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Charlie Sim
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Evaluation of the Temperature and Time Dependence of Electrostatic Breakdown

Charlie Sim

J.R. Dennison, Mentor

Physics Department, Utah State University

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ABSTRACT

The goal of this research was to investigate temperature and time dependent models for the electrostatic breakdown of polymeric spacecraft insulators. Temperature dependent breakdown was found by inducing an electrostatic breakdown in the prototypical polymer Low Density Polyethylene (LDPE) at various temperatures. Time dependent breakdown was found by applying a static voltage to LDPE and measuring the time to electrostatic breakdown. No significant temperature dependence of the electrostatic breakdown of LDPE was observed in a temperature range of 150 K to 300 K. The time dependent results show that the time to electrostatic breakdown is modeled by a negative logarithmic decay consistent with thermodynamic mean field multiple trapping models, with the electric field breakdown strength asymptotically approaching a constant value as the time to breakdown goes to infinity.

I. INTRODUCTION

The environment in which spacecraft and satellites operate is harsh [1]. One recurring, inevitable problem with spacecraft in this environment is the build up of electric charge on the surface of the craft and its internal components [2]. Such charging leads to electrostatic breakdown and eventual failure.

Knowing how the electrostatic breakdown of polymeric insulators depends on temperature and time the material is exposed to such charge (or electric field) is important in being able to predict, and extend, the lifetime of the spacecraft they are used on. This dependence is important because the spacecraft can experience a varied range of temperatures during its life cycle. The present research is based on a previously derived thermodynamic mean field multiple trapping model for time and temperature dependent aging and breakdown at high electric field given by [3,4]

$$t_{en} \approx (h / 2k_B T) * \exp ((\Delta G - q_e \lambda F_{esd}) / kT) \quad (1)$$

where t_{en} is the time to breakdown, T is the temperature of the material, F_{esd} is the electric field strength at breakdown, ΔG is the energy barrier height (Gibb's free energy), q_e is the charge of an electron, h is Planck's constant and k_B is the Boltzmann's constant. The microvoid dimension, λ , is a measurement of the size of microscopic voids between particular dense portions of the polymer or the mean distance electrons travel in an electric field between being trapped in localized states.

The Gibb's free energy (ΔG) and the microvoid dimension (λ) are both constants that are specific and intrinsic for different types of polymers. Knowing the values of these constants will allow for the development of a model for the time endurance of that specific polymer at any

temperature and electric field value within our range of measurements. These constants may also be used to extrapolate the model to make predictions for the materials reaction beyond the scope of our measurements. The data collected for temperature and time dependence on electrostatic breakdown allow us to determine the values of ΔG and λ for the polymer being tested. For a linear plot of $\ln(t_{en}/\tau_{en})$ vs $F_{esd}(t_{en};T)$, with $\tau_{en} \equiv (h/2k_B T)$, λ equals (kT/q_e) divided by the slope and ΔG equals $(-k_B T)$ times the ratio of the intercept to the slope.

II. METHODS

To measure electrostatic breakdown potentials using standard methods [5], samples of $27.4 \pm 0.2 \mu\text{m}$ thick LDPE were sandwiched between a copper electrode and a conducting metal plate on which the sample was mounted. To conduct temperature dependent tests, an aluminum cold reservoir for liquid nitrogen was stacked on top of the metal sample plate. This stacked configuration of cold reservoir, sample plate, sample, and copper electrode was all housed inside of the Utah State University Materials Physics Groups electrostatic discharge chamber [6-9]. The chamber had a base pressure of $<10^{-4}$ Torr. A voltage was then applied to the copper electrode (starting at 0 V) and increased at a rate of 20 V steps every 4 sec until an electrostatic breakdown was induced in the material [8]. Current and voltage were monitored using two computer interfaced multimeters under LabVIEW control.

Electrostatic breakdown occurs when the electric field exceeds the dielectric strength of the polymer (Figs. 1 and 2). Current increases significantly at breakdown and continues to rise linearly with a slope set by Ohm's Law, $V = IR_{limit}$ (V is applied voltage, I is the measured current, $R_{limit} = 176 \pm 2 \text{ M}\Omega$ is the current limiting resistance in the instrument), as seen in the breakdown regime in Fig. 1 (c).

Electrostatic breakdown tests were conducted multiple times at multiple temperatures in the range of 150 K to 300 K. The electric field strength and temperature at the time of breakdown were recorded and plotted on a graph of electric field vs vs. temperature (Fig. 4). Electric field

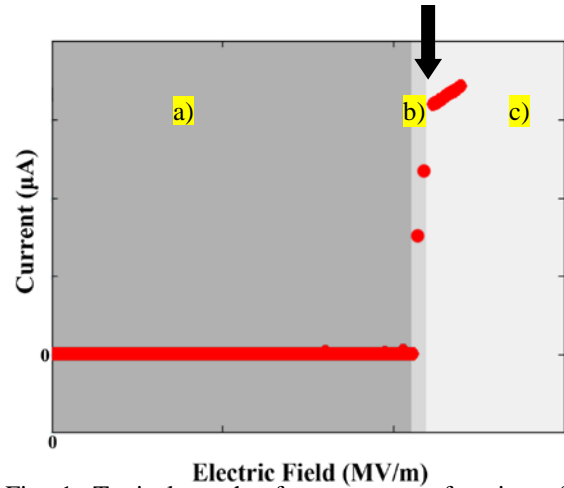


Fig. 1. Typical graph of current as a function of electric field. (a) Pre-breakdown regime: the material acts as an infinite resistor and negligible ($<10 \mu\text{A}$) current flows. (b) Onset regime: breakdown has started to occur, but a conduction path through the material has not been fully established. (c) Breakdown regime: Breakdown has occurred and a conduction path has been established for the rising current (black arrow).

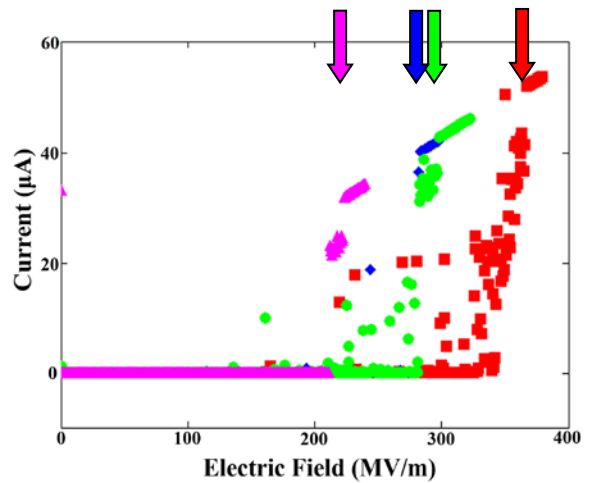


Fig. 2. Current vs electric field graphs of experiments ran on $27.4 \mu\text{m}$ LDPE at room temperature. The colored arrows mark the point of breakdown for each test run. Variations in the breakdown electric field are caused by impurities and slight variations in the thickness of the material.

strength (MV/m) is found by dividing the measured voltage by the thickness of the material. The data were analyzed to determine the electrostatic breakdown dependence on temperature [6,7].

To measure the time dependent breakdowns, the voltage was ramped up on the copper electrode at 20 V steps every 4 seconds [8] and then held at some predetermined voltage below the mean breakdown voltage at room temperature. This predetermined voltage is maintained until breakdown occurs. Time to breakdown is measured from the moment the maximum static voltage is attained until electrostatic breakdown occurs (Fig. 3). The experiment was conducted again at different predetermined voltages, each time with a lower predetermined voltage.

III. RESULTS

Figure 4 [9] shows the electric field strength at breakdown versus temperature for tests conducted on LDPE. Two possible models for the data shown in Fig. 4 are considered: (i) there is no dependence on temperature for electrostatic breakdown and (ii) there is a small linear dependence on temperature, that is the high T limit of Eq. (1).

A linear model for electrostatic breakdown as a function of temperature has the form:

$$F_{esd}(T) = F_1 + \beta(T - T_{RT}) \quad (2)$$

where F_{esd} is the computed breakdown electric field strength (MV/m), β (MV/mK) is the coefficient of thermal change and the slope of the graph, and F_1 (MV/m) is the breakdown electric field at room temperature, T_{RT} . The linear regression analysis returned values of 0.25 ± 0.55 MV/m-K and 265 ± 120 MV/m for β and F_1 , respectively, for the temperature dependent model.

A temperature independent model would indicate that the electrostatic breakdown of LDPE does not change as a function of temperature. Therefore, the mean of the electric field points at breakdown, $F_0 = 318 \pm 55$ MV/m, would be the best fit of the data. No measurements of F_{esd} below room temperature were found in the literature. However, our results are reasonably consistent with tests done in the temperature range of 300 K to 400 K (Fig. 5) [10]. The red marker with vertical blue bar in Fig. 4 indicates F_0 of LDPE with associated error.

A reduced chi squared method was used to determine the validity of the two models for temperature dependence. The temperature independent model has a lower reduced chi squared value (0.33) than that for the temperature dependent model (0.36), indicating that the temperature independent model provides a better fit. Therefore, in the range of 150 K to 300 K, there is no statistically significant temperature dependence of electrostatic breakdown in LDPE.

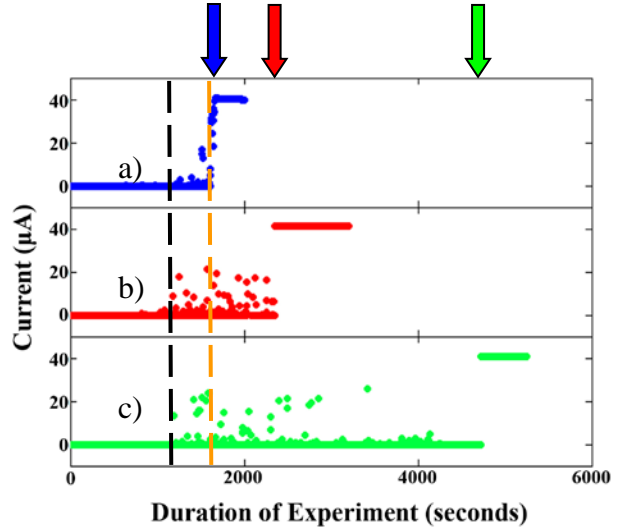


Fig. 3. Plots of current vs time for three time dependent breakdown experiments at different static voltages. The arrows indicate the time at which the material broke down. (a) Static voltage of 7509 V. (b) Static voltage of 7401 V. (c) Static voltage of 7313 V. The orange dashed line represents where the set voltage for each experiment was attained. The black dashed line represents the electric field threshold for unsustained current spikes.

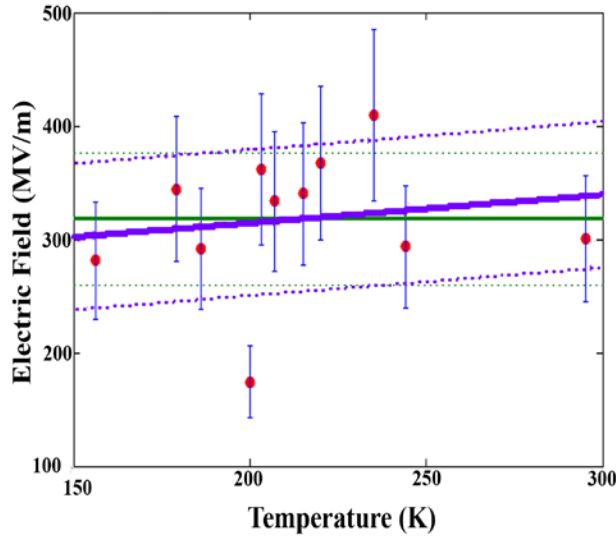


Fig. 4. Data of the electric field at the time of breakdown for 1 mil LDPE (dots). The solid green line is the mean breakdown electric field, 318 ± 55 MV/m. The solid purple line is the linear temperature dependent model, Eq. (2), for breakdown electric field.

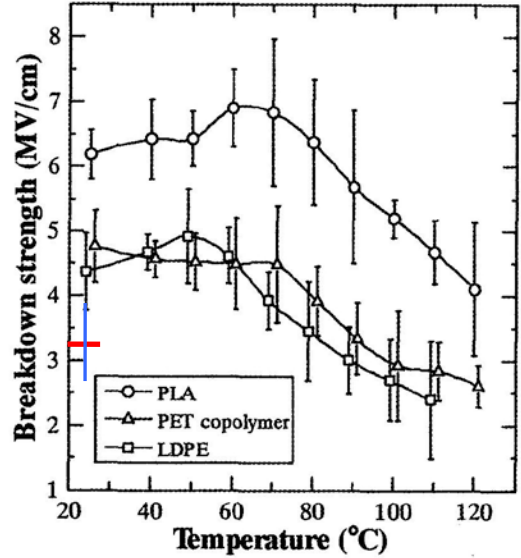


Fig. 5 Previous electrostatic breakdown tests in the range of 25 °C to 125 °C (300 K to 400 K).[10]. The mean electrostatic breakdown in the range of 150 K to 300 K (red marker with blue error bar) measured in this study is within the range of the previously conducted tests.

Four successful breakdown measurements were made using the methods described above for measuring electrostatic breakdown dependence on time. It is interesting to note there is a consistent threshold (black dashed line in Fig. 3) for unsustained current spikes (current $> 1 \mu\text{A}$) for each of the three time dependant data sets. The average threshold value is 215 ± 3 MV/m. This could possibly be interpreted as the threshold electric field that causes breakdown in localized regions of the material that are insufficient to initiate an avalanche effect across the full sample. In the proposed model in Eq. (1), this is equivalent to the limit of $t_{en} \rightarrow +\infty$.

Figure 6 shows three successful time dependent breakdowns plus the mean of the temperature dependent data collected. A negative logarithmic model of the breakdown electric field strength, as a function of time to breakdown, was derived from Eq. (1) and is as follows:

$$F_{esd}(t;T) = (k_B T / q_e \lambda) \cdot \ln(t_{en} / \tau_{esd}) + (-\Delta G / q_e \lambda) \quad (3)$$

where $F_{esd}(t;T)$ is the computed breakdown electric field strength (MV/m), τ_{esd} (MV/m) is the coefficient of time endurance, t_{en} (s) is the endurance time of the material, and F_2 (MV/m) is the electric field value as the endurance time approaches zero.

The data were analyzed to determine the best values for LDPE of the microvoid dimension,

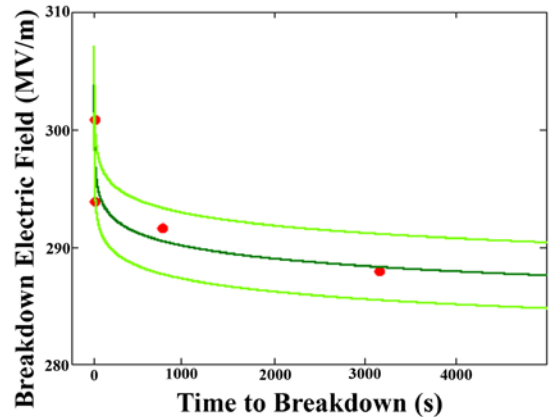


Fig. 6. Plot of electric field strength vs time to breakdown. Time to breakdown is measured from the moment the static voltage is reached until electrostatic breakdown occurs. A negative logarithmic fit (dark green line), Eq. (3), is shown with $\lambda = 16 \pm 1$ nm and $\Delta G = 5.7 \pm 0.6$ eV. Light green line shows the estimated uncertainty in the fit.

$\lambda=16\pm 1$ nm and the Gibbs free energy, $\Delta G=5.7\pm 0.6$ eV. These values are in reasonable agreement with those ~~determined~~determined by USU studies of the temperature and electric field dependence of conductivity and room temperature electrostatic breakdown which found $\Delta G=1.2$ eV and $\lambda= 0.6$ nm [11]. Griffiths [12] reported a more complete study of the electrostatic breakdown of cross linked polyethylene and fits to the data based on inverse power law, thermodynamic [3,4], and electrokinetic endurance models [13]. They found a value for the bond deformation activation energy, ΔG , of 1.2 eV. Based on their room temperature data, λ was estimated [11] to be 0.6 nm. These values are in surprisingly good agreement with activation energy or an average well separation ΔH of 0.78 eV [14]; 0.87 eV [15]; 0.80 eV to 0.83 eV [14]; and 0.6 eV to 1.1 eV [16] from previous studies of LDPE conduction. and $a = 1.33 \lambda$, a trap site separation (2.8 nm [15] and 2.0 eV at 303 K [16]) from previous studies of LDPE conduction.

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Table 1. URCO Expenses

Item	Vendor	Date	Account Charged	Amount
Vacuum Pump Refurbishment	LACO Technologies	5-7-2009	\$560.00	\$560.00
Liquid Nitrogen for Sample Cooling	USU Facilities Operations	5-11-2009	\$119.68	\$119.68
		6-1-2009	\$106.04	\$106.04
		6-13-2009	\$101.20	\$101.20
		9-30-2009	\$119.24	\$113.08
Total			\$1006.16	\$1000.00