2017

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Recommended Citation

Kippen, Tyler; Andersen, Allen; and Dennison, JR, "Temperature Dependence of Electrostatic Discharge in Highly Disordered Polymers" (2017). Fall 2017 Four Corner Section Meeting of the American Physical Society. *Posters.* Paper 80.
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Temperature Dependence of Electrostatic Discharge in Highly Disordered Polymers

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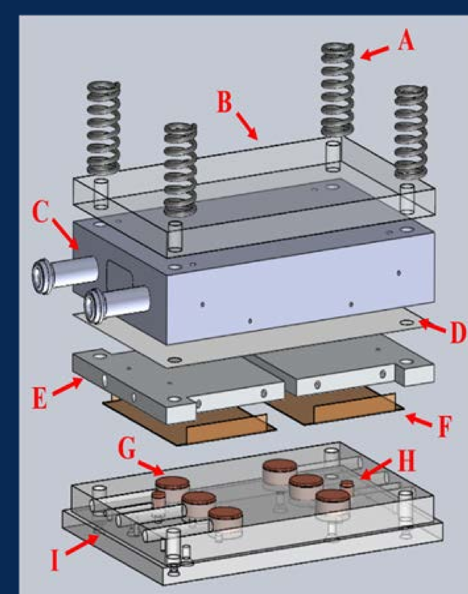
Introduction and Methods

Dielectric breakdown is the permanent, catastrophic failure of an insulating material due to an applied electric field. This results in the insulator becoming electrically conductive. Electrostatic discharge (ESD) is the sudden flow of current between two charged objects, and can result from dielectric breakdown among other causes. ESD is a leading cause of many of the anomalies and failures attributed to spacecraft interactions with the space environment. There are also direct applications to high voltage DC power transmission cables and switching, thin film dielectrics, and semiconductor devices and sensors. It is therefore critical to understand how ESD varies due to changing environmental conditions, including temperature.

Methods: Our method uses step-up to electrostatic discharge (ESD) tests on low density polyethylene (LDPE), polyetheretherketone (PEEK), and polyimide (Kapton) at temperatures ranging from 250 K to 360 K. These tests involve applying a voltage across a thin-film sample, and slowly ramping up the voltage until the sample breaks down. Breakdown is determined by measuring the voltage at which the sample becomes permanently conductive [1].



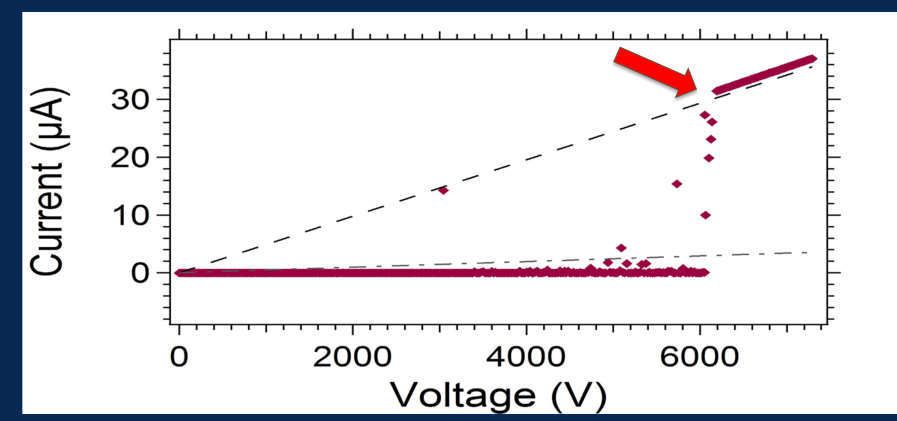
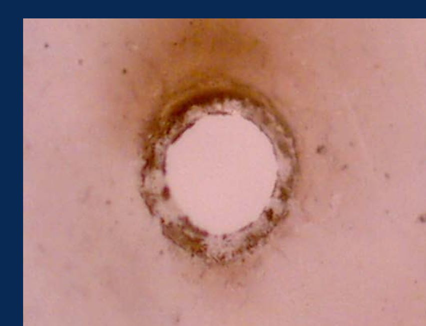


Figure 1 – A typical plot of the measured current vs. the applied voltage on a sample. An arrow points to where breakdown can be seen as the current abruptly increases to following an ohmic curve set by current limiting resistors.

Figure 2 – ESD Assembly **A.** adjustable pressure springs **B.** insulating layer **C.** cryogen reservoir **D.** thermally conductive, electrically isolating layer **E.** sample and mounting plate **F.** sample **G.** high voltage copper electrode **H.** copper thermocouple electrode **I.** insulating base [2]

Figure 3 – Breakdown site on a sample of LDPE. Note the melt and char marks around the hole signifying dielectric breakdown.



Results

The recorded breakdown field strengths were analyzed using Weibull statistics, which have been shown to better fit ESD data. To fit the data we used two fitting parameters, F_0 and β, which correspond to the average breakdown field strength and the width of the breakdown curve. The resulting curves are displayed in figures 4-6 [2]. Over the range of temperatures tested, there are not any spectacular changes, but it is possible to determine some trends in the data.

- Looking at figure 4 we see that for LDPE the breakdown curve narrows as temperature decreases, which implies that the material is more stable at lower temperatures.
- In figure 5 we see that for PEEK the breakdown field strength appears to decrease as the temperature increases, though most significantly from 280 K to 300 K.
- From figure 6, the average breakdown field strength for Kapton does not appear to be vary much with temperature, at least in the range of temperatures tested.

LDPE

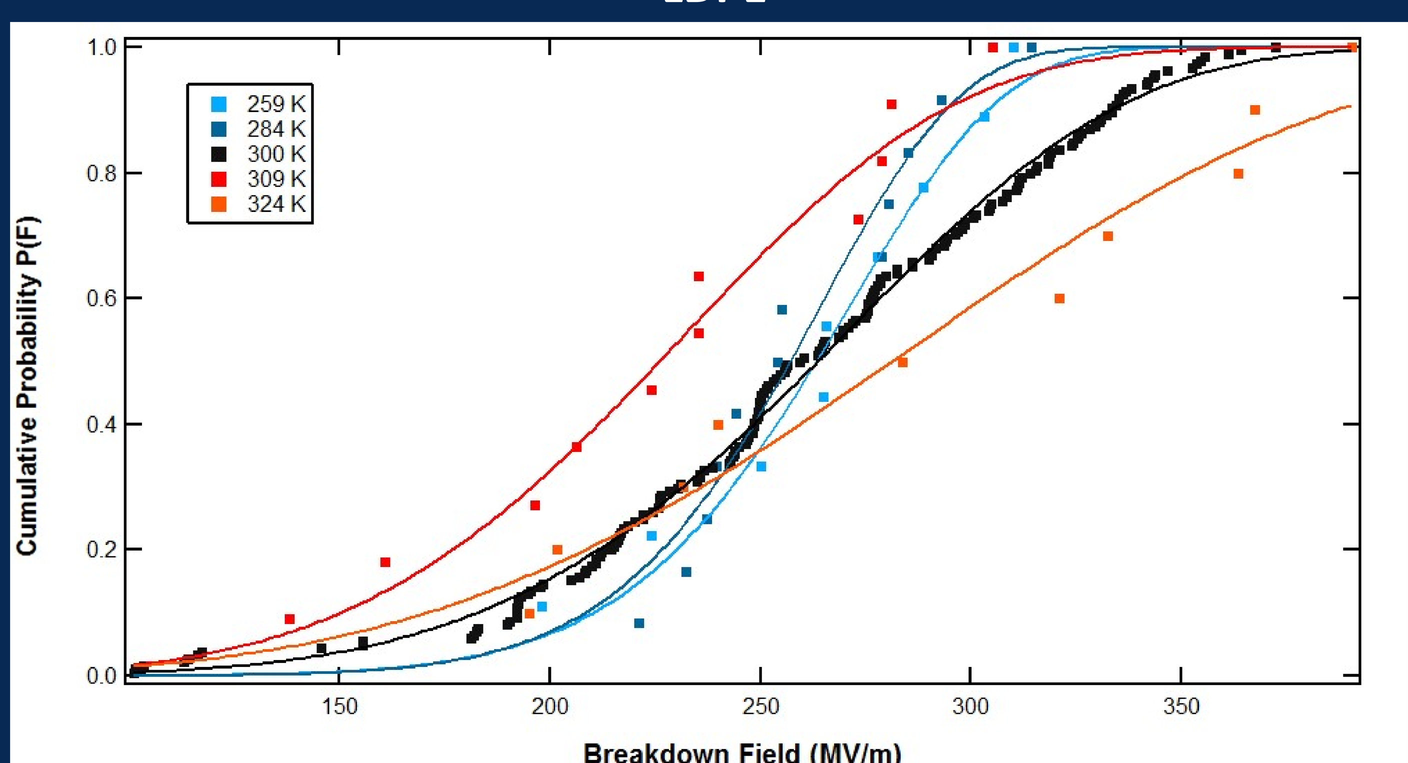


Figure 4a –Probability of a sample of LDPE breaking down compared to the breakdown field. This appears opposite of the PEEK data, with the low temperature curve being narrower than the high temperature curve, though the position of the curves vary.

Temperature [K]	F_0 [MV/m]	β
~259	275±2	8.4±0.8
~284	268±2	9.0±0.9
~300	283.1±0.3	5.1±0.1
~308	245±3	4.6±0.4
~324	310±6	3.8±0.4

Figure 4b – The Weibull parameters, $F_0$and β, for each curve. Especially of note is that while F_0 does not seem to follow a trend, β decreases as temperature increases.

Temperature [K]	F_0 [MV/m]	β
~280	239±2	6.5±0.6
~300	213.5±0.7	4.6±0.1
~359	205.8±0.6	7.2±0.2

Figure 5b – Fitting parameters F_0 and β of the graph. Notice that as temperature increases, F_0 decreases while β doesn't change significantly.

PEEK

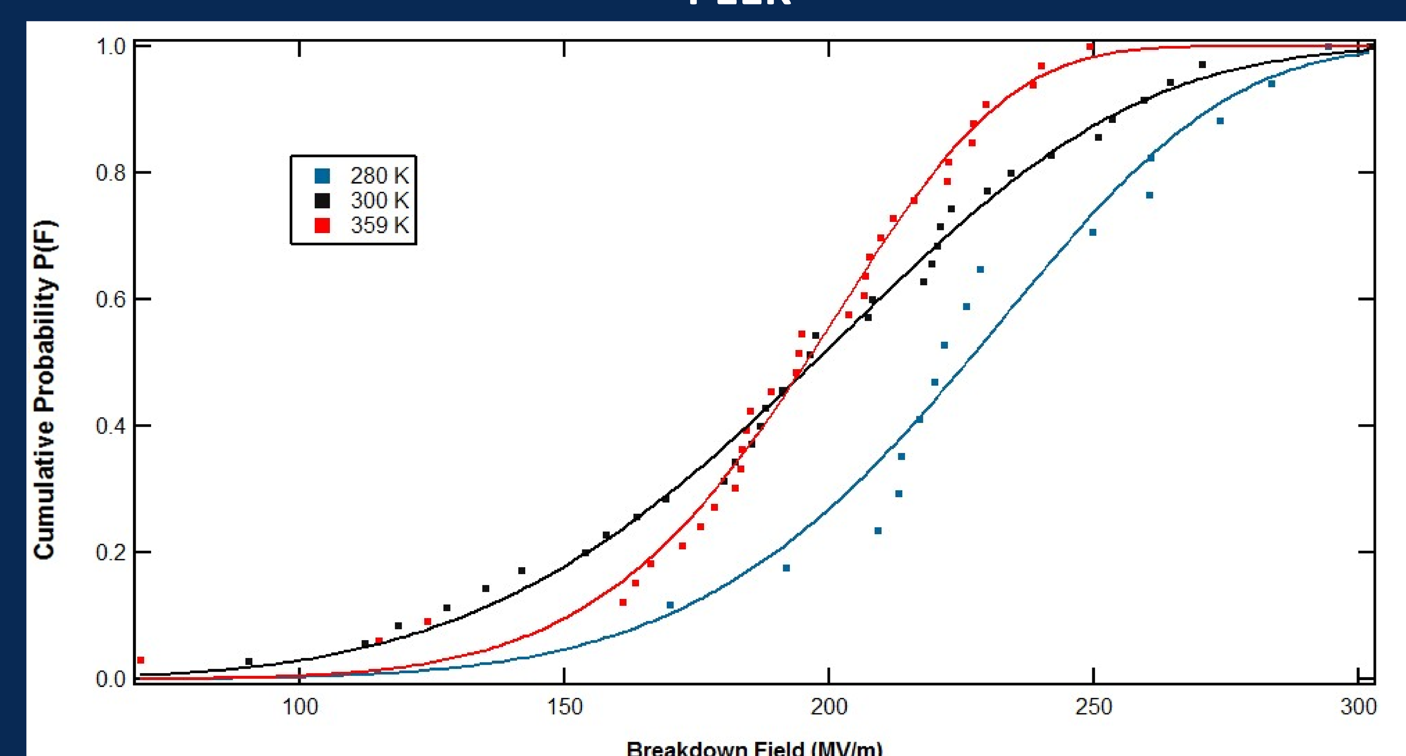


Figure 5a – Probability of a sample of PEEK breaking down compared to the breakdown field using a Weibull fit. Notice how at higher temperatures the breakdown field strength distribution narrows and shifts to the left while the opposite happens at low temperatures.

Dual-Defect Model

Equation (1) is a model of ESD developed at USU that considers two types of breakdown processes, A and B, where the probability of breakdown is the sum of the probabilities of A and B. A is a lower energy reversible process with a significant rate of defect repair and a low enough activation energy that the defects can be spontaneously repaired due to thermal activation. The second process is a higher energy, largely irreversible process with a negligible defect repair rate [3]. Charge migration between defects driven by the applied field allows charge to move through the material; when enough defects are accumulated, this leads to breakdown. For equation (1) it should be particularly noted that:

- Temperature, T, appears in each term, implying a high temperature dependence.
- The exponential term involves the ratio of the defect energy, ΔG_{def}, to the thermal energy, where k_B is Boltzmann's constant.
- The hyperbolic sine function involves the ratio of the energy gained in the electric field, F, from charge moving from one defect (density N_{def}) to the next, to the thermal energy.
- It is important to define Plank's constant, h, the wait time, Δt, and the vacuum and relative permittivity, ϵ_0 and ϵ_r [4].

$$P_{def}^{Tot}(\Delta t, F, T) = \sum_{i=A,B} P_{def}^{i}$$

$$= \left(\frac{2k_bT}{h/\Delta t}\right)\sum_{i=A,B} \exp\left[\frac{-\Delta G_{def}^{i}}{k_bT}\right]\sinh\left[\frac{\epsilon_0\epsilon_r F^2}{2N_{def}^{i}k_bT}\right]. \quad (1)$$

Kapton

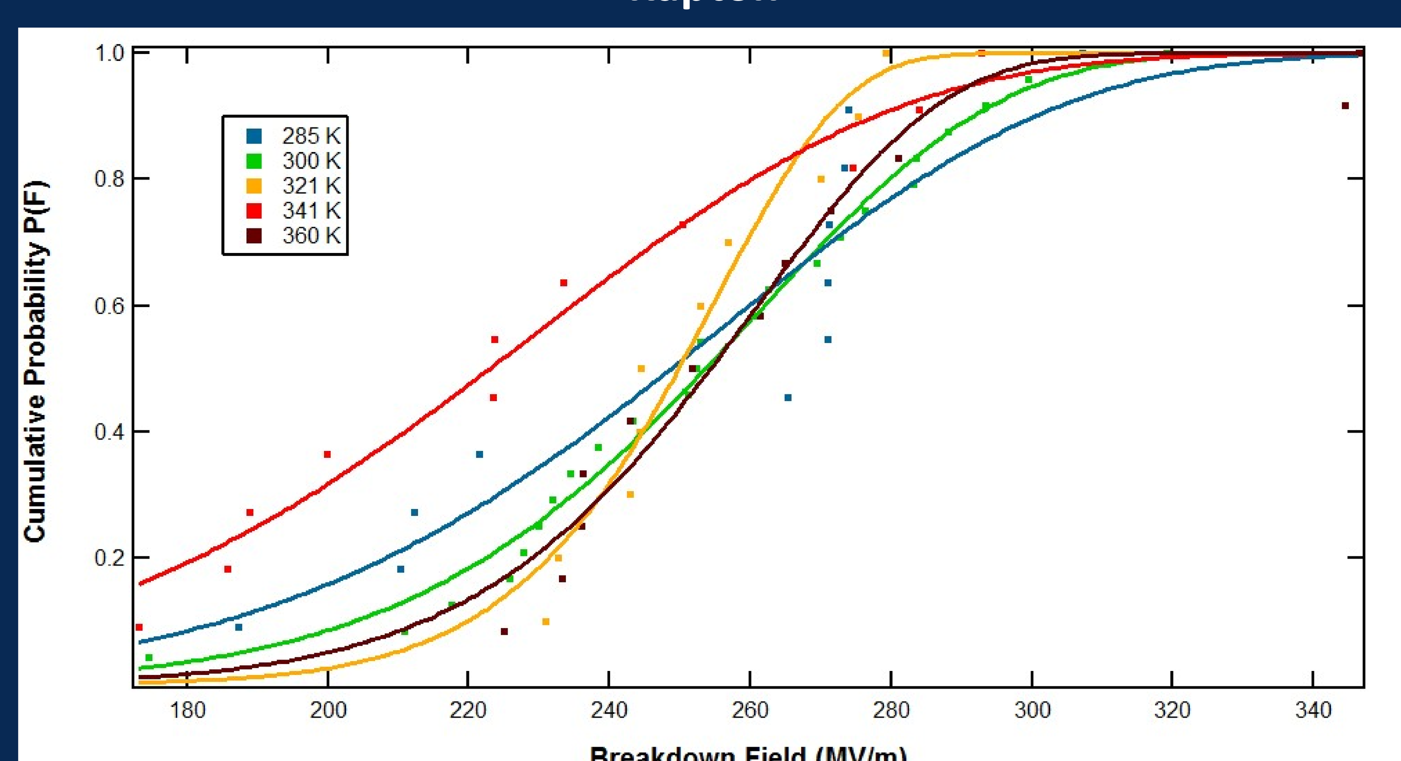


Figure 6a – Probability of a sample of Kapton breaking down compared to the breakdown field using a Weibull fit. Notice how that, other than the test at 341 K, the average breakdown field strength is very similar, even when the temperature varies by up to 75 K.

Temperature [K]	F_0 [MV/m]	β
~285	264±5	6±1
~300	264.7±0.7	8.6±0.3
~321	256±2	15±2
~341	238±3	5.5±0.4
~360	263±2	11±1

Figure 6b – The Weibull parameters , F_0 and β, for each curve. Notice again how there doesn't appear to be any trend in either of the fitting parameters.

Conclusions and Future Work

Conclusions:

- Temperature appears to affect breakdown field strength, but it seems dependent on the material. Some materials, like Kapton, appear to be much less affected by temperature than others like LDPE.
- The effects of temperature appear in the data in different ways. For PEEK the average breakdown field strength decreases with temperature while with LDPE only the β parameter changes.
- These results are in line with our model, because the breakdown probability depends on material specific parameters such as the defect energy or defect density.

Future Work:

- Test additional insulating polymers, such as polypropylene, and test other types of materials, like ceramics, to see if temperature plays as significant a role without the possibility of the thermal annealing that can result with polymers.
- Test the effects of extreme low temperatures using liquid nitrogen and use the lab's newly acquired chiller to perform more tests in the 230-300 K range .
- Test the effect of radiation damage on breakdown to examine more closely the effects that high energy defects have on the breakdown field strength. This should have a separate effect from temperature, which mostly affects the low energy defects where the applied temperature can anneal some of the defects.

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Scan code to access accompanying paper and references, as well as other USU MPG articles.

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