Dependence of Electrostatic Field Strength on Voltage Ramp Rate for Spacecraft Materials

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Abstract— **This work investigated the dependence of electrostatic field strength for spacecraft materials on voltage ramp rate, by applying an increasing incremental electrostatic field until electrostatic breakdown occurred. Tests on Kapton E found that at ramp rates two or three orders of magnitude lower than the maximum recommended rate, the electrostatic breakdown field, F_{ESD} was lower by a factor of two or more. This suggests that tabulated values of F_{ESD}, which have been used by the spacecraft charging community, could substantially overestimate F_{ESD} in common slowly evolving spacecraft situations. This study expanded these ramp rate tests to include a wider range of ramp rates and additional materials. By contrast, Kapton HN and BOPP data were found to be consistent with a single mean value F_{ESD}, rather than the proposed mean field and incremental voltage step ramp rate models.**

Index Terms*—*Electrostatic discharge, arcing, breakdown, spacecraft charging, space environment effects, polymers.

I. Introduction

Electrostatic discharge (ESD) and the associated material breakdown at the electrostatic field strength (F_{ESD}) is the primary cause for spacecraft damage due to space environmental interactions [1-2]. For many real spacecraft charging situations, standard tests [3-4] with rapidly increasing applied fields may not provide an appropriate measure of the likelihood of failures or an accurate determination of F_{ESD} under space-like conditions [5]. Enhanced understanding of prolonged exposure to high static electric fields (DC aging) of insulating materials based on expanded experimental studies is critical to understand the physics of highly disordered insulating materials, as well as its applications in spacecraft charging [6-7].

The primary objective of this work was to test the dependence of electrostatic field strength on voltage ramp rate for spacecraft materials by applying an increasing electrostatic field until electrostatic breakdown occurs. The data from these tests for the polymeric materials polyimide and biaxially oriented polypropylene are compared to a microscopic mean field theory for dielectric breakdown in highly disordered insulating materials [5]. The broader range of measured ramp rates (~0.1 V/s to ~500 V/s) provides a test of the signature curves predicted by approximate and more complete theoretical models.

II. Theory

The simplest model for F_{ESD} proposes a single parameter or constant value for a specific material. These constant values for a particular material can depend on the details of the defect distributions, such as defect type, defect density or trap depth. They could also reflect changes in the defect distribution for a particular material due to static material modification through, for example, irradiation, thermal annealing, or even electric field-induced DC aging. However, such models are independent of the time a field is applied, that is they are independent of the ramp rate. In general, such models do not reflect the stochastic nature of the breakdown process, although the variability (*e.g.*, standard deviation) in measured F_{ESD} can provide some estimate of this.

A common mean field approximation considering only two material dependent parameters for breakdown —a mean defect energy, ΔG_{def}, and mean defect density, N_{def}—is the Crine model [8-9]. The probability of a breakdown due to an applied electric field, F, for a time interval, Δt, is

$$P_{def} = \frac{2k_BT\Delta t}{h} e^{\frac{-\Delta G_{def}}{k_BT}} \sinh\left[\frac{\varepsilon_0\varepsilon_r F^2}{2k_BTN_{def}}\right] \equiv \alpha\Delta t \sinh[\beta F^2], \quad (1)$$

where $\alpha(\Delta G_{def}, T) \equiv \frac{2k_BT}{h} e^{\frac{-\Delta G_{def}}{k_BT}}$ and $\beta(N_{def}, T) \equiv \frac{\varepsilon_0\varepsilon_r}{2k_BTN_{def}}$; k_B is Boltzmann's constant, h is Planck's constant, ε_o and ε_r are the vacuum and relative permittivity; and T is the temperature. A first order approximation for how the estimated breakdown field, F_{ESD}, depends on the uniform ramp rate $r \equiv dV/dt$, comes by assuming that the ratio of breakdown fields at two different ramp rates is the same as the ratio of the probability of breakdowns at those same ramp rates. This is done by setting the ratio of Eq. (1) evaluated at $\Delta t = \Delta t_{step}$ and $\Delta t = 1\ s$ equal to the ratio of the mean experimental ramp rate r over $r_0 \equiv 1\ Hz$. Recalling that $\sinh^{-1} x = \ln\left(x + \sqrt{1+x^2}\right)$ we can estimate that

$$F_{ESD}(r) \approx F_{ESD}(r_0)\sqrt{\gamma \ln\left(r + \sqrt{1+r^2}\right)}, \quad (2)$$

where $\gamma \equiv \left[\ln\left(1+\sqrt{2}\right)\right]^{-1} = 1.1346$ and r is in Hz. Note, Eq. (2) corrects a mathematical error found in [5]. This

This work was supported by a Utah State University Undergraduate Research and Creative Opportunities Grant (Moser), a NASA Space Technology Research Fellowship (Andersen), and funding through NASA GSFC and the James Webb Space Telescope (Dennison).

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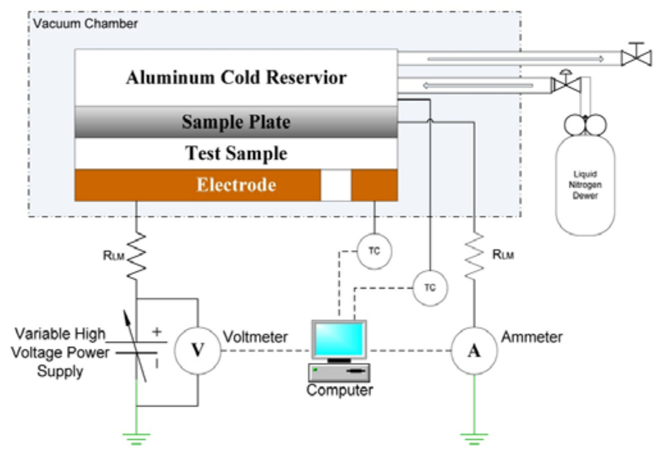

Fig. 1. Schematic of ESD test chamber [5].

approximation is quite simple, but as it neglects much of the ramping process; it may not be suitable in many cases. With Δt in (1) set to the step-up interval Δt_{step}, this model assumes that the probability for breakdown is zero for all voltage step leading up to the last, highest voltage step.

A more complete model considers the full breakdown probability over a full step-up test, including the smaller—but finite—probabilities at lower voltages as the applied field is ramped up. By considering such incremental voltage step-up tests the full probability for breakdown, P_{BD}, becomes [5]

$$P_{BD} = 1 - \prod_{j=1}^{V/\Delta V}[1 - \alpha\Delta t \sinh[\beta(j\Delta V)^2]] \qquad (3)$$

Here the step-up test occurs in $V/\Delta V$ discrete voltage increments, up to the breakdown voltage V. The breakdown voltage V as a function of $\Delta V/\Delta t$ is impossible to determine analytically. Given changes in either ΔV or Δt only, it should be possible to fit data using numerical schemes. Similarly, an analytic solution for (3) may be possible in the limit of a continuous ramp rate, $V/\Delta V \rightarrow \infty$. These will be the topics of future work.

III. Experimental Methods

We present ramp rate testing data on Kapton HN polyimide (PI), and biaxially oriented polypropylene (BOPP), in addition to the Kapton E data presented in [5]. Standard step-up voltage tests [4] were performed in a custom high vacuum chamber (<10^{-3} Pa base pressure) at room temperature (see Fig. 1) [5]. Well-characterized, high-uniformity polymer samples with fewer mechanical defects and inclusions from Goodfellow were used for all tests. Kapton HN PI samples had measured thicknesses of 25.0 µm ± 2%, density of 1.43±0.01 g/cm^3, and a relative dielectric permeability of 3.5 [10]. Kapton E PI samples had measured thicknesses of 23.0 µm ± 4%, density of 1.46±0.02 g/cm^3, and a relative dielectric permeability of 3.1 [11]. BOPP samples tested had measured thicknesses of 27.6 µm ± 1%, density of 0.90±0.05 g/cm^3, and a relative dielectric permeability of 2.4±0.2 [12]. Nominal breakdown field strengths for unbaked samples using standard ASTM 149 test methods were listed as 303 MV/m for Kapton HN [10], 276 MV/m for Kapton E [11] and 110-150 MV/m for BOPP [12],

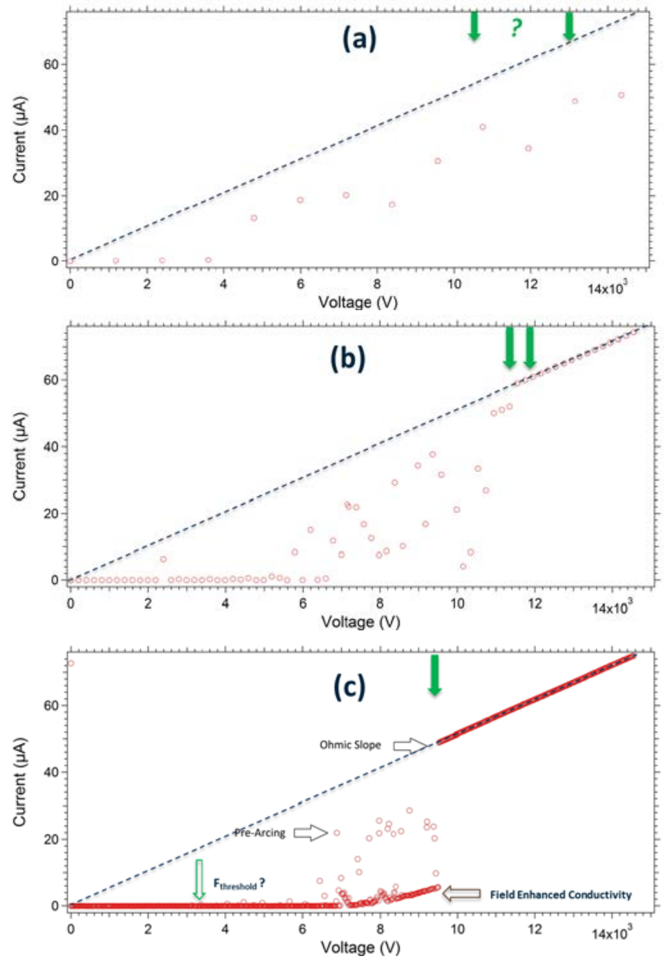

Fig. 2. Comparison of representative step-up voltage tests of Kapton HN at fast, medium and slow ramp rates: (a) 300 V/s (1200 V per 4 s), (b) 100 V/s (400 V per 4 s), and 5 V/s (20 V per 4 s) tests. Arrows indicate the range of F_{ESD}. Dashed line indicates ohmic dependence.

respectively. All samples underwent a standard vacuum bake out for ~72 hr at ~380 K and <10^{-3} Pa to minimize the amount of water and other volatile compounds. Samples were placed between metal sample mounting plates and six highly polished Cu high voltage electrodes, using a recommended uniform clamping pressure of ~0.4 MPa [4].

For ramp rate tests, voltage was incrementally increased at a constant time interval until breakdown occurred, which was evident by an abrupt current increase followed by a ohmic linearly current above breakdown set by limiting resistors [5] [13], as can be seen in Fig 2 (c). Different ramp rates were used in order to compare the dependence of electrostatic field strength on ramp rate for each polymeric material to the theory applied to past experiments. Fig. 2 shows three step-up tests done at fast, medium, and slow ramp rates.

IV. Results

Each ramp rate test was compiled into a single graph for each material showing the breakdown field at that ramp rate. Fig. 3 shows the breakdown field versus ramp rate for three polymeric materials, Kapton E, Kapton HN and BOPP. Ramp rates shown in Fig. 3 vary from 20 V per 4 s up to 2000 V per 4 s [4]; standard protocols suggest using rates less than 500 V/s [4]. Between three and six tests were done at each ramp rate; each point in Fig. 3 shows the average and standard deviation of the tests at a given ramp rate. Also shown are the average F_{ESD} and a fit based on Eq. (2).

Fig. 3(a) shows previous data taken at five voltage ramping rates between 1 and 25 V/s for Kapton E [5]. A total of twelve voltage ramping rates between 0.5 and 500 V/s were tested for BOPP [10]. A total of six voltage ramp rates between 10 and 300 V/s were tested for Kapton HN.

A significant result is that slower ramp rates reveal insightful behavior that is unclear or indistinguishable at faster ramp rates. Note that in Fig. 2 (c), in addition to a clear transition to an ohmic IV curve, indicating breakdown, additional behavior is clearly evident. The baseline current gradually increases indicating field-enhanced conductivity in the material. Superimposed on this behavior are many transient current spikes. The distribution of these events, termed "pre-arcing" or "non-shorting DC partial discharge," has been shown to match the probability distribution of destructive breakdowns with applied voltage [14]. We see in Fig. 2 (b) a region between measurements of essentially no current with some non-shorting DC partial discharging and ohmic breakdown. It is unclear if in this intermediate region some kind of erratic breakdown has occurred or if non-shorting DC partial discharges are so frequent compared to the ramp rate that return to baseline current cannot be measured. In Fig. 2 (a) ohmic breakdown was never achieved yet large currents were achieved and the sample was clearly damaged.

The most salient result of this study however, was that in addition to more realistically recreating a spacecraft charging situation, slower ramp rates also yield more accurate and precise data simply because the step size is smaller.
Additionally, it is significant that tests with slower ramp rates produce data with more physical meaning than the fast tests do. Voltage step-up data on microcrystalline aluminum oxide ceramic samples shown in Fig. 4 lack ohmic breakdown; however, it has useful data including surface flashover events, non-shorting DC partial discharges and field enhanced conductivity [14]. Occasional voltmeter errors are distinguished by current traces well above the ohmic breakdown curve. Surface flashovers are marked by sudden voltage drops to current signatures lying on the expected ohmic breakdown curve. These phenomena are simply unclear or unobservable with faster ramp rates used more commonly in step up tests. Data for a polymer, polyether ether ketone (PEEK), exhibit similar features to those shown in Fig. 4 [15].

V. Conclusion

The original impetus of this study was to test various models of the ramp rate dependence of breakdown. The initial tests for Kapton E agreed with the theoretical model presented here, albeit over a limit range of ramp rates. However, expanding the range of ramp rates and the extending the number of materials tested has not confirmed the trend set by these initial results. Kapton HN and BOPP results do not show the ramp rate dependence predicted by Eq. (2). These materials showed no statistically significant variations with ramp rate and had reduced standard deviations over the measured ramp rates of ±3% compared to ±10% in Kapton E (see Fig. 3). Ramp rate

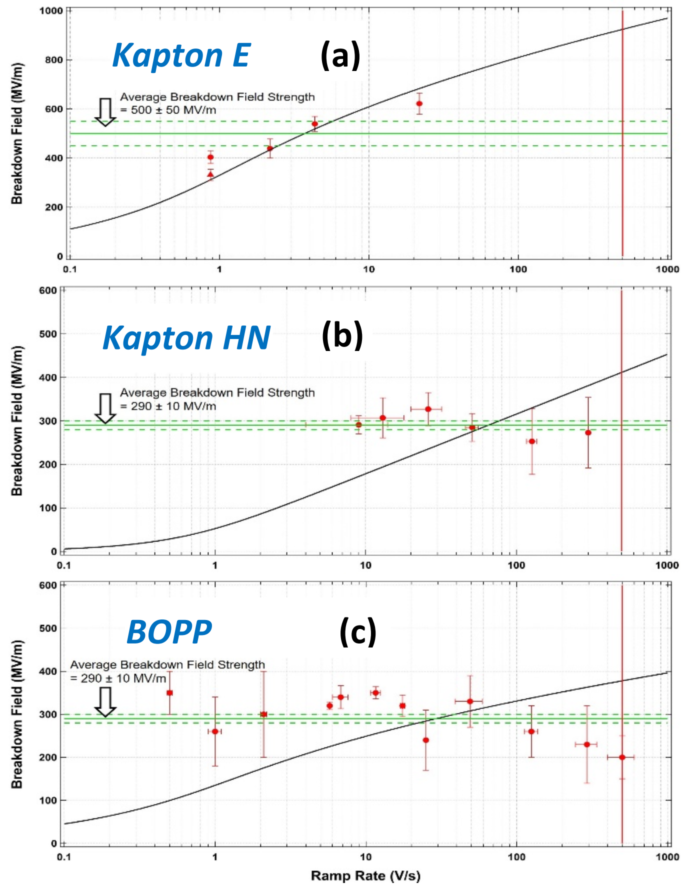

Fig. 3. Breakdown field versus ramp rate for: (a) past tests on Kapton E, (b) tests on Kapton HN, and (c), results for BOPP. The black curves are fits based on Eq. (2). Horizontal lines show the mean F_{ESD} and one standard deviation. The recommend maximum ramp rate of 500 V/s [4] is marked by the vertical red line.

has less direct effect on F_{ESD} for Kapton HN and BOPP than for Kapton E; however, ramp rate still physically affects all materials tested. These effects become significant when tests are orders of magnitude faster than real spacecraft charging situations, which is the case when the standard ramp rate of 500 V/s is used. More data for additional ramp rates, lower uncertainties at a given ramp rate, and more diverse material tests are required to investigate the applicability and accuracy of the mean value, mean field [Eq. (2)] and incremental voltage step [Eq. (3)] models.

Acknowledgement

We gratefully acknowledge contributions to the development of the instrument and test methods by Dan Arnfield, Anthony Thomas, and Ryan Hoffmann. Charles Sim, Matthew Stromo, Dan Arnfield, and Anthony Thomas helped with ESD data acquisition.

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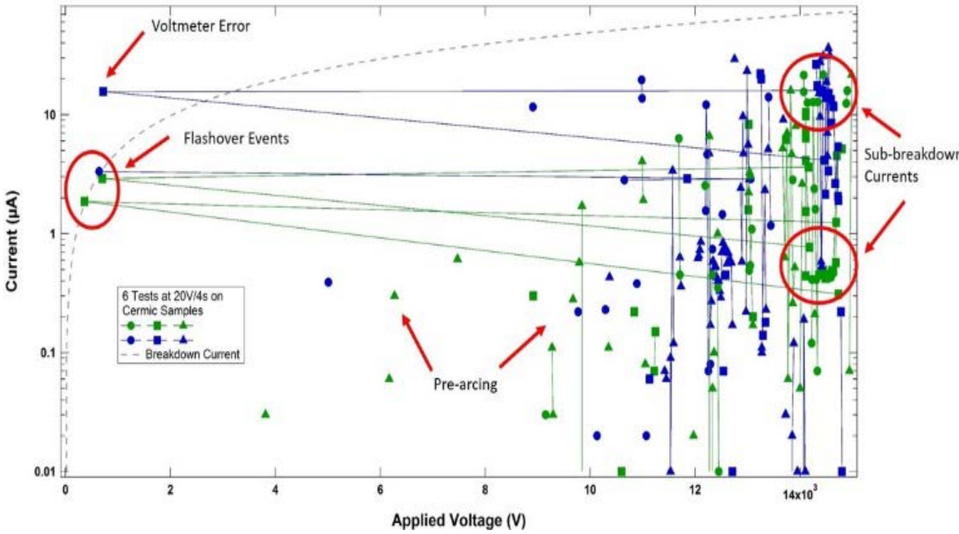

Fig. 4. Semi-log plot of voltage step-up tests on microcrystalline aluminium oxide ceramic insulators. Complete breakdown was not observed however many other current signatures are present including surface flashover, pre-arcing, sub-breakdown currents, and voltmeter errors.

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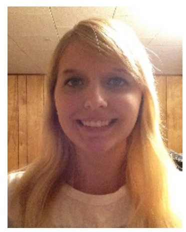

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