Temperature Dependency of Electrostatic Breakdown in LDPE and PEEK

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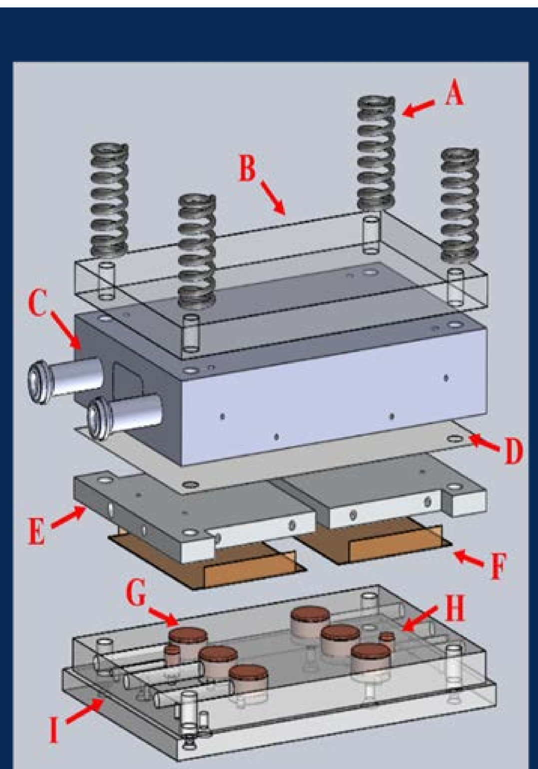
Introduction and Methods

Electrostatic breakdown is an abrupt reduction in the resistance of an electrical insulator when a voltage that is being applied across it exceeds a breakdown voltage. This results in the insulator becoming electrically conductive. Breakdown occurs in most dielectric materials at tens to hundreds of MV/m, reflecting the similarities in atomic spacings and bond strengths in most materials. It is therefore critical to understand how the breakdown electric field strength varies due to changing environmental conditions, including temperature and radiation dose.

Methods: Our method uses step-up to electrostatic discharge (ESD) tests on low density polyethylene (LDPE) and polyetheretherketone (PEEK) at temperatures ranging from 300 K to 350 K. These tests involve applying a voltage across a thin-film sample, and slowly ramping up the voltage until the sample breaks down [1].



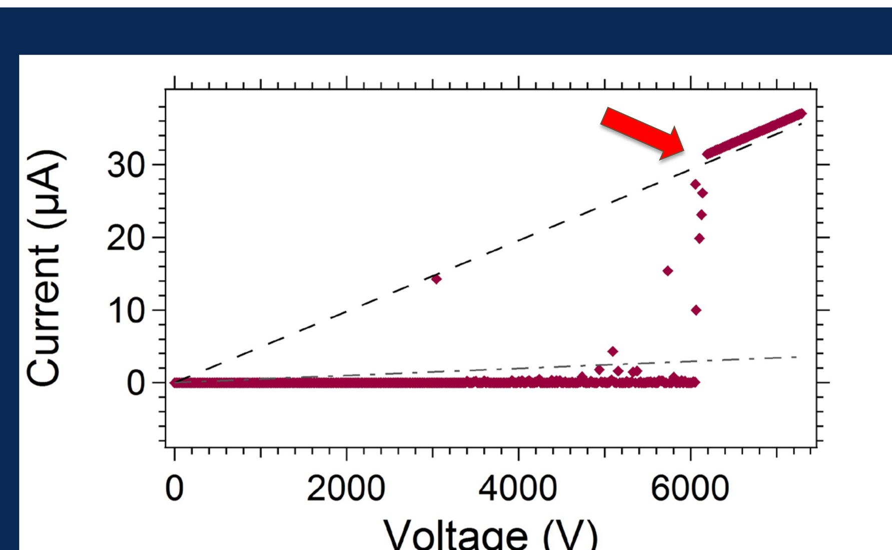


Figure 1 – A typical plot of the measured current vs. the applied voltage on a sample. An arrow points to where breakdown can be seen as the current abruptly increases to following an ohmic curve set by current limiting resistors.

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]

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 tunneling frequency, $\nu_{A,B}$, and the vacuum and relative permittivity, ε_0 and ε_r [4].

$$P_{def}^{Tot}(F,T) = \sum_{i=A,B} P_{def}^{i} = \sum_{i=A,B} \left(\frac{2k_B T}{h\nu_{A,B}}\right) \exp\left[\frac{-\Delta G_{def}^{i}}{k_B T}\right] \sinh\left[\frac{\varepsilon_r \varepsilon_0 F^2}{2N_{def}^{i} k_B T}\right]. \quad (1)$$

Results

Initially these tests were done to test how both the radiation dose and temperature affect the breakdown field strength in PEEK. At first look, using the average breakdown field strength and the standard deviation, neither appeared to have a significant effect. This is because the normal average and standard deviation don't model ESD very well. Under further analysis using Weibull statistics, which have been shown to better match with breakdown field curves compared to Gaussian or other forms of analysis, this yielded much better results and lead to the data in figures 3a and 3b [2]. Equation (2) gives the Weibull parameters where F is the field strength, F_0 is the is the center of the curve, and β is the width parameter. To further examine these results, tests were done using LDPE at several temperatures ranging from 259 K to 324 K. The resulting data is shown in figures 4a and 4b. From these data we see:

- In figure 3a we see that at high temperature the curve narrows and shifts to the left, while at low temperature the curve shifts to the right though interestingly also narrows.
- This is easier to notice when we linearize our data from the Weibull fit in figure 3b. Now the width and center parameters roughly correspond to the slope and intercept.
- In figure 4a we see that for LDPE the breakdown field strength does not seem to follow a pattern though at low temperatures the breakdown curve appears to narrow.
- Looking at the fitting parameters in figure 4c, we can see this affect. The breakdown field strength does not seem to follow a pattern as temperature changes, though the β parameter steadily decreases as the temperature increases.

$$P(F) = 1 - \exp\left(-\left[\frac{F}{F_0}\right]^{\beta}\right) \quad (2)$$

PEEK

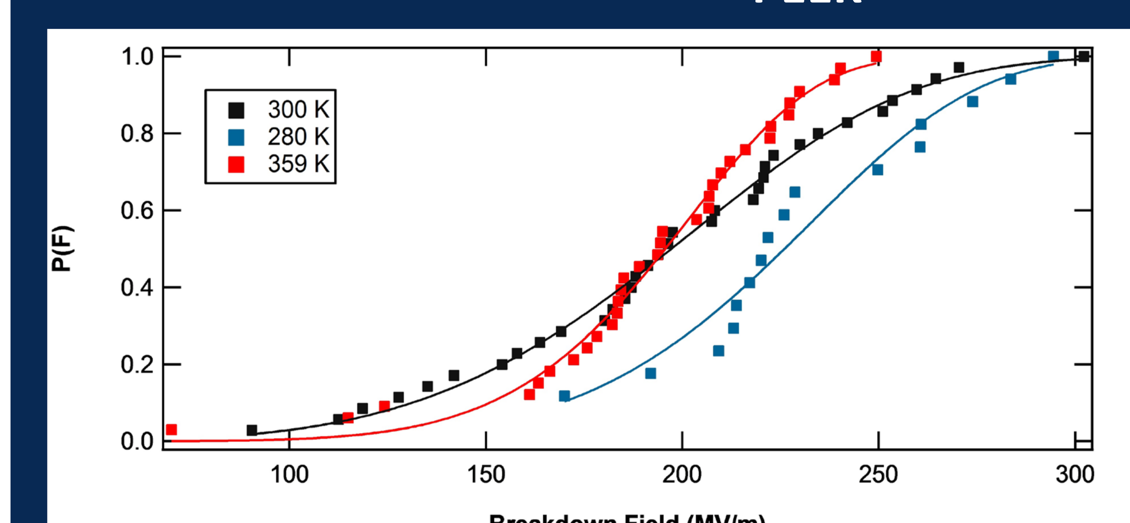


Figure 3a – Probability of a sample of PEEK breaking down compared to the breakdown field using a Weibull fit. Notice how at higher temperatures the breakdown field strength distribution narrows and shifts to the left while the opposite appears to happen at low temps.

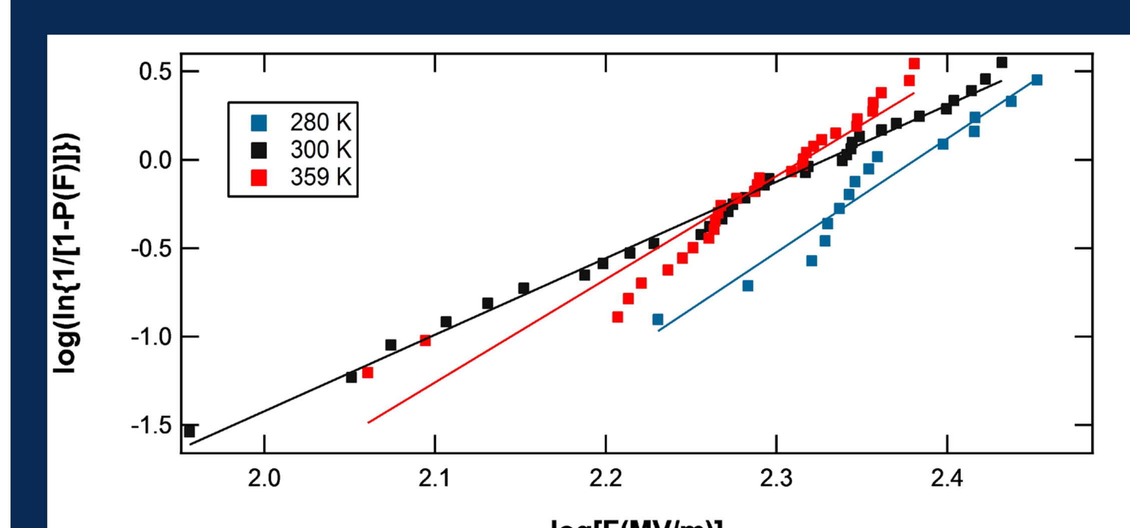


Figure 3b – Linearization of figure 3a. In these coordinates the width and center roughly correspond to the slope and intercept of the linearized curve. Note that the slopes are different between temperatures.

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 3c – Fitting parameters F_0 and β of the graph. F_0 controls the center location of the curve while β controls the width. Notice that as the temperature increases, the breakdown field strength decreases while β changes slightly.

LDPE

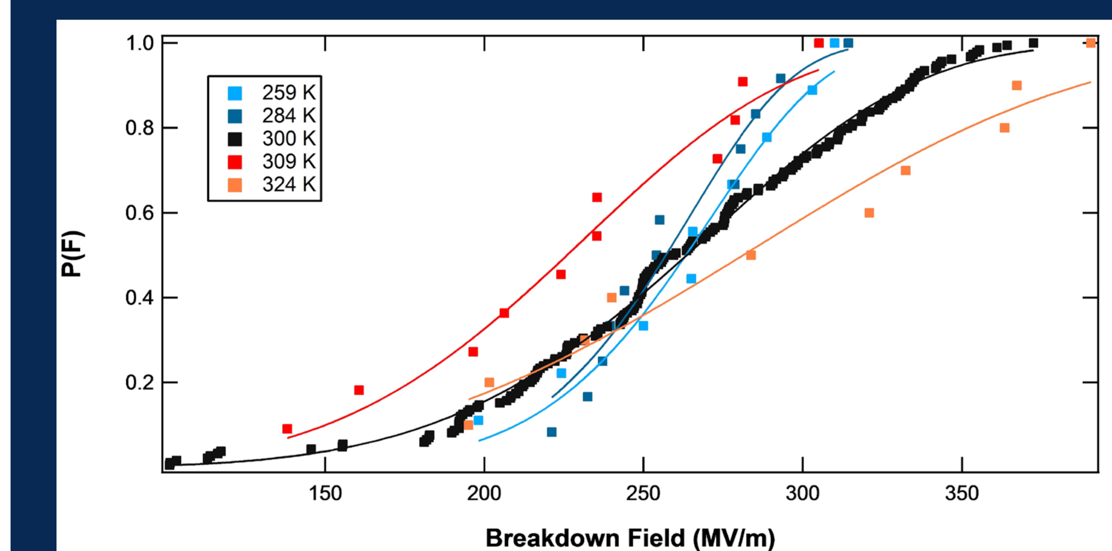


Figure 4a –Probability of a sample of LDPE breaking down compared to the breakdown field. This appears opposite of the PEEK data, with the low temperature curve being narrower than the high temperature curve.

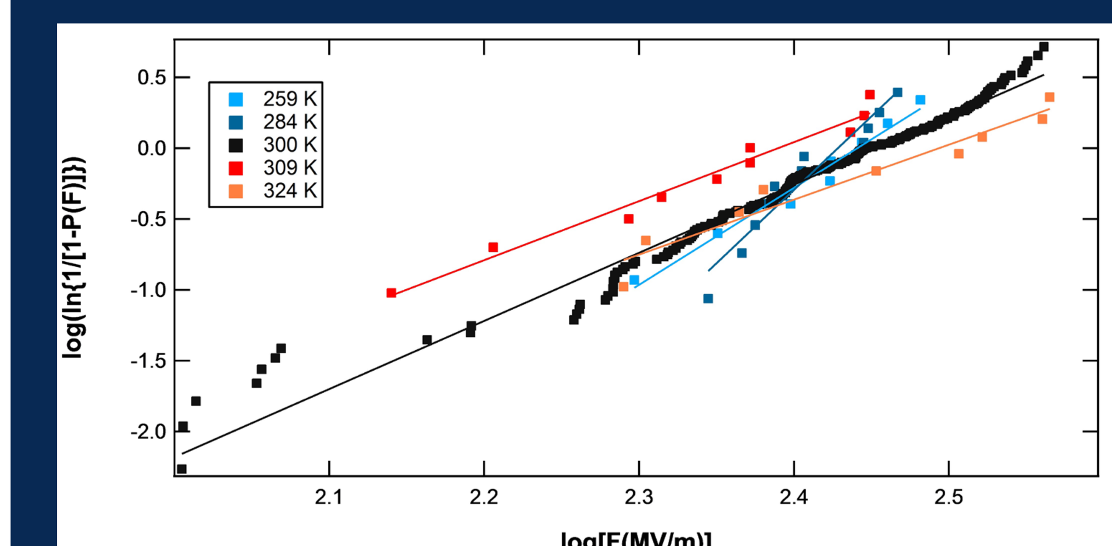


Figure 4b – Linearization of figure 4a. Notice that with these data, the slopes at higher temperatures are similar though distinctly different from the slope of the low temperature curves.

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
~309	245±3	4.6±0.4
~324	310±6	3.8±0.4

Figure 4c – 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.

Conclusions and Future Work

Conclusions:

- Temperature appears to affect breakdown field strength, but it seems dependent on the material. This is in line with our model, because the breakdown probability depends on material specific parameters such as the defect energy or defect density.
- Using better models and statistics makes a difference. When we analyzed the data using the normal average we didn't see any difference between the different temperatures. It wasn't until we applied our model and used the Weibull distribution and linearized it that we were able to obtain results.

Future Work:

- Perform more tests on LDPE and PEEK to develop a better data set.
- Test the effects of extreme low temperatures using liquid nitrogen and additional high temperatures to gain a better range of data.
- Test other materials, specifically Kapton, to better understand how much the effect of temperature depends on the material.
- Test the effect of radiation damage on breakdown. This would examine more closely the effects that high energy defects have on the breakdown field strength. This should have a separate effect from temperature, because temperature 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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