Perspectives on the Distributions of ESD Breakdowns for Spacecraft Charging Applications

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Abstract— **Electrostatic discharge (ESD) continues to pose significant risks to space missions despite decades of intense study. Tabulated values of material breakdown strength used in spacecraft charging models are often based on cursory measurements that may not be fully relevant to a given mission. Materials physics offers insight into the pertinent variables that affect breakdown and how to address them experimentally for spacecraft applications. We present measured distributions of ESD data across several test configurations for three polymeric materials that, taken together, begin to provide an understanding of how to estimate the likelihood of ESD events over a spacecraft's mission lifetime. We discuss how consequences of these results apply to spacecraft charging modelling and design considerations.**

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

I. Introduction

Electrostatic discharge (ESD) can cause serious upsets or failures to space assets and continues to pose a challenge to spacecraft designers and modelers [1]. Dielectric materials on spacecraft can accumulate charge from the space plasma environment. As charging and associated electric fields increase, so does the likelihood of ESD. It is critical to mitigate the risk of ESD for mission success, especially as mission lifetimes increase, components become more compact and sensitive, and spacecraft venture into more extreme space environments.

The purpose of this paper is to offer experimental and theoretical insight from a materials science perspective to help spacecraft designers improve estimates of ESD breakdown fields used in space environment interaction models. Spacecraft charging effects mitigation standards offer the following guidelines for spacecraft modelers to design spacecraft systems to be immune to the effects of expected ESD pulse characteristics and frequencies:

- Refer to a table of breakdown voltage values for common insulators measured using standard methods [2-4].
- For materials not listed in available tables use a conservative estimate. Spacecraft charging standards estimate minimum breakdown thresholds—below which spacecraft are assumed to be safe from ESD—over a wide range of 1 to 20 MV/m [2, 3, 5, 6].
- Test specific materials and components to be used to determine breakdown thresholds and add a safety margin either by testing in conditions exceeding expected worse case scenarios or simply assuming the thresholds stated above [2, 3, 5, 6].
- Given a breakdown voltage threshold, use spacecraft charging software to estimate the time the spacecraft will spend at potentials at or exceeding the threshold value and assess the ESD threat for the mission [2, 3, 5-7].

II. Materials Physics Perspective

Dielectric breakdown on spacecraft may result from various mechanisms in space environments (*e.g.* differential charging as a spacecraft comes in and out of eclipse, deep dielectric charging in high radiation environments, etc.). Regardless of the source of excessive electric fields, dielectric breakdown is a complicated stochastic process. In the cases of sensitive missions, especially in extreme charging environments, the concept of dielectric strength may not be well approximated by a constant value. Nevertheless, breakdowns strengths are most often represented by a single value, perhaps with the occasional caveat that it may depend on thickness or temperature [2, 3, 7-11]. Concurrently, guidelines and relevant literature also strongly advise that materials be tested for their specific application [2, 3, 6, 7, 11, 12]. In this section we discuss how physical theories of breakdown can improve mission relevance of tests, what tests to consider, and how to interpret their results.

A. Defect Driven Theory of Breakdown

Physical models of conductivity and breakdown in insulating materials are driven by electronic defect energies and densities, temperature, applied electric field, the time over which a given set of conditions persists, and the history of the materials (aging) [13]. Assuming static, intrinsic defect energies and densities, the breakdown strength may vary significantly with extrinsic conditions such as temperature and charging rate. One should also beware of aging effects, contamination, or even variations in manufacturing as any of these can significantly alter defect populations and therefore charging properties [14-15]. Breakdown field strengths can evolve as the interaction

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with the space environment modifies the defect distributions and conductivity. For example, radiation damage can introduce new defects and increase the defect density, thereby affecting the distributions of ESD events. For most space missions it is important to bake test samples *in vacuo* to drive off water and other volatile compounds which can significantly affect conductivity, work function and electron emission [3, 13, 17, 18].

B. *Zeroth Order Breakdown Testing: Look Up a Number*

Spacecraft charging standards from different space agencies estimate a lower bound for ESD threshold fields below which the risk of ESD is insignificant [2, 3, 5, 6]. Although these recommended values range over an order of magnitude from 1 MV/m to 20 MV/m, it is noteworthy that they represent an ESD design criterion that does not depend on temperature, charging history, or even material!

To estimate such an absolute lower bound in the electric field needed to achieve breakdown, F_{min}, we assume that breakdown is a cascade process where a free charge (*e.g.*, an electron of charge q_e) must gain enough energy ΔE to liberate additional charges upon impacting another defect, as it is accelerated over a distance a (the average distance from one defect to the next) in an electric field This threshold field is given in one dimension by

$$F_{min} = \frac{\Delta E}{q_e a}. \quad (1)$$

To estimate F_{min}, it is reasonable to assume that the lowest possible defect energies that could contribute to ESD must greater than a few $k_B T$ at room temperature, *i.e.*, $\gtrsim$0.1 eV. Assuming a maximum average defect spacing smaller than 50 to 500 atomic spacings (<10-100 nm) gives, as an extreme limiting case, that electric fields below 1-10 MV/m can be considered safe for insulators in general barring any extrinsic damage, even for very long times. This agrees with the lowest value of 1MV/m for such a rule cited in a charging standard [6]. For fields above 1 MV/m more consideration is required.

The next logical step might be to be look up the tabulated dielectric strength of the material in question. Materials manufacturers, spacecraft charging standards, and other sources list tables of dielectric strengths for many insulating materials. *Caveat emptor*! These sources most often lack even basic experimental details (*e.g.*, test method used, sample preparation, temperature or voltage ramp rate) needed to gauge their relevance for a given space mission. Consider Fig. 1, which compares breakdown field estimates for three common insulating polymers, low-density polyethylene (LDPE), biaxially-oriented polypropylene (BOPP), and Kapton HN (PI). Fig. 1 (a) shows the manufacturer's published values for breakdown for 25 μm films of these polymers; other than noting substantially lower values for these materials in bulk rather than in thin films, no uncertainties, qualifiers, sample preparation (*e.g.*, cleanliness or vacuum bake out) or test methods are stated explicitly [19-21]. Handbook values can be useful for some applications, or as a starting point for comparing materials, but there are simply too many variables to take handbook values for granted when materials are to be used on sensitive space missions.

It is impossible to perfectly simulate both flight conditions and mission durations on the ground; however, considering mission conditions and possible changes in material properties over mission lifetimes can guide accelerated test methods. Taken together, tests such as the following begin to predict how materials' likelihood for dielectric breakdown can change with different conditions.

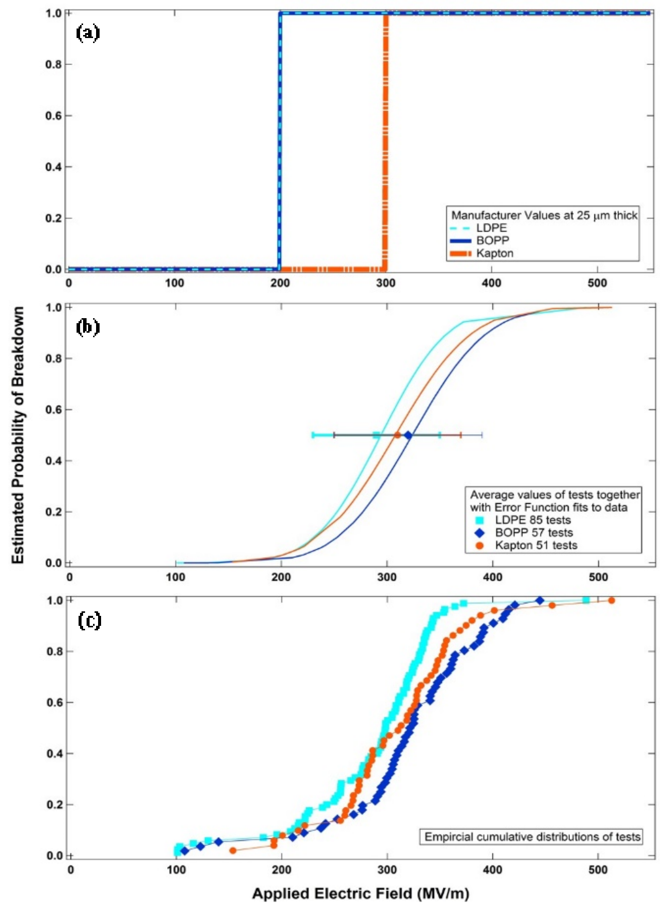

Fig. 1. Successively more accurate representations of dielectric strength for LDPE, BOPP, and PI (Kapton). (a) Manufacturer values [17-19]. (b) Averages and standard deviations with underlying error function fits to USU step-up tests. (c) Empirical cumulative distributions of USU step-up tests.

C. *First Order Breakdown Testing: Voltage Step-Up Tests*

First, a nominal room temperature breakdown field should be established using voltage step-up to breakdown tests with a moderate ramp rate [16]. Such tests are typically performed in a simple parallel plate geometry *in vacuo*, by increasing the applied voltage until breakdown occurs. Industry standard test configurations subject samples to up to 500V/s [2, 4]. Not only is this voltage ramping rate much higher than any realistic operational charging condition encountered by spacecraft [2, 3], but accuracy and precision of such tests suffer significantly as a result [16]. Standard ESD tests performed by the USU Materials Physics Group typically use a conservative—though still very rapid compared with space applications—stepwise ramp rate of 20 V per 4 s at room temperature [15]. Further experimental details are available in a previously published work [15].

The careful interpretation of voltage step-up tests is important for estimating the fields at which ESD is likely to occur. At least 50 of our standard ESD tests were performed on

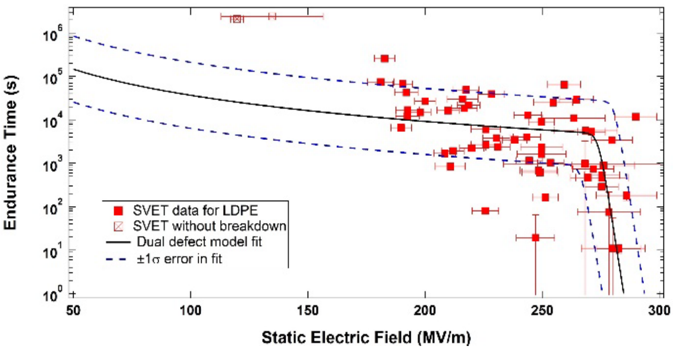

Fig. 2. Static voltage endurance time tests in LDPE fit to a dual-defect breakdown model [13].

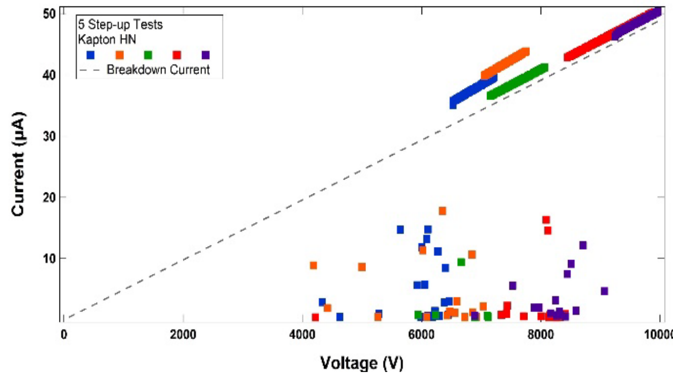

Fig. 3. Examples of "pre-arcing" below the breakdown current in 5 Kapton step-up to breakdown tests.

each of the materials in Fig. 1 [13]; Fig. 1 (b) shows the averages and standard deviations together with error function fits to the data. This method assumes a Gaussian distribution of the results.

Fig. 1 (c) is the empirical cumulative distribution (ECD) of the results. The ECD describes the fraction of total breakdowns observed in a set of experiments at or below a given field. For each material the ECD predicts higher probability of breakdown at lower fields than predicted by a Gaussian or other symmetrical distributions. A well-chosen physics model or a Weibull distribution would a be better suited fitting function for modeling this behavior [22]. Thus a more accurate average breakdown threshold may be significantly lower than what one would expect from application of just an average and standard deviation of voltage step-up test results. This has important consequences in establishing the highest acceptable field in a given spacecraft or component design, especially for missions with long duration or for low tolerance of the number of acceptable ESD events. This reinforces the importance of measuring and considering a field dependent probability distribution of breakdown strength over a single average value.

D. Second Order Testing: Varying Key Test Parameters

Given this baseline, voltage step-up tests at different temperatures, radiation doses, or different ramp rates can be done to determine the dependencies of the material in question [13]. For example, static voltage endurance time (SVET) experiments hold a sample below its nominal breakdown voltage and measure the time to breakdown. Samples held at subcritical voltage for extended times—as will typically be encountered in space applications—will often breakdown over extended times. In essence, SVET tests determine the time a sample must be held at a given subcritical field before a significant probability of breakdown is reached. Fig. 2 is an example of a series of SVET tests. The test time required to obtain these data was 68 days making it likely to be impractical to obtain such results for many different candidate spacecraft materials [13]. Results from smaller data sets at fields near the nominal electrostatic breakdown field can be fit to empirical or physical models in order to extrapolate the results to the comparatively very slow ramp rates and much longer times typical of spacecraft missions [13, 22].

An important open question in the study of ESD is whether there is a threshold field below which breakdown will not occur [23]. Measurements for LDPE shown in Fig. 2 taken at fields below 130 MV/m did not observe breakdown in more than 20 days, suggesting that there may be a threshold field somewhere below the lowest observed breakdown after ~3.5 days at ~170 MV/m. Unfortunately, the time required to obtain the data necessary to definitively establish such threshold fields can be extremely long.

Arcing tolerances and risks will depend on individual spacecraft or systems and space environments. Therefore, modelers will have to ask themselves how much risk they can tolerate and how much testing is feasible given budget and time constraints.

E. Possible Highly Accelerated Testing: Non-Shorting DC Partial Discharging

Many materials have been observed to exhibit a phenomenon that may serve as an early low-field indicator or proxy for eventual electrical breakdown [24]. Voltage step-up tests with a slow enough ramp rate exhibit non-shorting transient current spikes before final destructive breakdown. These events—referred to as "pre-arcing" or "non-shorting DC partial discharge"—correlate strongly to the electric field distribution of ESDs [24]. Given that there are most often many non-shorting DC partial discharges per destructive breakdown test (see, for example, Fig. 3), measurements of the distribution of non-shorting DC partial discharges with applied field could be used as an accelerated means of estimating ESD threshold fields [13, 24]. If resources for only a few voltage step-up tests are available, the destructive breakdowns alone are unlikely to yield information about the threshold field (as seen in Fig. 1 (c), only a small fraction of total events occur at the lowest fields); however, after only a few breakdown tests the more numerous non-shorting DC partial discharges are much more likely to reveal lower fields with small likelihoods of breakdown which only become more significant (and more apparent) at long endurance times. It should be noted that this new accelerated test method needs further development, especially in the form of tests of reproducibility by other research groups.

III. Conclusion

In summary we offer the following considerations when selecting breakdown thresholds for use in models.

- Define your mission parameters and requirements then tailor ESD tests, together with materials and components, to be as close to worst case flight conditions as possible. Dielectrics that will experience fields less than 1 MV/m are very unlikely to be at risk for ESD.
- Handbook values for breakdown are not wrong, but they were often developed for very different applications (*e.g.*, breakdown tests in oil with a pin electrode at 500V/s). However, these handbook test values are often inappropriate for spacecraft charging applications.
- Breakdown is not well characterized by as single number. Consider a probability distribution that depends not only on the material, but the conditions it is subjected to over time [13-15, 22]. The acceptable probability for a given mission needs to be determined by considering mission objectives and ESD tolerances.
- Taken together, SVET tests, tests at different ramp-rates, total radiation doses, and temperatures, can be used to more accurately estimate material behaviors, particularly at subcritical fields, extended radiation exposure times, slower ramp rates of field build up and different temperatures.
- Physics-based or even well-chosen empirical models can estimate behavior of materials for times and conditions not achievable with testing of materials [13, 14, 22].

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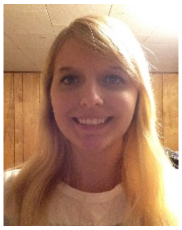

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