# Electrostatic Discharge Testing of Carbon Composite Solar Array Panels for Use in the Jovian Environment

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**NASA is currently considering a mission to investigate the moons of Jupiter. When designing a spacecraft for this type of mission, there are a number of engineering challenges, especially if the mission chooses to utilize solar arrays to provide the spacecraft power. In order for solar arrays to be feasible for the mission, their total mass needed to fit within the total budget for the mission, which strongly suggested the use of carbon composite facesheets on an aluminum core for the panel structure. While these composite structures are a good functional substitution for the metallic materials they replace, they present unique challenges when interacting with the harsh Jovian space environment. As a composite material, they are composed of more than one material and can show different base properties depending in differing conditions. Looking at the electrical properties, in an Earth-based environment the carbon component of the composite dominates the response of the material to external stimulus. Under these conditions, the structures strongly resembles a conductor. In the Jovian environment, with temperatures reaching 50K and under the bombardment from energetic electrons, the non-conducting pre-preg binding materials may come to the forefront and change the perceived response. Before selecting solar arrays as the baseline power source for a mission to Jupiter, the response of the carbon composites to energetic electrons while held at cryogenic temperatures needed to be determined.**

**A series of tests were devised to exam the response of a sample solar array panel composed of an M55J carbon weave layup with an RS-3 pre-preg binder. Test coupons were fabricated and exposed to electrons ranging from 10 keV to 100 keV, at 1 nA/cm2, while being held at cryogenic temperatures. While under electron bombardment, electrical discharges were observed and recorded with the majority of discharges occurring with electron energies of 25 keV. A decrease in temperature to liquid nitrogen temperatures showed a marked increase in the magnitude of these discharges. The results indicate that dielectric discharges are primarily produced due to the presence of large regions of the non-conductive pre-preg on the surface of the carbon sheets. The frequency and magnitude of discharges decreased when layers of the pre-preg material were removed from the composite surface. These tests indicate that solar array panels may be used in the Jovian environment, but that electrostatic discharges can be expected on the carbon composite solar arrays.**

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

## I. Introduction

ONE of the challenges that any deep space mission must face is the choice of how to power the spacecraft. NASA is presently planning a mission to Jupiter's moon, Europa, and has chosen utilize solar arrays for spacecraft power. While solar arrays have been used for the vast majority of Earth orbiting spacecraft, their use for deep space missions has been very limited. In order for them to be feasible on a mission to Jupiter, they must satisfy a number of requirements covering such issues as power output, limited mass, structural rigidity, and survival in the Jovian environment. In order to meet the power requirements and still satisfy mass and structural rigidity needs, the panel structures will likely utilize carbon composite facesheets with an aluminum honeycomb structural as the core.

The use of composite facesheets on solar array panels has become commonplace in Earth orbit, but is still new for missions to the outer planets. Similar solar arrays are currently in use on the Juno mission to Jupiter, but since it has not yet arrived at the planet, the operation of solar arrays constructed with these composite structures in the Jovian environment has not yet been experienced.

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One of the issues to be considered for use around Jupiter is the effects of the heavy radiation environment on the composite structures. The principle risk involved the reaction of materials under electron bombardment. When energetic electrons impact a material they will impart energy to the material and, depending on amount of energy lost, will come to rest in the material. If these electrons deposit in a highly conductive material, they can move freely. Provided that the conductor is bonded well with the structure of the spacecraft, the electrons can be distributed throughout the structure and bled away through a variety of means to maintain a charge balance in the spacecraft.[1]

If the electrons impact a non-conductive element, the electrons cannot freely move. These fixed electrons form localized electric fields that grow with continued electron bombardment. When the fields exceed the breakdown strength of the material, an electrostatic discharge (ESD) occurs. In many cases, these discharges produce a plasma that spreads over the surface which can couple into exposed conductors on the surface leading to a localized current spike. With rapid reduction of electric fields at the location of the discharge, there may also be capacitive or inductive current spikes in nearby conductors.[2,3]

The majority of materials in the solar array panel structures can be considered conductors from a spacecraft charging/ESD point of view. The facesheets, however, are composed of both the conductive carbon fibers and a non-conductive binder that provides structural integrity. While this non-conductive material is not the majority of the facesheet panel, it needs to be considered when the material is placed in an energetic electron rich environment. The binder material may collect sufficient charge to produce electrostatic discharges.[4,5] Depending on its size, a discharge may be harmful to the active elements in the solar array. Any built up electric fields and resulting discharges may also negatively impact the operation of science equipment on the spacecraft depending on size, frequency of occurrence, and location.

A series of tests were performed on sample solar array structural material to examine this risk and help determine if it would be cause a significant negative effect on the use of solar arrays,. The tests were performed to obtain a better understanding of the risk rather than serve as a qualification of the array structural panels. These tests primarily consisted of electron bombardment of sample coupons with energies from 10 keV to 100 keV at temperatures ranging from 298K to 93K. Samples were also tested with varying degrees of surface preparation to examine the effects of roughing the carbon composite surface on the production of discharges.

## II. Testing

The first and foremost question that was addressed was whether ESD's would occur when the solar array structural pieces were exposed to energetic electrons. Provided they did, other questions centered on how large were the discharges, how often did they occur, and their dependence on electron energy and sample temperature. The study also sought to determine if there were some relatively simple methods available to attenuate the size and frequency of any discharges that would occur.

To conduct test on a realistic sample, a flight-like panel was obtained that was composed of two carbon composite facesheet composed of M55J carbon weave with an RS3 pre-preg binder with an inner honeycomb aluminum core.

### 1.1 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 the sample, can connecting that conductor to ground through a resistor, the size of the image charge can be measure using an oscilloscope.[6]

The total energy from each discharge can difficult to obtain. The energy emitted by each blowoff 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 using 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.

$$\boldsymbol{E = \sum \frac{V^2}{R} \Delta t} \qquad (1)$$

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 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.

### 1.2 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” to match the size of the cooling plate. In all cases, all testing was performed in a vacuum chamber held at vacuum levels of approximately $1\times10^{-6}$ torr.

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.

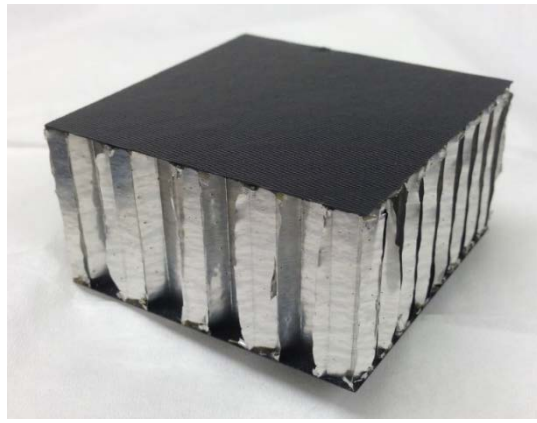

***Figure 1. Small coupon showing composite facesheets and aluminum core***

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 make an ohmic contact between the aluminum mounting plate and the aluminum core of the sample coupon.

### 1.3 Surface Modification

Samples of the same coupon 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, the quantity of the RS3 was reduced. In the case of the sanded surface, Figure 3,

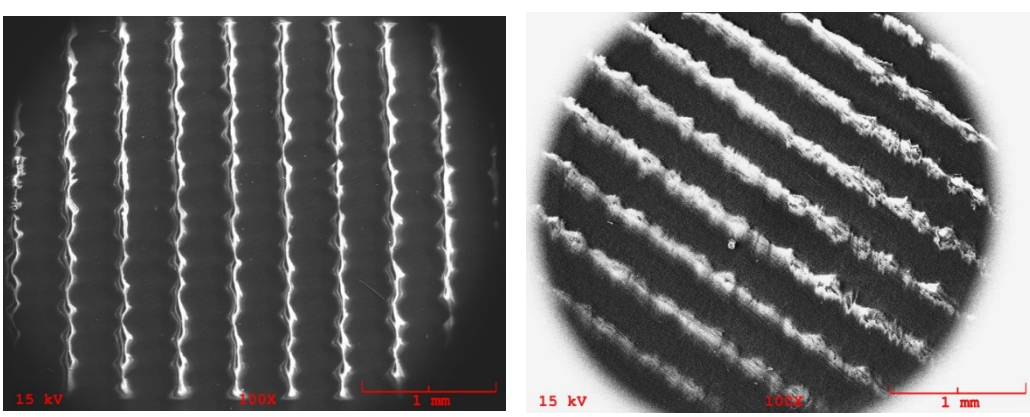


***Figure 2. SEM image of the 'As Received' (left) and ‘Scotchbrited’ (right) sample surfaces***

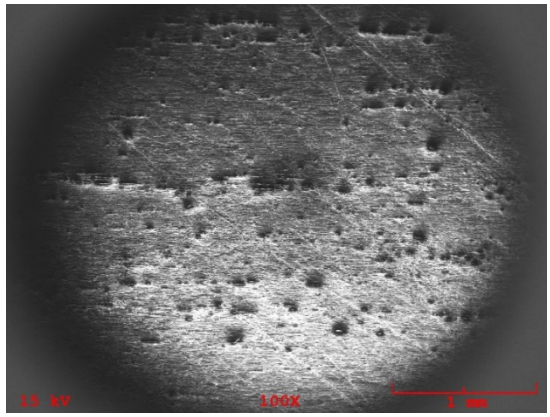


***Figure 3. SEM image of the 'Sanded' sample surface.***

the bands of RS3 were completely removed leaving only the carbon weave and small regions of the RS3 between the fibers.

## III. Test Results

### A. 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 were examined. 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.

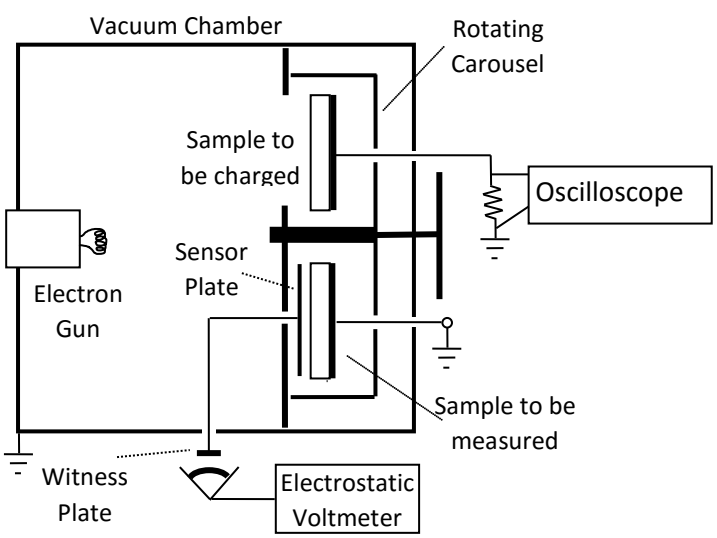


***Figure 4. Schematic of the fixture used for small sample testing.***

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.

**Error! Reference source not found.** gives the results for all small sample coupon testing. As can be seen in the table, 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 the 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 with 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 |

**1.4 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$^2$. 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 | 1.423 amps | 11.23 amps | 12.61 µJ | 679.8 µJ |
| Scotchbrite | 93K | 25 keV | 0.488 amps | 4.506 amps | 1.020 µJ | 41.60 µJ |
| Sanded | 93K | 25 keV | 0.121 amps | 0.391 amps | 10.68 nJ | 145.3 nJ |

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 modification. 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.

***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 | 22180 seconds | 3406 | 153 mHz 1 per 6.5 s | 64.6 mHz 1 per 15 s |
| Scotchbrite | 93K | 25 keV | 22522 seconds | 2690 | 119 mHz 1 per 8.4 s | 21.2 mHz 1 per 47 s |
| Sanded | 93K | 25 keV | 22003 seconds | 123 | 4.5 mHz 1 per 222 s | none |

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. As has been seen in all aspects, the frequency of discharges decreased with the reduction of non-conductors on the surface of the M55J/RS3 coupons. A graphical representation of the average and maximum energy dissipated across a 50 ohms resistor for the M55J/RS3 coupons is shown in Figure 5. Large Sample test results for M55J/RS3 coupons showing energy dissipated in a 50 ohm resistor Figure 5.

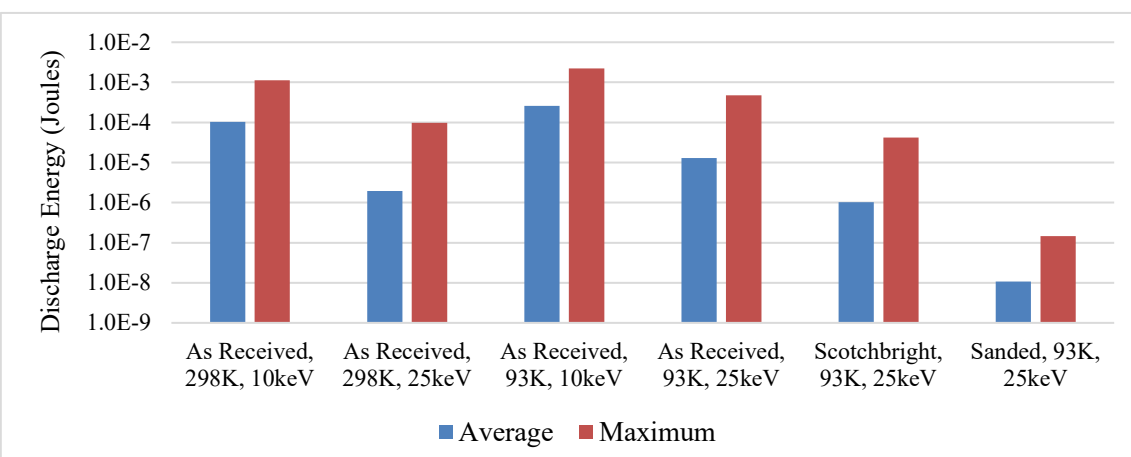


***Figure 5. Large Sample test results for M55J/RS3 coupons showing energy dissipated in a 50 ohm resistor***

## IV. 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. 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.

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 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.

## Acknowledgements

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