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Temperature Dependence of Electrostatic Discharge in Highly Disordered Polymers

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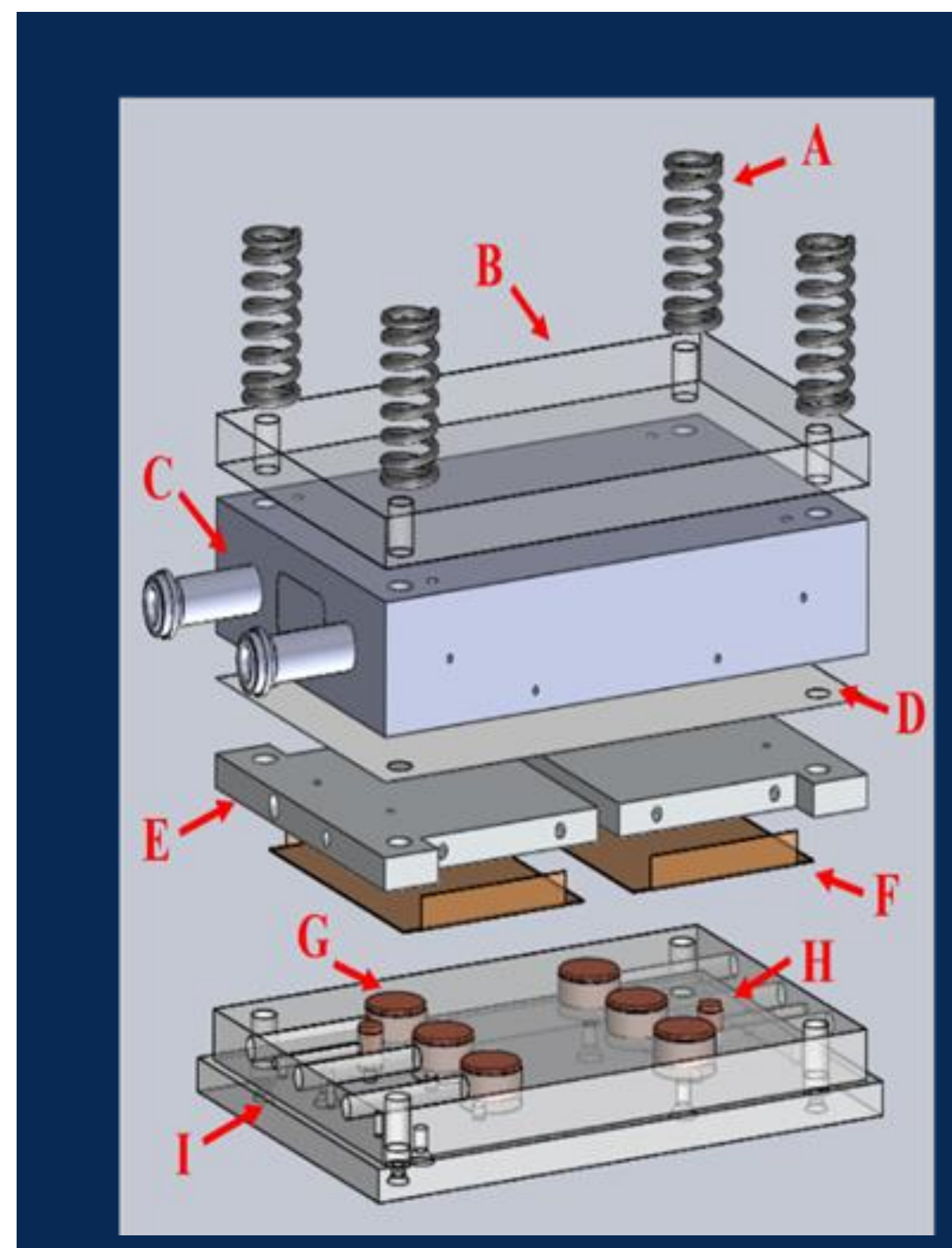
Introduction and Methods

Modern electronics operate in many different environments, from burning deserts to freezing tundra and even to the cold darkness of space. The temperature is different in each of these locations, and from the controlled testing environment of the lab. For this reason it is important to understand how the materials used to insulate these electronics react to changing temperatures, especially when it comes to their probability of breaking down.

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.

Methods: Our method uses step-up to electrostatic discharge (ESD) tests on low density polyethylene (LDPE) and polyetheretherketone (PEEK) 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 [1].



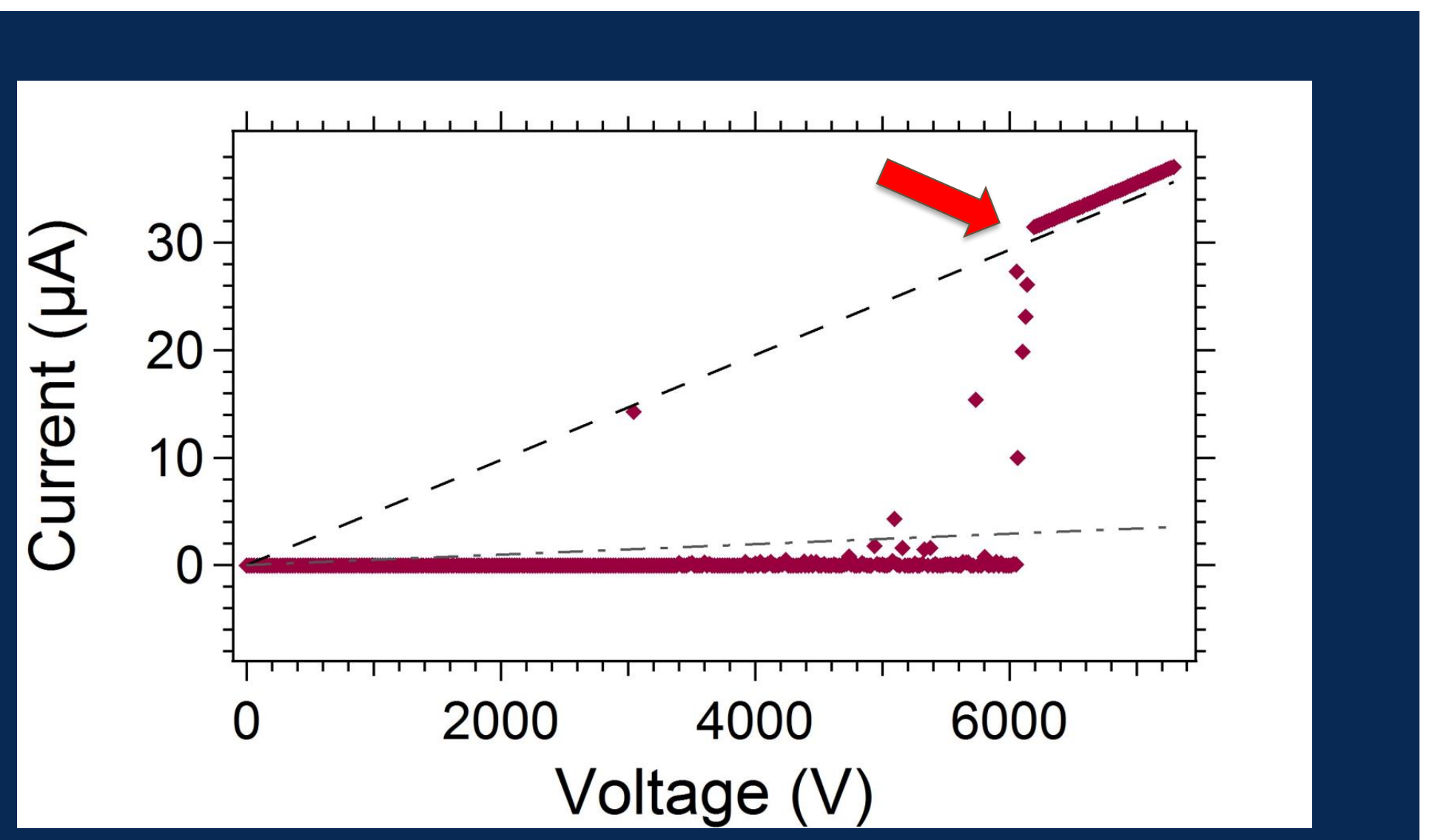


Figure 1 – A typical plot of the measured current vs. the applied voltage on a sample. An arrow points to where breakdown can be seen as the current abruptly increases to following an ohmic curve set by current limiting resistors.

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 [3]. 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].

$$P_{def}^{Tot}(F,T) = \sum_{i=A,B} P_{def}^{i} = \sum_{i=A,B} \left(\frac{2k_BT}{h\nu_{A,B}}\right) \exp\left[\frac{-\Delta G_{def}^{i}}{k_BT}\right] \sinh\left[\frac{\varepsilon_r\varepsilon_0F^2}{2N_{def}^{i}k_BT}\right]. \qquad (1)$$

PEEK

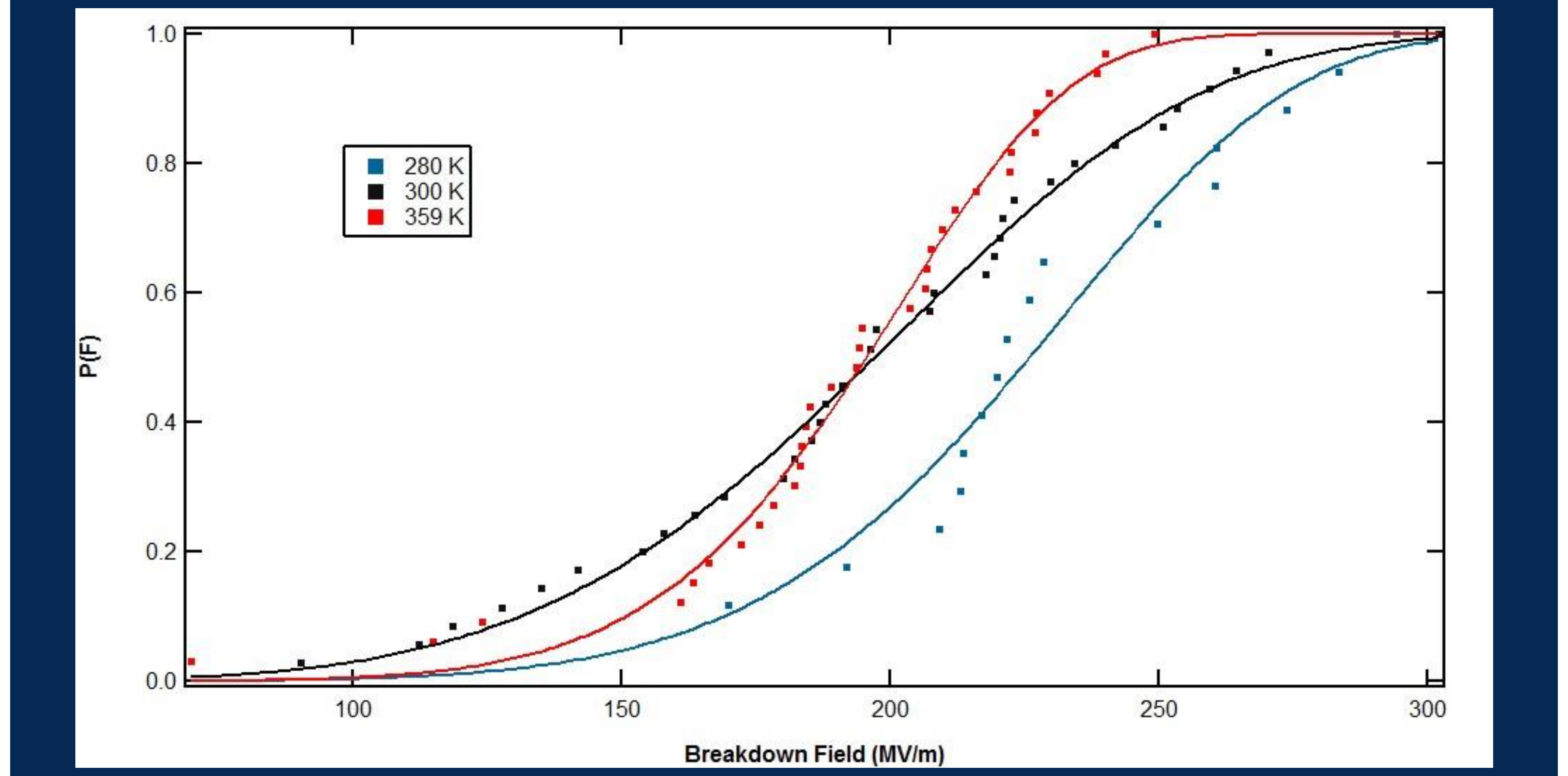


Figure 3a – Probability of a sample of PEEK breaking down compared to the breakdown field using a Weibull fit. Notice how at higher temperatures the breakdown field strength distribution narrows and shifts to the left while the opposite happens at low temperatures.

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 3b – Fitting parameters F_0 and β of the graph. Notice that as temperature increases, F_0 strength decreases while β changes slightly.

LDPE

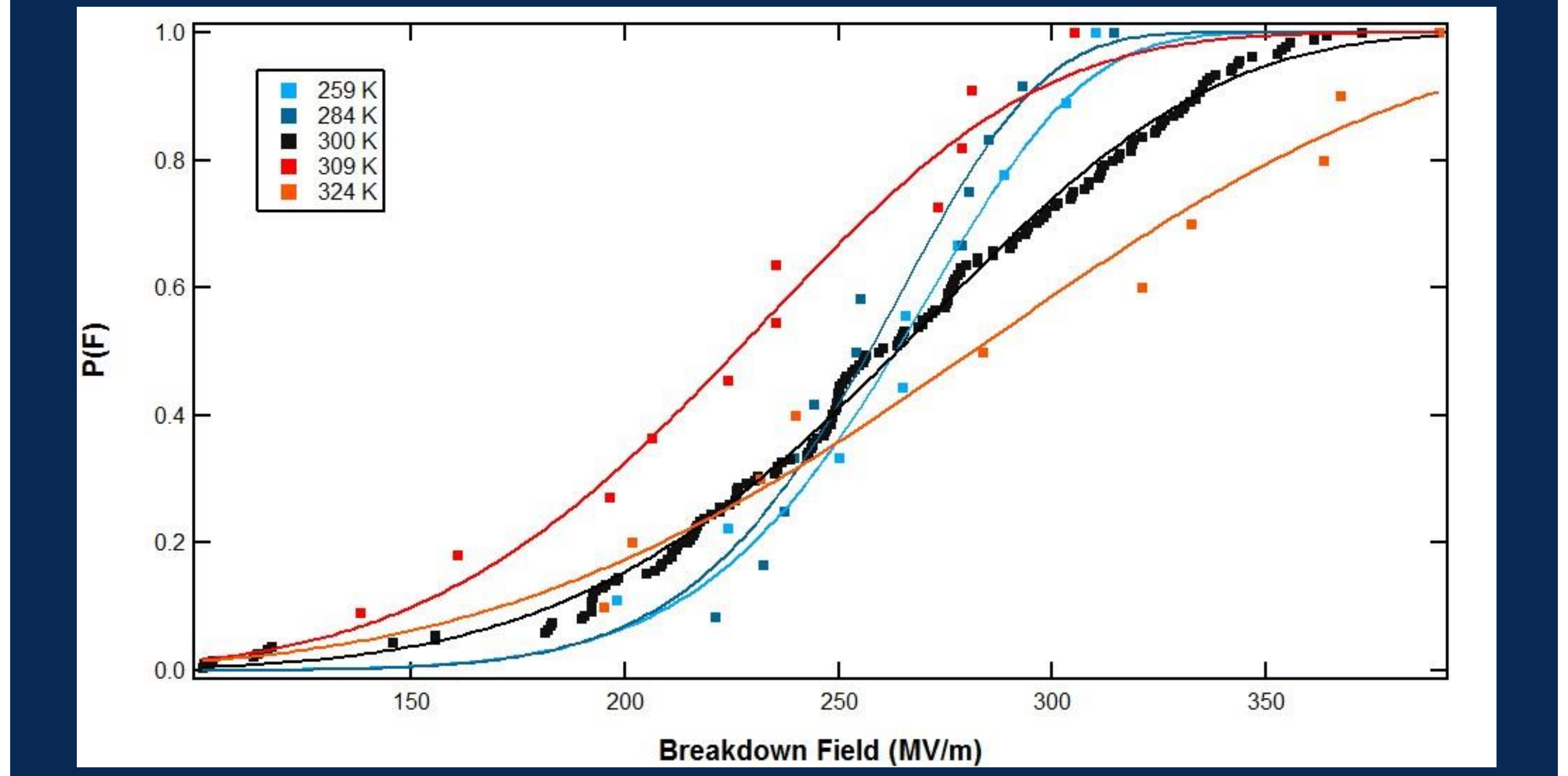


Figure 4a –Probability of a sample of LDPE breaking down compared to the breakdown field. This appears opposite of the PEEK data, with the low temperature curve being narrower than the high temperature curve, though the position of the curves vary.

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.

Results

The recorded breakdown field strengths were analyzed using Weibull statistics and the resulting curves are displayed in figures 3-5 [2]. From these data we see:

- In figure 3 we see that the breakdown field strength appears to decrease as the temperature increases.
- In figure 4 we see that for LDPE the breakdown curve narrows, which implies that the material is more stable at lower temperatures.
- Looking at figure 5, the average breakdown strength of the 300 K tests is significantly higher then any other data set. This could be because most this data was taken in 2013 and used a different batch of Kapton. There may have been small differences in the material that caused the discrepancy.

Kapton

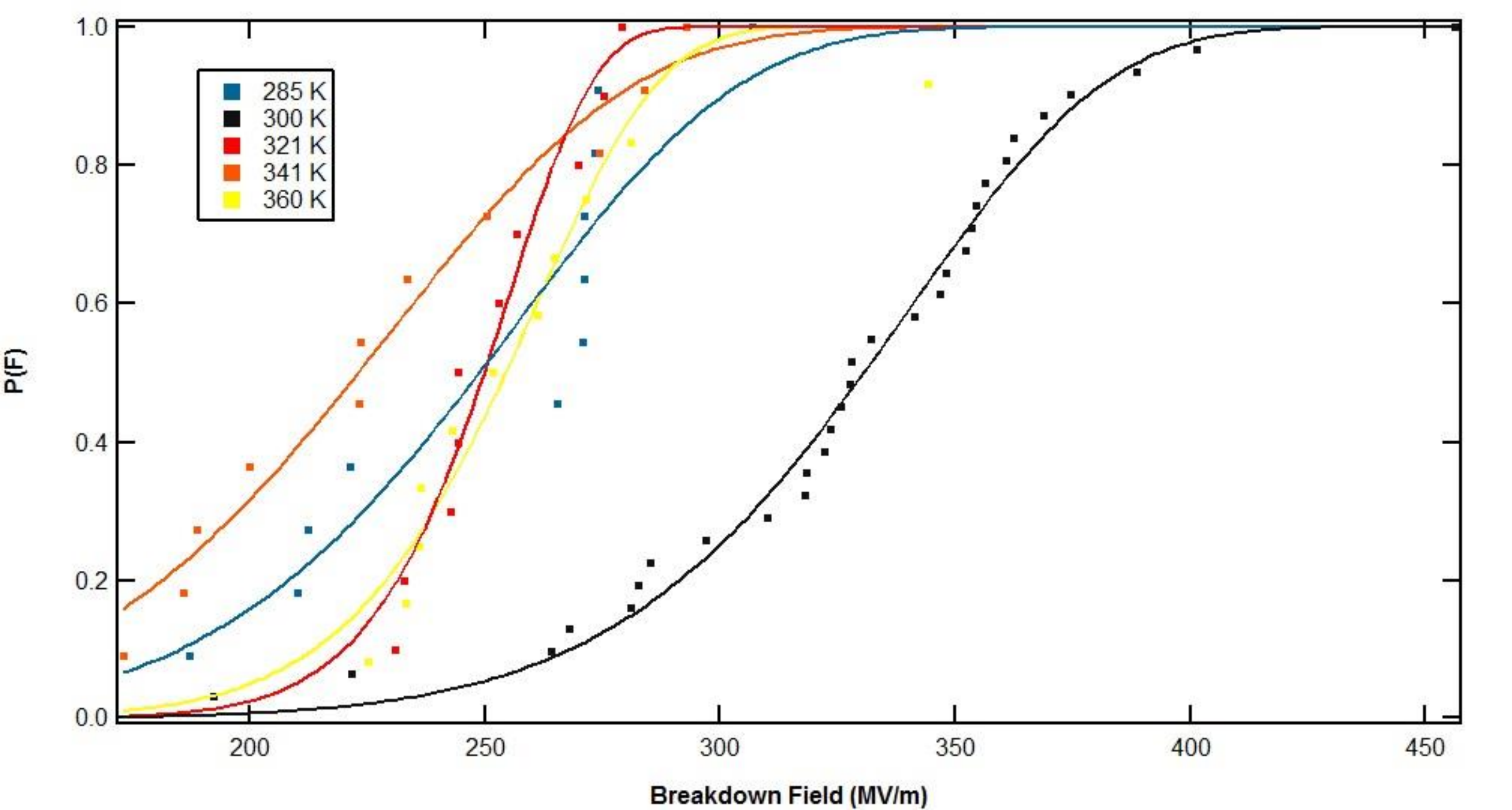


Figure 5a – Probability of a sample of Kapton breaking down compared to the breakdown field using a Weibull fit. Notice how the previously taken room temperature (300 K) data has a significantly different average. This could be because it was a different batch of Kapton

Temperature [K]	F_0 [MV/m]	β
~285	264±5	6±1
~300	344.4±0.8	9.0±0.3
~321	256±2	15±2
~341	238±3	5.5±0.4
~360	263±2	11±1

Figure 5b – 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

Conclusion:

- 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.

Future Work:

- Perform more tests on LDPE,PEEK, and Kapton to develop a better data set.
- Test additional insulating polymers.
- Test the effects of extreme low temperatures using liquid nitrogen. 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.

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

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[4] Allen Andersen, and JR Dennison, "A Dual-defect Model for Predicting Lifetimes for Polymeric Discharges from Accelerated Testing," *American Physical Society Four Corner Section Meeting,* Utah Valley University, Orem, UT, October 17-18, 2014.