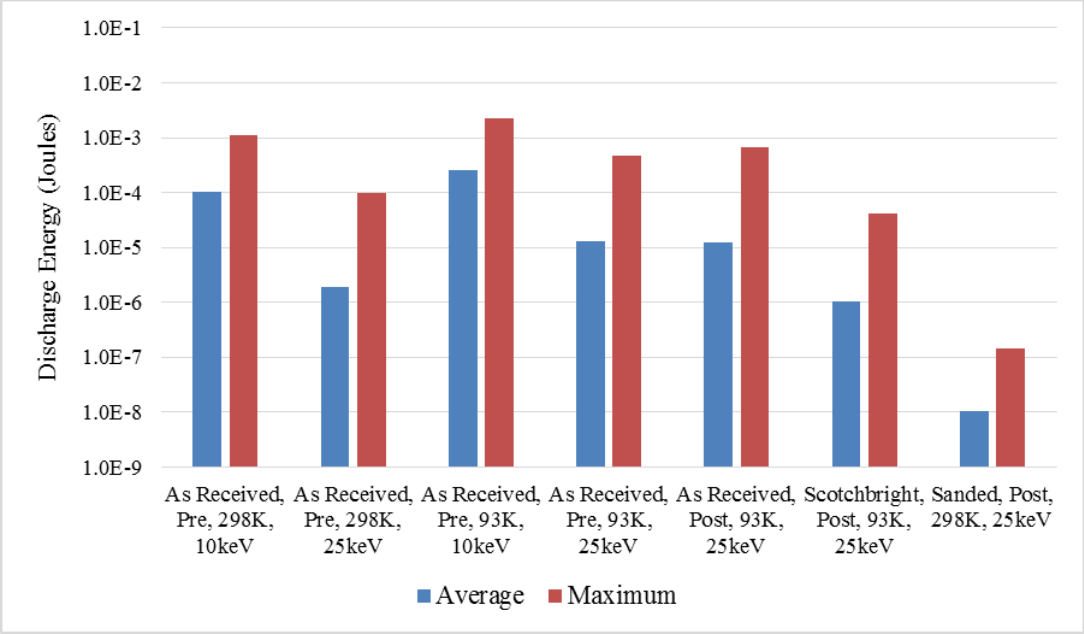

Figure 5. Large Sample test results for M55J/RS3 coupons showing energy dissipated in a 50 ohm resistor

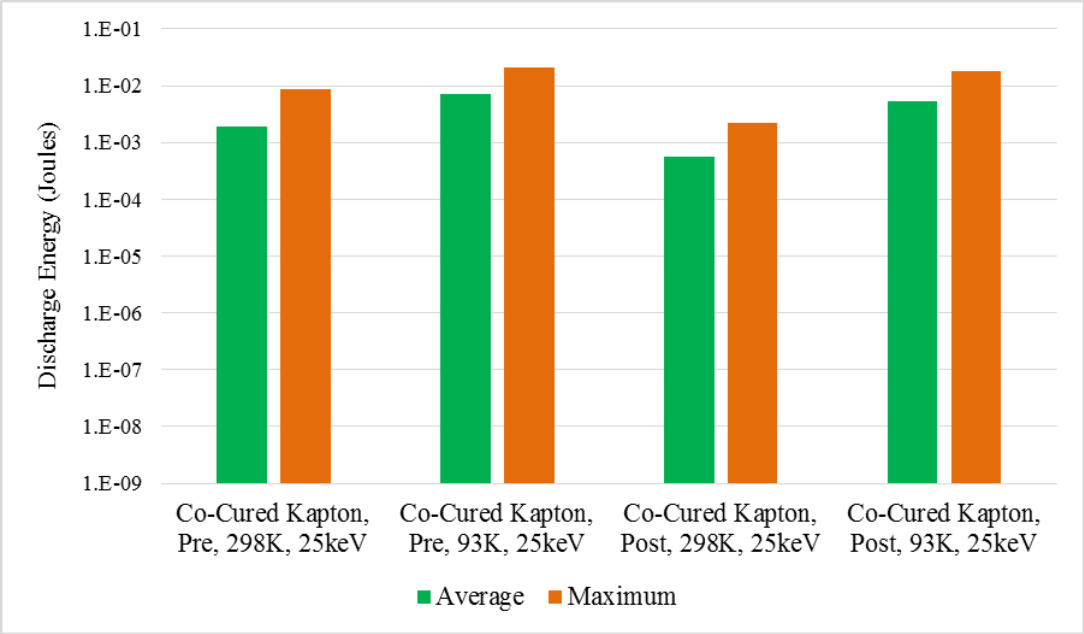

Figure 6. Large Sample test results for Co-Cured Kapton coupons showing energy dissipated in a 50 ohm resistor

A graphical representation of the average and maximum energy dissipated across a 50 ohms resistor for the M55J/RS3 coupons is shown in Figures 5 and 6.

4 Conclusion

Looking over the results from all testing, it is clear that energetic electrons can indeed produce electrostatic discharges on solar array structures. The size and frequency of the discharges is heavily influenced by a number of parameters with temperature and quantity of exposed dielectric on the surface of the facesheet being the largest factors. The discharges seem to result from electrons that come to rest in non-conductive RS3 pre-preg that pools on the surface of the M55J carbon weave or the Kapton co-cured into the facesheet material.

The abrasion of the surface to reduce the quantity of RS3 on the surface gave a substantial reduction in the size and frequency of the discharges. In the case of a surface abraded with scotchbrite versus one that was untouched, at 93K, the size of discharges dissipated in the 50 ohm measurement resistor decreased by a factor of 16 going from 680 μJ to 41.5 μJ at maximum and the frequency from 153.5 mHz (1 every 6.5 seconds) to 119.4 mHz (1 every 8.4 seconds) for nanoJoules sized discharges. When the surface was more fully reduced using sandpaper, the maximum discharge decreased by a factor of 4680 going from 680 μJ at maximum to 145 nJ. In this case, the frequency went from 153.5 mHz (1 every 6.5 seconds) to 4.5 mHz (1 every 222 seconds) for nanoJoules sized discharges.

The temperature of the material was another contributing factor. A reduction from 298K to 93K produced a 5 fold increase in the size of the discharges produced. The radiation dose received by the samples did produce a slight increase in the total number and rate of discharge occurrence, but the changes were slight with the dose given to these samples

The strongest result from these tests on how to reduce the risk to the solar arrays from electrostatic discharges is to reduce the quantity of non-conductor on the surfaces of the structural facesheets.

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References

[1] Garrett, H.B. and Whittlesey, A.W., *Guide to Mitigating Spacecraft Charging Effects*, NASA-HDBK-4002A, pp. 171-184 June 2011.

[2] S. A. Czepiela, H. McMagnus, and D. Hastings, “Charging of Composites in the Space Environment,” AIAA Journal of Spacecraft and Rockets, Vol. 37, No. 5, September-October 2000, pp. 556-560.

[3] A. L. Bogorad, J. J. Likar, and R. Herschitz, “Charging of Composites in Space Environment: Ground Test Data,” IEEE Transactions on Nuclear Science, Vol. 54, No. 6, December 2007, pp. 1981-1984.

[4] A. R. Fredrickson, D. B. Cotts, J.A. Wall, F. L. Bouquet, “Spacecraft Dielectric Material Properties and Spacecraft Charging,” AIAA Progress in Astronautics and Aeronautics, Vol 107, 1986.

[5] A. L. Vampola, “The Nature of Bulk Charging and its Mitigation in Spacecraft Design,” IEEE WESCON/96, pp. 268-273, 22-24 October, 1996.

[6] J. R. Dennison, J. Brunson, P. Swaminathan, N. W. Green, and A. R. Fredrickson, “Methods for High Resistivity Measurements Related to Spacecraft Charging,” IEEE Transactions on Plasma Science, Vol. 34, No. 5, October 2006, pp. 2191-2203.

[7] N. W. Green, A. R. Fredrickson, and J. R. Dennison, “Experimentally Derived Resistivity for Dielectric Samples from the CRRES Internal Discharge Monitor,” IEEE Transactions on Plasma Science, Vol. 34, No. 5, October 2006, pp. 1973-1978.

[7] N. W. Green and J. R. Dennison, “Deep Dielectric Charging of Spacecraft Polymers by Energetic Protons,” IEEE Transactions on Plasma Science, Vol. 36, No. 5, October 2008, pp. 2482-2490.