Electrostatic Discharges from Conductive Thermal Coatings

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Abstract— **Selecting the correct thermal control coating for a spacecraft can be a significant challenge. From the start, the process includes balancing conflicting needs. Thermal control paints must have the ability to either absorb or emit heat as desired and this property cannot change beyond a set point over the life of the mission. When the mission involves operating in a heavy charging environment, the control coating must be static dissipative enough to bleed away absorbed energetic electrons to minimize induced electric fields and the risk of electrostatic discharges.**

Finding the right balance of thermal performance and electrical performance can be difficult for spacecraft designers. In an effort to aid in spacecraft design, a number of white and black thermal control coatings were tested at the Jet Propulsion Laboratory using a two-part test campaign. These tests involved an initial screening test to determine the bulk resistivity of the material using a traditional parallel plate test, but placed in a vacuum chamber immersed in a bath of liquid nitrogen to obtain data over a range of temperatures. The most promising materials were then exposed to a stream of energetic electrons and monitored for the production of electrostatic discharges.

Results from these tests indicated that only a few of the common thermal control coatings have a resistivity below 10^9 ohm-cm as suggested in NASA-HDBK-4002A. Of those that meet this criterion, most will still produce electrostatic discharges when exposed to electrons with energies from 20keV to 60keV while held at cryogenic temperatures. Additional testing is required to characterize additional coatings to create a database that designers may use when selecting an appropriate coating for their application.

Index Terms— **coatings, cryogenic temperatures, electrostatic discharge, energetic electrons, ESD, paint, thermal control**

I. Introduction

AFTER nearly sixty years of experience in space, it would be reasonable to assume that the aerospace community knows how to build spacecraft that operate well in the space environment. In general, we do, and we do it quite well, but we also seem to always find ways to make it difficult for ourselves at the same time. This tendency manifests itself in multiple ways, but it generally comes down to changing technology to make spacecraft more capable or changing our processes to be more cost effective or more environmentally friendly. As we make spacecraft instruments more sensitive or more capable, and thus a better platform for science or other needs, we also open ourselves up to be more susceptible to naturally occurring events in space that older, less sensitive, spacecraft would have ignored. Along the same lines, as we change our processes for making spacecraft to include materials that are less expensive or hazardous to produce, sometimes the trade is that they are less effective in space, or at minimum do not perform the same as the older formulations. All of this is to say that there is a continual need to check and recheck the materials and processes used to build spacecraft, even if the material or process was previously successful. Depending on the use, the material or process may, or may not, be appropriate for the next project.

One area where change seem to occur frequently is in the production of thermal control paints and coatings. The materials used, the formulation, and the application techniques seem to go through cycles requiring the periodic re-evaluation of the paints or coatings on a semi-regular basis. The thermal properties are regularly evaluated and will not be described here, but one of the lesser discussed properties, their ability to bleed away electrical charge is the subject of this research effort.

It is reasonable to wonder why the electrical properties are important for a material crafted explicitly to control temperature. In many environments where spacecraft travel, they are exposed to radiation in the form of both energetic electrons and protons. Theses charged particles can become embedded in non-conductive elements on the spacecraft including paints, harnesses, and other dielectrics. In sufficient quantities, these embedded charges create large electric fields that can have multiple detrimental effects including both static electric fields that can generate offsets in scientific instruments and electrostatic discharges (ESD). These latter discharges can be either induced by surface charging effects where there are elements of the spacecraft at different electric potentials or by internal charging effects where the large fields are generated within the dielectric itself. In both cases, bursts of plasma can be emitted from the painted surface generating pulses of charge

The research described in this paper was carried out at the Jet Propulsion Laboratory, the California Institute of Technology under a contract with the National Aeronautics and Space Administration.

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that can couple directly with sensitive electronics and associated current pulses in capacitively coupled conductors situated near to the discharge site.

To mitigate the possibility of spacecraft charging, there are several possible techniques ranging from adding shielding around the dielectric regions to choosing materials with resistivities low enough that collected charges bleed away fast enough to preclude the generation of large electric fields. For most painted surfaces, the later solution is the most relevant since the thermal control surfaces are often on the exterior of the vehicle or sufficient shielding is impractical. Recognizing this possible need, some manufacturers provide a limited amount of electrical properties for their paints within the data sheets for the white or black paints, but these values are often insufficient to make intelligent decisions since they may not represent the properties of the paint in a relative environment for a particular use.

This paper documents a test campaign that took place at the Jet Propulsion Laboratory to select candidate paints for use on the Europa Clipper Mission headed to Jupiter. For this mission, both white and black paints were needed that would have low enough resistivity to reduce the likelihood to generate large ESD pulses.

II. Test Plan

A two-part process was chosen to select an appropriate white and black paint for use on the spacecraft. Since Jupiter is a very cold environment with heavy doses of energetic electrons when flying through the radiation belts, it was necessary to select a paint with good thermal properties, but also one that would not produce large ESD events. The first step in the selection path was to take a number of paints and measure their resistivity as a function of temperature. Once the resistivity was known, a select few paints would be subjected to energetic electron exposure to determine if the paints did procedure discharges, how many, how often, and with what energy.

A. Parallel Plate Resistivity test

To determine the resistivity of the paints or coatings, a specialized parallel plate apparatus was utilized. This system was based on the more standard parallel plate test described in ASTM-D257[1], but optimized for space applications. The basic system can be seen in Figure 1. The parallel plates have been incorporated into a vacuum chamber to more closely emulate the space environment and to eliminate the humidity content as a test condition. A guard ring is included in the test hardware to ensure that results are due to measurements through the bulk of the material and not due to surface or edge effects. Paints are baked out prior to insertion into the test apparatus to release trapped volatiles or moisture that could skew the results.

A voltage applied across the bulk of the paint sample and the results in a current measured using a sensitive picoammeter or electrometer. A resistance is thus determined using Ohm's law $R=V/I$. Knowing the geometry of the sample, including the area measured, A, and the thickness of the paint, t_s, the resistivity, ρ of the material can be determined. In this case, $\rho=R*t_s/A$.

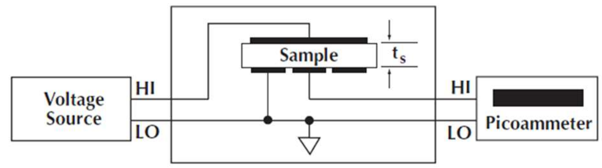

Figure 1. Parallel plate measurement system

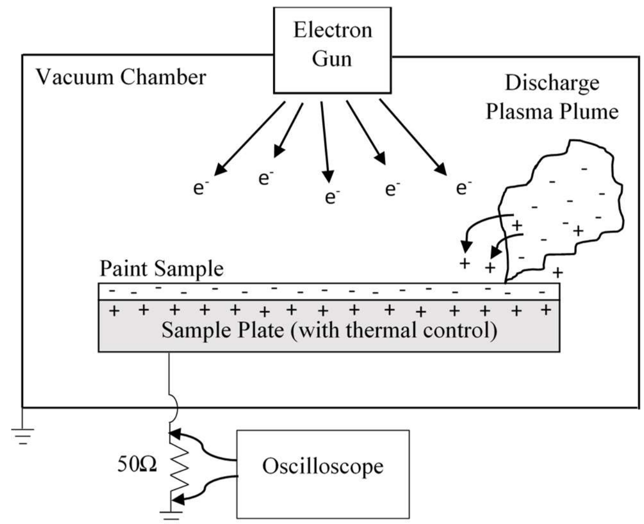

Figure 2. Electron bombardment system

While the technique for taking test measurements is similar to the ASTM-D257 standard, measurements are taken over a much longer time period. The standard calls for a 60 second measurement window. According the work of Dennison and others[2], this 60 seconds is an insufficient measurement duration for highly resistive materials. In highly resistive materials there may be a polarization factor that can produce inaccurate results over short time periods. By measuring over a much longer time, in this case multiple measurements over a period of approximately a week, the polarization factor is reduced to a negligibly small factor in the overall resistance measurement and the resulting resistivity calculation.

Once the vacuum chamber has been sealed and brought to vacuum, initial measurements are taken at room temperature. To obtain resistivity as a function of temperature, the entire apparatus is then immersed in a vat of liquid nitrogen. As the entire vacuum chamber system is cooling in the liquid nitrogen bath, resistance measurements are taken periodically and recorded with the associated temperature. The cooling rate is slow enough that the change is a gradual one rather reducing the possibility of thermal shock and changes over the increment of each resistance measurement. Data is taken as the sample cools and also as the chamber warms following the evacuation of the liquid nitrogen dewar either through evaporation or intentional removal of the liquid nitrogen. The resulting data is resistance, and thus resistivity, as a function of temperature. Thermal related hysteresis in the data may be seen when comparing the results as the chamber cools versus as it warms.

Using the resistivity data, a subset of the original group of paints was selected for further testing using the electron bombardment test.

B. Electron bombardment test

While the parallel plate test is effective for determining the average resistivity of the paints, it is highly unlikely that there will be a situation where the paint is sandwiched between two continuously conductive plates. In actual use, there may be conductive surfaces on one side, but the other will likely be exposed to space. With a continuous conductive surface, as long as there is a conductive path between the two surfaces, there will be a current flow and a measured resistance. Regions of non-conductive material are of lesser importance during this test. Under electron exposure, as would be found in space, the entire surface may be exposed to energetic electrons. Areas with conductive paths would flow these electrons through the material, but if there were larger regions of exposed non-conductors, electrons could be trapped allowing for the buildup of electric fields. If these fields became large enough, ESD events could result even for a material that otherwise shows a moderate average resistivity.

In order to determine if the paints selected by the resistivity testing will have issues when exposed directly to the space environment, they needed to be exposed to a beam of energetic electrons and monitored for ESD production. The methods have been described in other papers[3-5], but in essence, the dielectric in question is placed on an electrically isolated thermal stage and exposed to a mono-energetic electron beam as shown in Figure 2. As charge is collected in the non-conductive material, there is a reciprocal movement of image charge to the conductive sample plate holder to balance out the fields within the conductor. When a discharge occurs, it forms a circuit between the sample and the vacuum chamber walls through the emitted plasma and is completed through a resistor connected to the metallic sample plate. By monitoring the voltage across the resistor, a measurement of the current associated with the discharge can be obtained and the energy of the discharge that is dissipated across this resistor can be calculated. The metrics of this test are then the rate of the

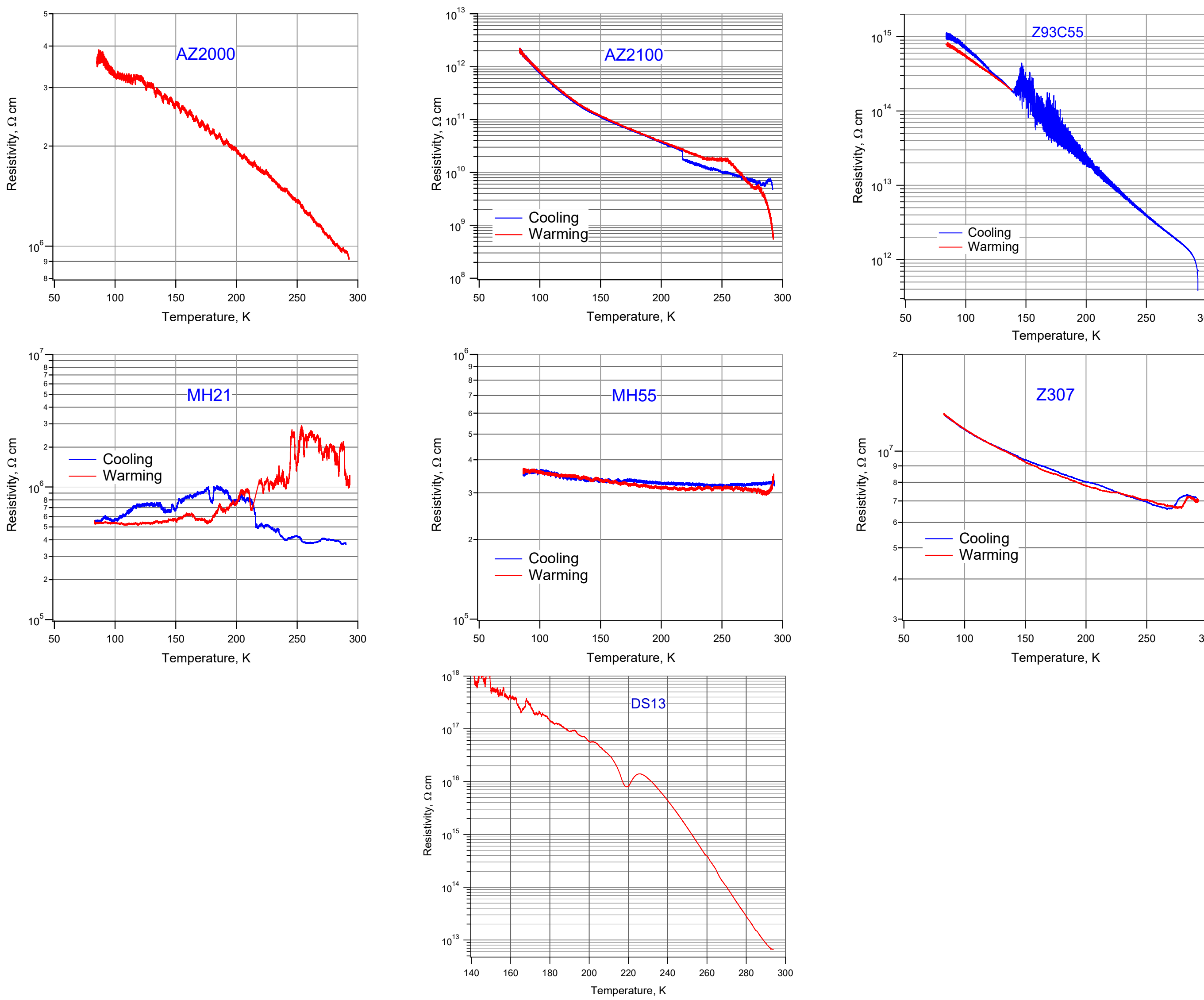

Figure 3. Resistivity as a function of temperature for seven thermal control coatings

production of discharges, the total number over the test duration, and the measured size in either max voltage across the resistor or the calculated current and energy. Measuring surface voltage would also be desirable, but the apparatus used for these tests did not have a means of obtaining that information.

III. Test Results

A. *Parallel plate resistivity testing*

After reviewing available paints, seven paint samples were gathered. Paints were chosen based on both availability and their manufacturer's stated resistivity values. All paint samples were applied to 30 cm^2 copper disks for testing purposes and were baked at 100°C for ten hours before testing to remove volatiles and moisture from the applied paint. Each sample was individually tested in the parallel plate resistivity apparatus while being held at $1x10^{-5}$ torr or better. In order to cool the samples and obtain resistivity as a function of temperature, the entire vacuum chamber was immersed in a dewar of liquid nitrogen and allowed to slowly cool. The time required for the test varied, but was on the order of four days per sample. These tests were lengthy, but not labor intensive since once started, they required minimal user input.

Measurements were automatically gathered at three second intervals using an electrometer with a built in power supply to provide both an accurate voltage and current reading from the same unit. Resistance measurements were directly obtained for all samples and resistivities derived from the test geometry. Since the test apparatus included a guard ring to eliminate edge and surface effects, the area of the actual sample area was controlled to 8.5 cm^2. Sample thicknesses were on the order of 0.005 to 0.010 cm. Results from the parallel plate testing can be in the resistivity as a function of temperature plots in seen in Figure 3.

Based on the parallel plate test results, three paints were selected for further testing under an electron beam. These included two black paints, MH55ICP and Aeroglaze Z307, and one white paint, AZ2000IECW. These three were chosen due to both their low measure resistivity and their minimal change in resistivity as the material cooled to cryogenic temperatures.

B. *Electron gun bombardment*

New paint samples were created for the electron gun bombardment test since the test apparatus required samples that were 8.9 x 15.2 cm (3.5 x 6 inches). The selected paints were applied to aluminum mounting plates that would be attached to the sample holder inside of the vacuum chamber. Each sample was baked prior to testing at 100°C for 72 hours at ~$5x10^{-5}$ torr or better to remove water and other volatiles in a separate chamber. When ready for the electron bombardment test, each sample was bagged and moved to the electron gun chamber. Once mounted and at vacuum, the sample was given an additional 10 hour bake at 100°C *in situ*.

Due to the sensitivity of the electron bombardment test apparatus to the presence of any dielectric material, empty chamber tests were conducted and the chamber was repeatedly cleaned until no discharges were recorded when a bare aluminum plate was installed on the sample holder. These tests were conducted at the planned 20 keV electron energy with

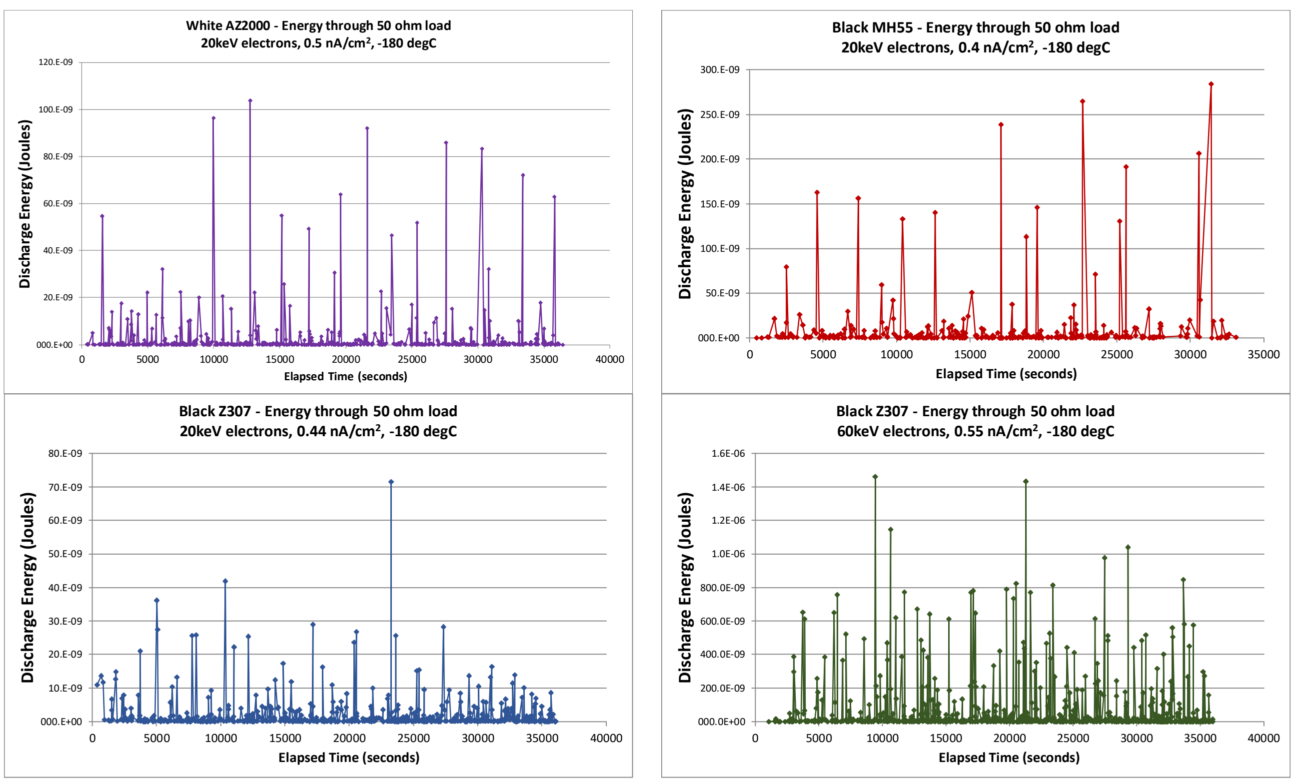

Figure 4. Dissipated energy from electrostatic discharge as a function of time

Table 1. Electron bombardment test results

Coatings	Electron Energy (keV)	Electron Flux (nA/cm^2)	Temp (^{o}C)	Duration (hours)	Discharges	Max Energy (nJ)	Notes
AZ-2000IECW	20	0.5	25	4	0	0	No discharges
	20	0.5	-180	10	565	104	majority <1 nJ; ~12 >50 nJ
MH55ICP	20	0.42	25	4	0	0	No discharges
	20	0.42	-180	10	323	284	majority <50 nJ; ~16 >50 nJ
Aeroglaze Z307	20	0.44	25	4	0	0	No discharges
	20	0.44	-180	10	576	71.5	Majority <20 nJ; ~14 >20nJ
	60	0.55	-180	10	755	1460	Majority <200 nJ: 4 >1uJ
Empty Chamber	20	10	25	0.5	1	n.a.	One tiny discharge
	60	10	25	0.75	17	0.498	17 discharges with 500 pJ
	60	10	-180	0.15	98	107	1 discharges with 100 nJ
	60	0.55	-180	1.75	112	337	1 discharges with 340 nJ

current densities of up to 10 nA/cm^2 which far exceeded the current densities used during testing.

All three paints were tested one at a time in the electron bombardment chamber. Tests included exposure to 20 keV electrons with current densities of approximately 0.5 nA/cm^2 varying slightly with the thickness and density of the paint. These parameters were chose to mimic possible exposure for a Jupiter mission to Europa. Test temperatures were initially 25°C for four hours for initial screening results, and then changed to -180°C for ten hours to more closely approximate temperatures that expected at Jupiter. The final paint tested, Z307, also received additional testing with 60 keV electrons at 0.55 nA/cm^2 for an additional ten hours of testing. The higher energy electrons penetrated more of the paint and the concept was to examine the results exposing more of the bulk of the paint rather than just the surface.

With this test apparatus, discharges are recorded as voltage spike across a 50 ohm resistor that connects the sample plate to the chamber ground. Discharges are thus originally measured as voltages as a function of time. For ease of comparison, these discharge measurements were integrated to determine the energy dissipated in the 50 ohm resistor for each discharge. This technique allows for more facile comparison between discharges and give a better representation of the amount of energy that might be absorbed by nearby spacecraft elements as a result of a similar discharge in actual use.

Results from the tests can be seen in Table 1. All three paints produced no discharges at room temperature. When the temperature was decreased to -180°C, discharges were recorded. As can be seen from Table 1 and graphically in Figure 4, the vast majority of the recorded discharges has energies well below 50 nJ and the largest ones were below 300 nJ for MH55ICP and less for the other two paints. These energies are well below the damage threshold for the space rated parts and at worst would provide a small degree of electromagnetic noise in the background. When the Z307 was exposed to 60 keV electrons, it produced a larger spectrum of discharges with energies reaching 1.26 µJ at peak. The danger of this level of discharge is still likely to be low, but must be considered on a case by case basis depending on the location of the paint and any sensitive electronics nearby.

IV. Discussion

Use of this two-step approach to obtaining a paint that will meet a project's spacecraft charging performance needs has proven to be useful. Neither of the two tests alone show the entire picture of a particular paint's performance. By starting with the parallel plate test, a larger group of paints was winnowed down to a select few. This test is particularly useful to examine how a particular material will behave over a wide range of temperature regimes that could be encountered while in space.

The results did not always agree with manufacturer's data, but are generally more trustworthy since they were taken in vacuum over a lengthy period of time an over a wide temperature range. It is particularly useful to note when the data taken while cooling overlaps those taken while the sample is coming back to room temperature.

Some of the paints tested show fairly flat performance as a function of temperature. That was seen as a positive when the paints were being evaluated for further testing since it indicates stable results over a wide range of conditions. Others showed orders of magnitude increase in resistivity as the temperature was decreased. While these paints may still be useful, their performance would be difficult to predict under a number of temperature conditions making them less desirable from an electrical perspective.

The electron bombardment tests were an effective second step for this testing campaign. Since all paints are a composite by nature – composed of pigment, binder, and some kind of electrically conductive additive, testing them where each element interacts independently with the environment is a useful tool. Even with those paints that showed overall resistivities in the 10^6 Ohm-cm range, as in AZ2000 and MH55ICP, some discharges were observed as the paint was cooled to cryogenic temperatures. The overall resistivity was still low, and a majority of the incident electrons were safely conducted through the material, but enough were retained in the non-conductive regions of the paint to produce electrostatic discharges, albeit with small amounts of dissipated energy.

Of particular interest is the difference between the ESD production of Z307 when exposed to 20 keV vs. 60 keV electrons. The higher energy electrons should disperse further into the material and were chosen to give a more even distribution of charge within the paint. The resulting discharges were much larger. The peak with 20 keV electrons was 71.5 nJ while with 60 keV electrons, the peak was 1.46 µJ, a 20x jump in magnitude. Since the higher energy was not added to the test suite until after the other two paints were tested, it is not known if the increase in energy would result in a similar increase of energy for the other two materials. That testing will have to wait for another time.

After removing Z307 from the test chamber, another empty chamber test was conducted using a bare aluminum plate as the test article. Since the later tests showed a number of discharges, this time the electron energy was set to 60 keV and the current density set to 10 nA/cm^2 and then 0.55 nA/cm^2. Tests were conducted at 25°C and -180°C as per the regular test parameters. At room temperature and 10 nA/cm^2, a few discharges below 500 pJ were recorded, but considered unimportant. When the temperature was decreased to -180°C, more discharges in the empty chamber were observed with most around 30 nJ with a single large spike at 337 nJ. That single spike is troublesome as it indicates that there is still some additional dielectric in the chamber beyond the sample that could be influencing the results as it is only 4x smaller than that maximum discharges seen on the Z307. The results still stand, but with some reasonable doubt.

In both cases, the tests have their limitations. The parallel plate test has a conductor in constant contact with the paint and as a result can only give an average result over a small surface area. The absolute value of the results is dependent on good contact between the parallel plates and the sample material. To ensure good contact between the measurement plate and the paint, a thin crushable conductive foil was placed between the two surfaces.

For the electron bombardment tests, the system is limited to a monotonic electron energy and flux and does not fully represent the environment of space. Other factors, such as Radiation Induced Conductivity (RIC) are not well represented by these results, but should only reduce the likelihood of the production of dielectric discharges.

V. Conclusion

When a spacecraft is heading into an environment where high levels of energetic electrons are expected, it is important that the thermal control coatings be conductive enough to mitigate charge buildup and resulting electrostatic discharges (ESD) that can be damaging to sensitive electronics. Manufacturing data is generally insufficient for determining how a particular material will perform in a relevant environment and older test data, while useful as a starting point, may not be fully valid due to changes in paint formulations over time.

The combination of both a vacuum mounted parallel plate resistivity test and an electron bombardment ESD test has provided a useful tool for obtaining a well-rounded analysis of the electrical performance of a thermal control coating. By combining a direct measurement of a material's resistance as a function of applied voltage, measured current, and temperature, the temperature dependent resistivity of a paint may be obtained over a very wide temperature range.

Exposing these same materials to energetic electrons provides an evaluation of the ability of the materials to create ESD events due to collection of charge in non-conductive components of the paints. Measurements of the rate of discharge occurrence and their size helps fill out the questions associated with choosing one paint over another in a particular environment.

By combining data from both tests, a well informed decision is possible with regards to the spacecraft charging potential of a particular thermal control material.

Acknowledgements

The authors gratefully acknowledge G. Forsberg and P. Narvaez for their contributions to this research effort.

The research described in this paper was carried out at the Jet Propulsion Laboratory, the California Institute of Technology under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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