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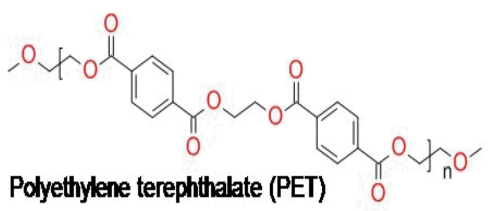

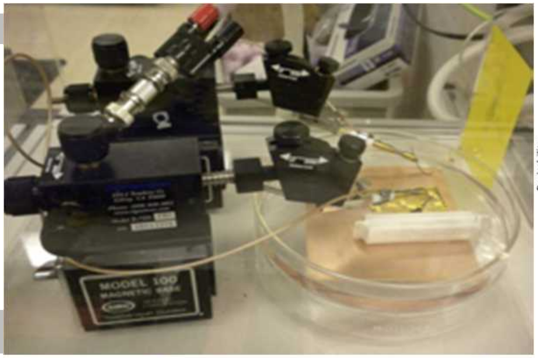

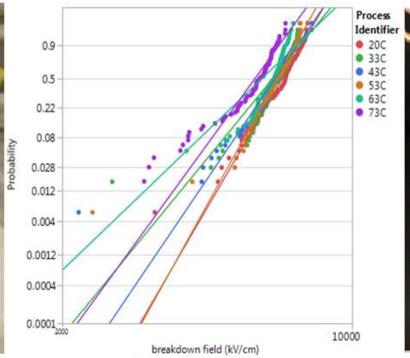

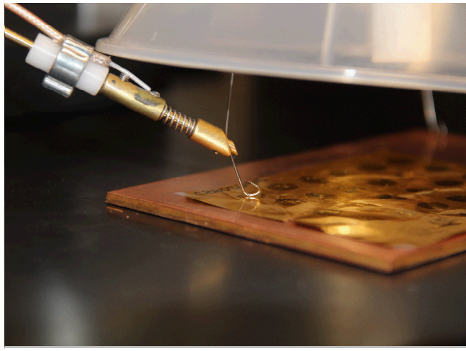

Effects of Environmental and Experimental Design Parameters on the Dielectric Properties of Poly(ethylene) Terephthalate

<u>Cami Belcher</u>, Leah Appelhans

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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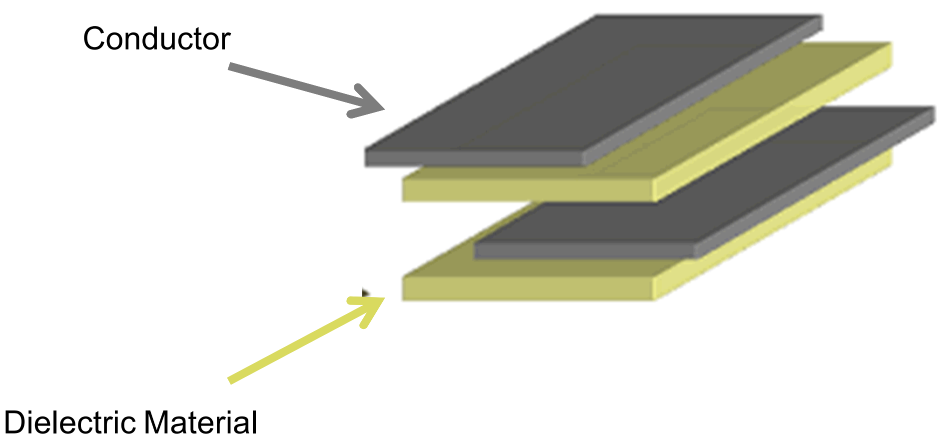
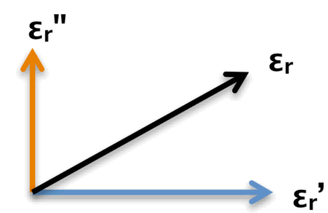
Dielectrics

- Electrically insulating materials can act as a dielectric if they can be polarized by an applied electric field.
- Dielectric materials are widely utilized in science and technology, specifically in capacitors.
- Dielectrics are characterized by the permittivity and dielectric loss.
- All dielectrics have a field limit at which the material catastrophically fails (conduct charge). This is called the dielectric breakdown strength.



- Permittivity (κ)
  - Defining property of a dielectric material, measure of the material's ability to store charge.
- Dielectric Loss (DF)
  - Measurement of stored charge dissipation within the dielectric
- Dielectric Breakdown Strength
  - The field at which the insulating properties of the material fail.

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$



$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} = Df = \frac{1}{Q} = \frac{\text{Energy lost per cycle}}{\text{Energy stored per cycle}}$$

Weibull Statistics

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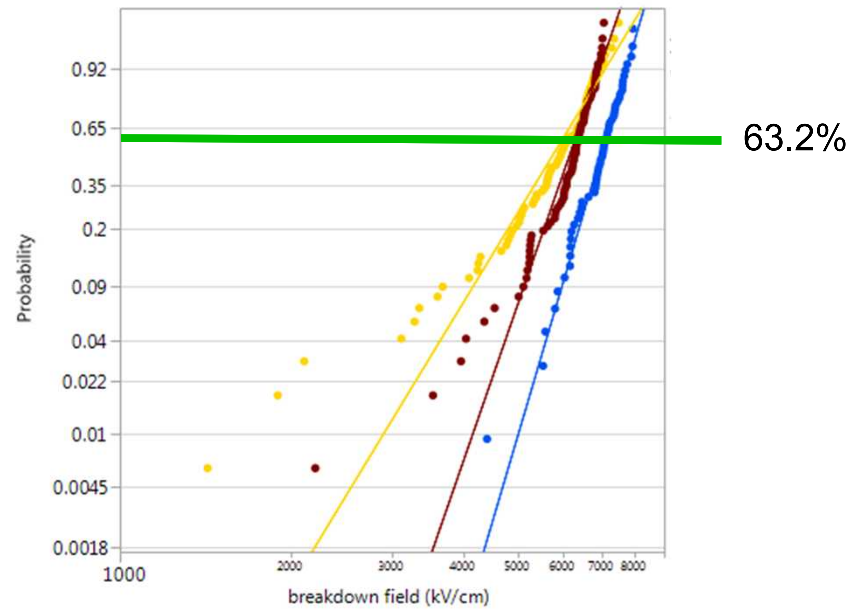
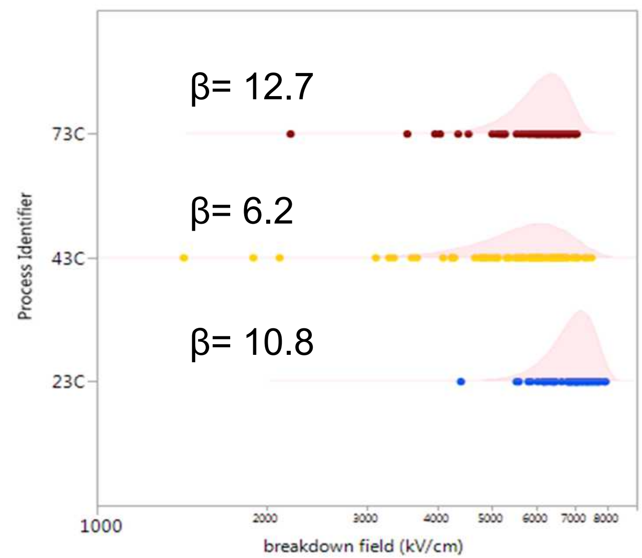
- A Weibull distribution is customarily used in the analysis of breakdown strength data.
- α Parameter- dielectric breakdown strength, the breakdown field at which 63.2% of samples have failed.
- β Parameter- data dispersion
  - High β parameter desired
- γ Parameter- threshold parameter

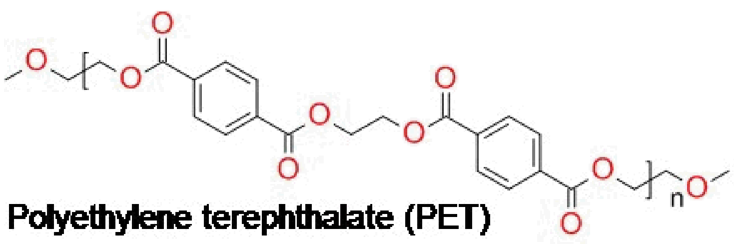
$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}}$$





Mylar® Dielectrics

- Mylar is the trade name for DuPont poly(ethylene terephthalate)
- Mylar films are utilized as the dielectric material in high voltage capacitors.



Polyethylene terephthalate (PET)

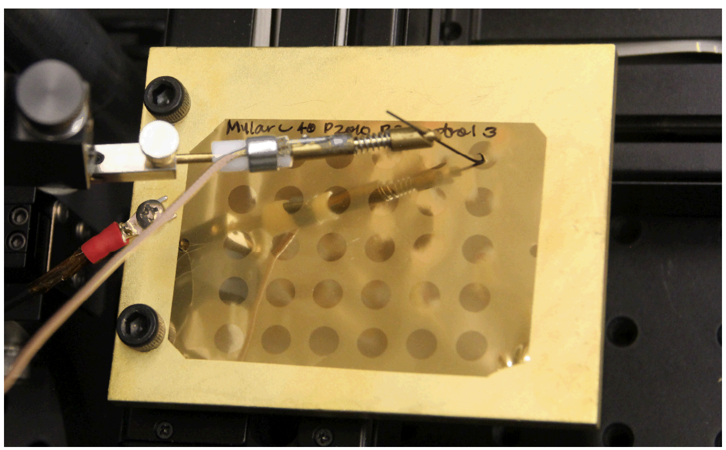


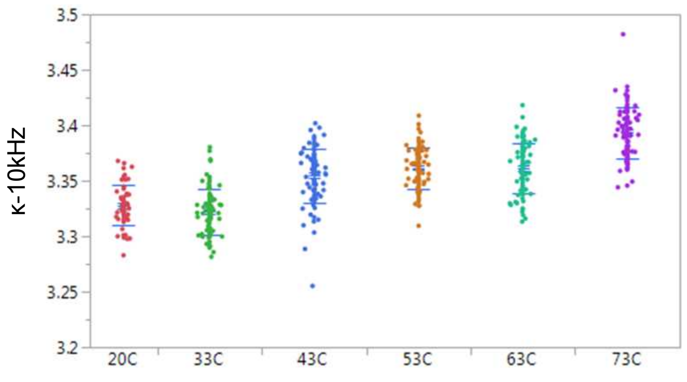
Figure 1: Test electrode array, consists of 30 - 6.3mm diameter electrodes

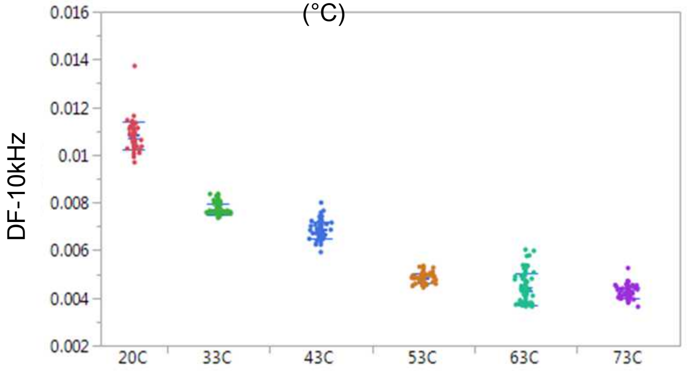
This Study

- Measure and investigate changes in the dielectric properties of Mylar as test temperatures approach Tg.
- Measure dielectric properties at various relative humidity levels ranging from 0% to 75%.
- DC voltage ramp rate affects on measured breakdown strength from 50V/s to 3000V/s.
- Determine dependence of dielectric properties on electrode area by varying electrode diameter.

Elevated Temperature

Permittivity/Dielectric Loss (10kHz)





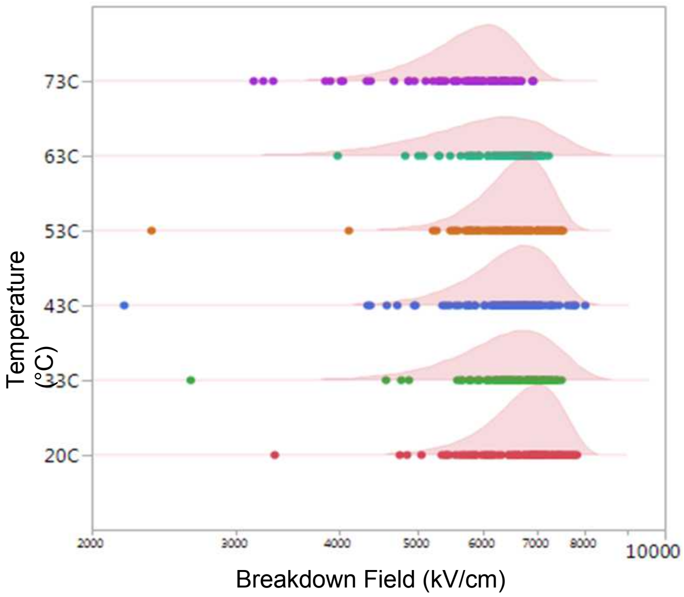
Permittivity increases as temperature increases, likely due to increased dipole mobility allowing dipoles in the material to align more readily. Loss decreases with elevated temperature.

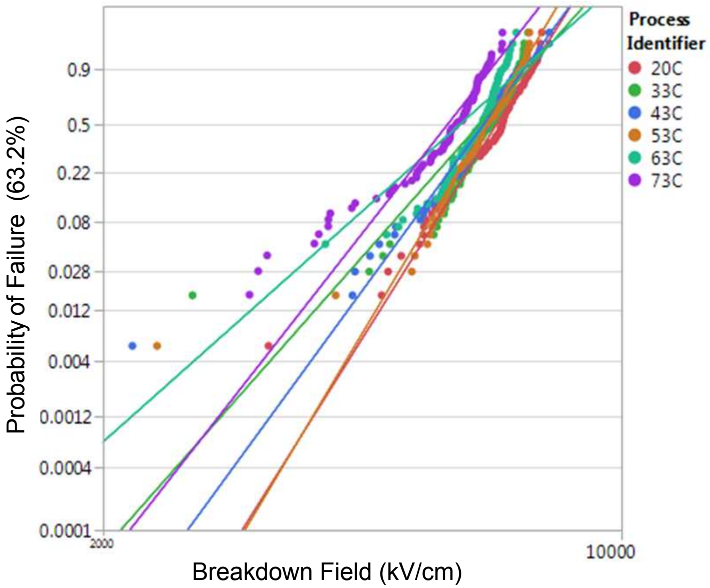
Permittivity, κ (10kHz)		
Temperature	κ	Std Dev.
20°C	3.24	0.018
33°C	3.24	0.020
43°C	3.26	0.024
53°C	3.27	0.018
63°C	3.27	0.022
73°C	3.30	0.023

Dielectric Loss, DF (10kHz)		
Temperature	DF	Std Dev.
20°C	0.0108	0.00058
33°C	0.0077	0.00028
43°C	0.0069	0.00034
53°C	0.0048	0.00046
63°C	0.0044	0.00065
73°C	0.0042	0.00023

Elevated Temperature

Dielectric Breakdown Strength (E_b)





Parameter	Weibull α (kV/cm)	Weibull β
20°C	7006.3	11.2
33°C	6824.1	13.3
43°C	6766.1	9.6
53°C	6788.9	11.8
63°C	6516.3	11.1
73°C	6067.0	9.0

Significant decrease in breakdown strength as temperature increases from room temperature to 73°C.

As temperature increases thermal breakdown pathways may be activated, contributing to the decrease in breakdown strength.

Variable Relative Humidity

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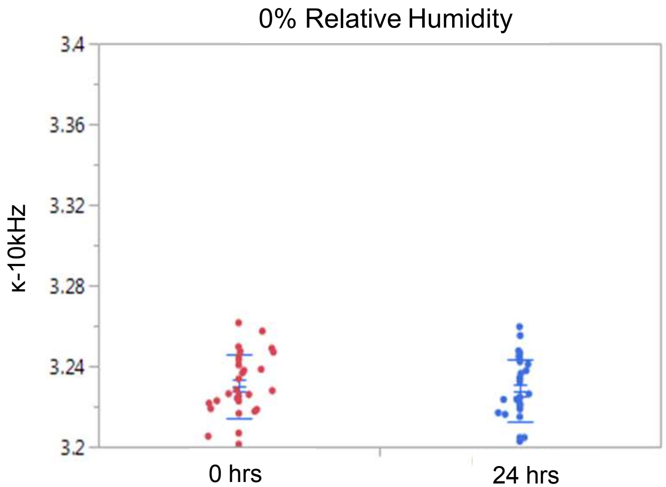
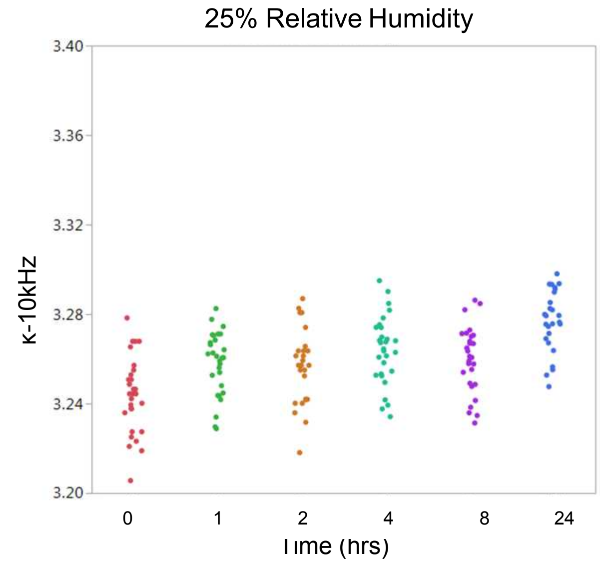
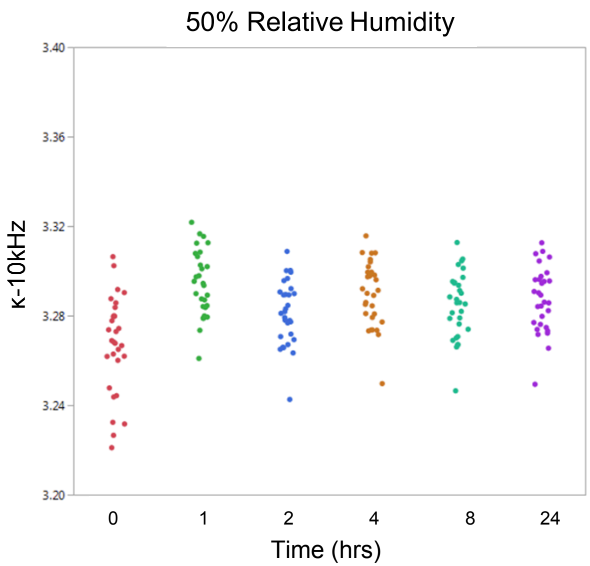
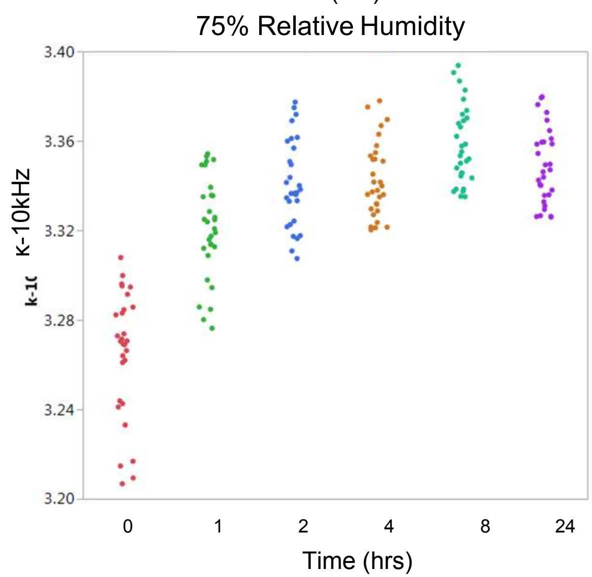
Permittivity (10kHz)







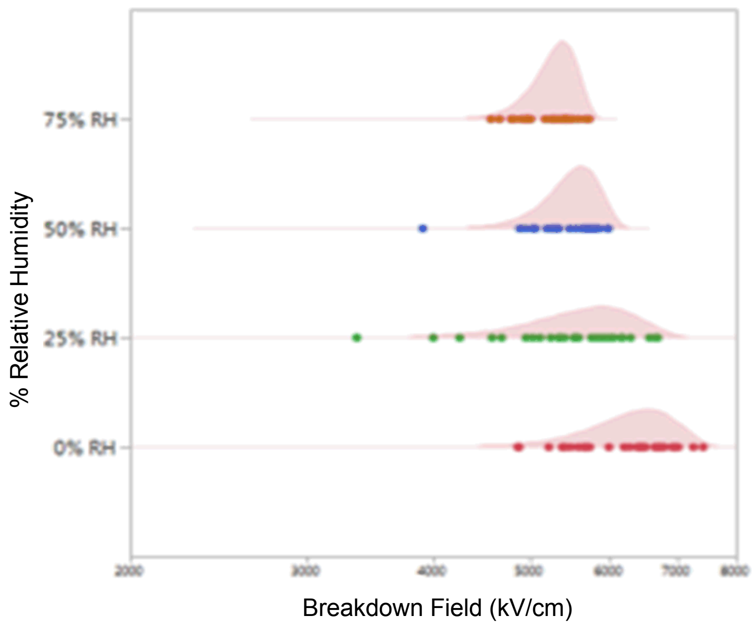


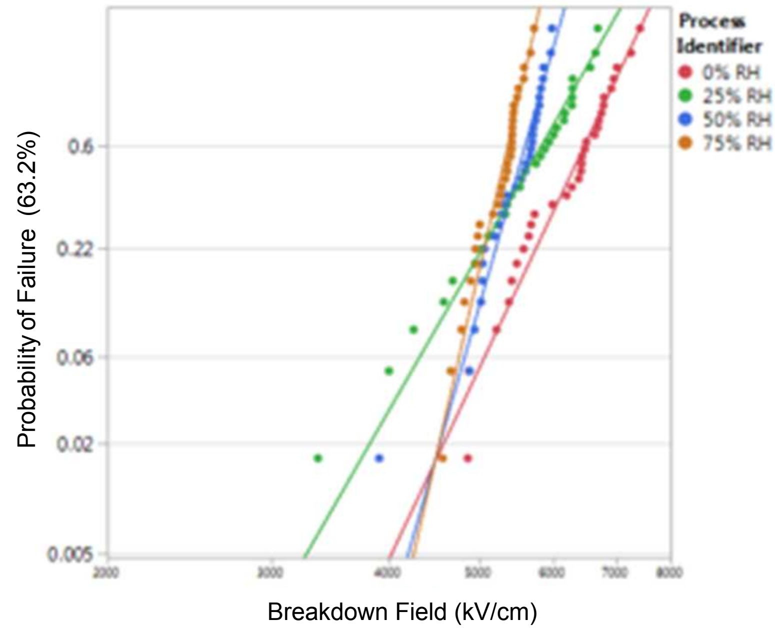
It is suggested that the water molecules form clusters at the terminal –OH groups of PET, which can sustain an effective dipole within the material, contributing to the existing polarization and increasing permittivity.

Lightfoot, S.; Xu, G. *Polymer-Plastics Technology and Engineering* **1993**, *32*, 21.

Variable Relative Humidity

Dielectric Breakdown Strength (E_b)





% RH	Weibull α	Weibull β	ΔE_b
0	6167.3	7.4	0
25	6474.9	17.5	307.6
50	6066.8	19.7	-100.5
75	5504.6	26.5	-662.7

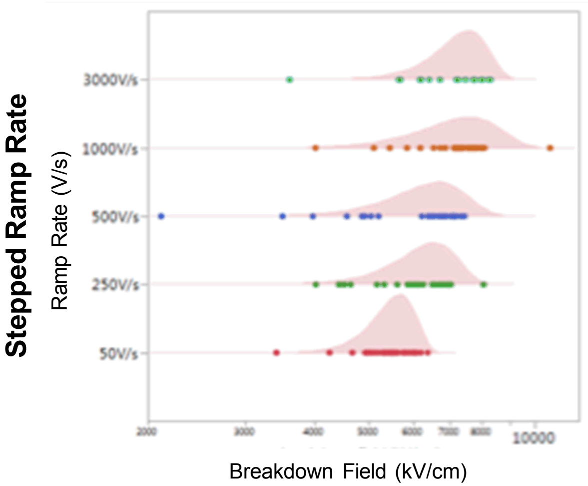
As the percentage of relative humidity increases, the dielectric breakdown strength decreases. This decrease is a result of new breakdown pathways created by the presence of water.

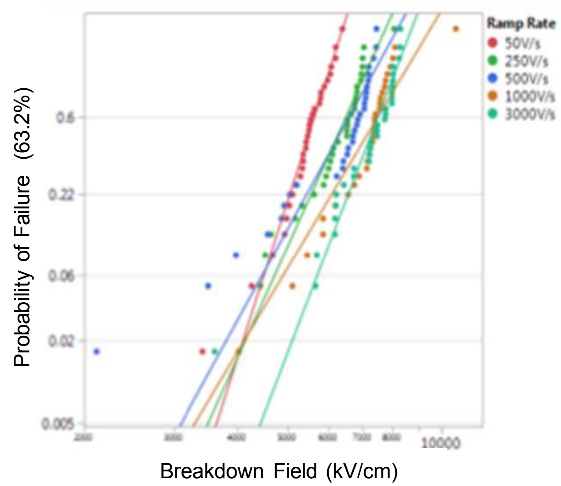
The Weibull β parameter also increases as humidity is increased.

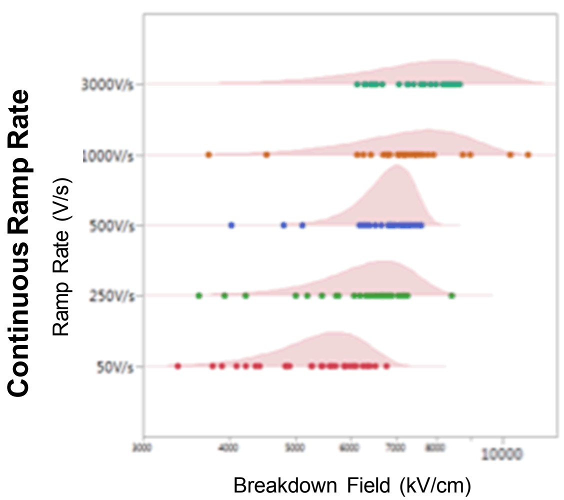
Keiichi M 191 Jpn. J. Appl. Phys. 20 2325

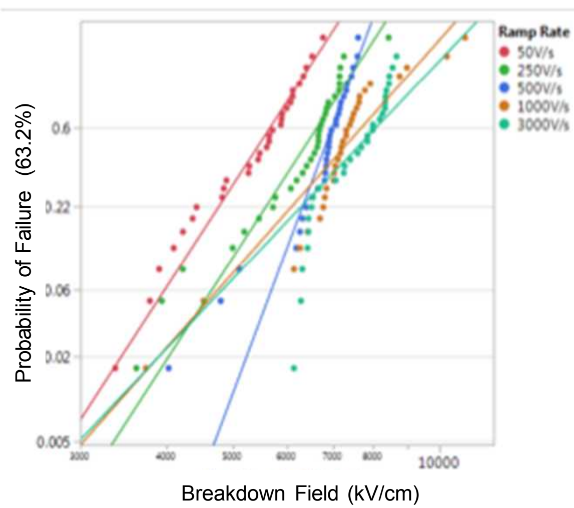
DC Voltage Ramp Rate

Stepped Ramp Rate vs. Continuous Ramp Rate









Stepped Ramp Rate Weibull Analysis

Ramp Rate (V/s)	Weibull α (kV/cm)	Weibull β
50	5881.3	15.5
250	6911.4	10.6
500	6679.2	7.07
1000	7730.7	5.2
3000	7431.2	8.6

Continuous Ramp Rate Weibull Analysis

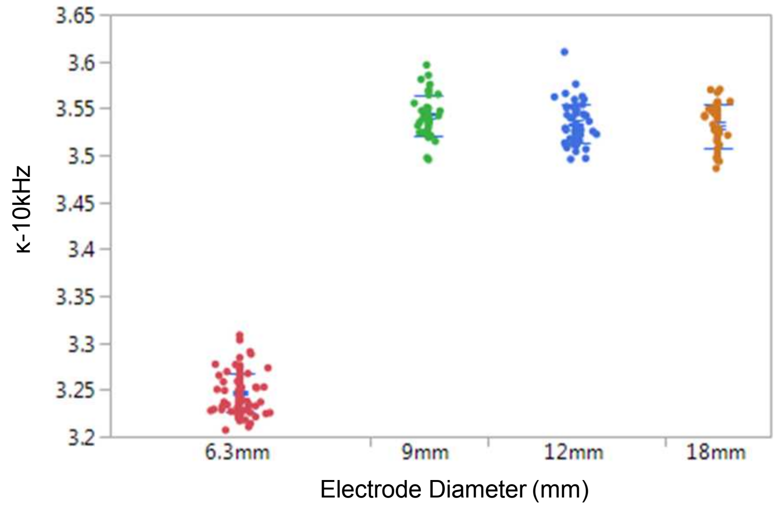
Ramp Rate (V/s)	Weibull α (kV/cm)	Weibull β
50	5870.7	6.7
250	7029.0	8.9
500	7206.2	15.1
1000	7938.3	5.4
3000	8639.6	4.7

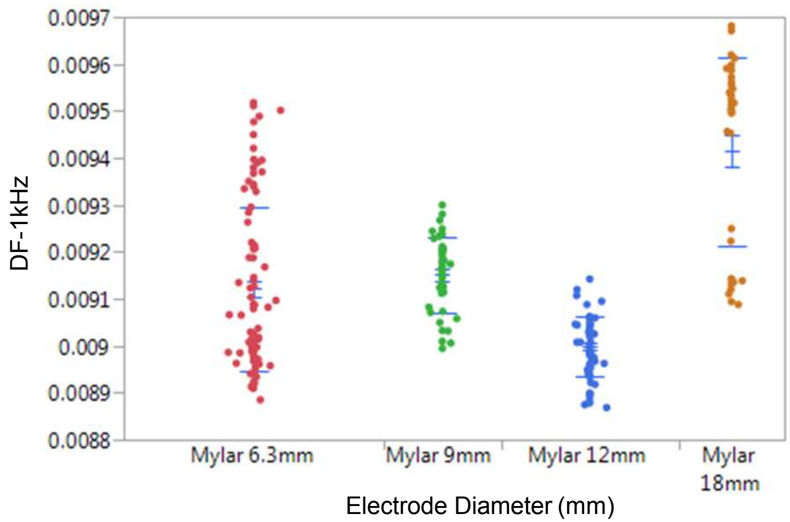
As DC voltage ramp rate in increased, the breakdown strength (Weibull α) of the materials increase as well. This may be attributed to the decrease in time exposed to field as the ramp rates increase.

Breakdown can occur at lower voltages with slow ramp rates due to the increased time under electrical stress.

Electrode Area

Permittivity/Dielectric Loss





Electrode Diameter	Permittivity	Dielectric Loss
6.3mm	3.25±0.02	0.0091±0.0002
9mm	3.54±0.02	0.0091±0.0001
12mm	3.53±0.02	0.0089±0.0001
18mm	3.53±0.02	0.0094±0.0002

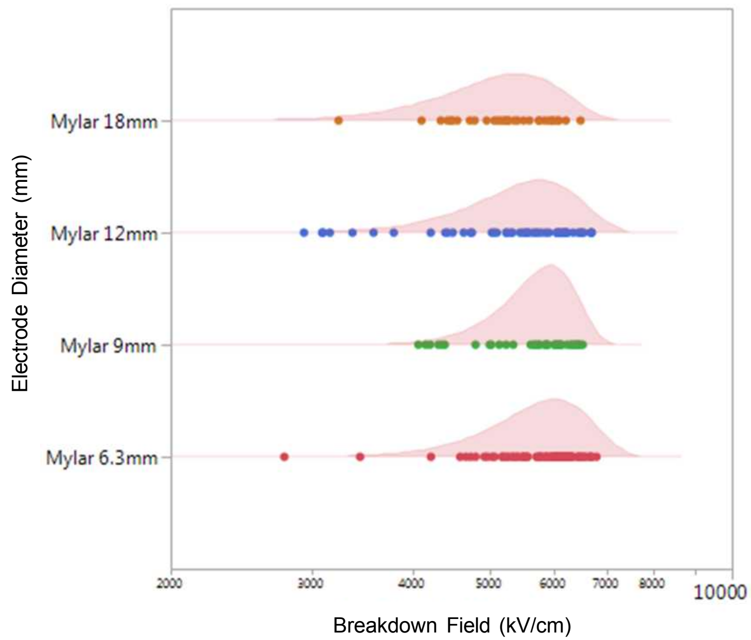
Electrode area has no significant effects on the dielectric loss of Mylar. There is a significant difference in the 6.3mm permittivity, which is lower than the other diameters, due to possible interfacial effects.

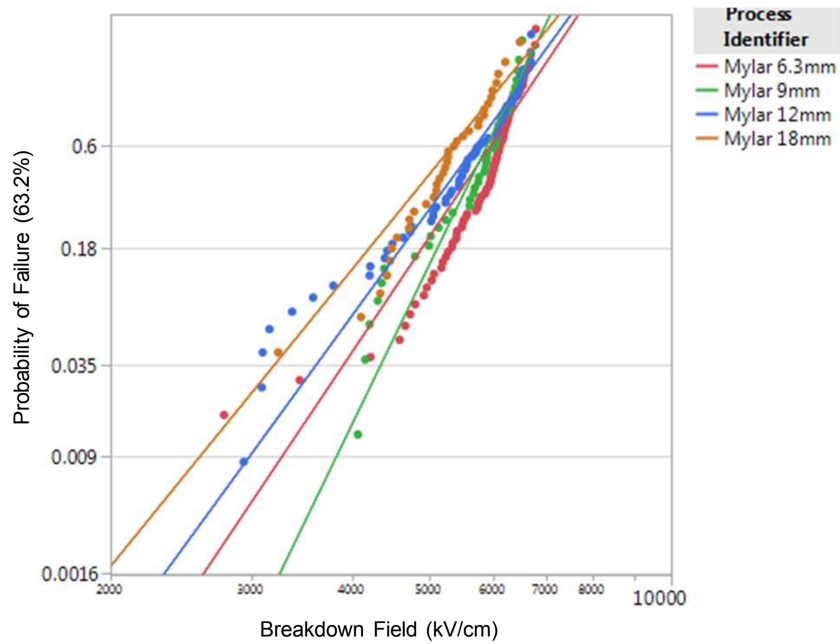
Area is taken into consideration for calculation of permittivity.

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

Electrode Area

Dielectric Breakdown Strength (E_b)



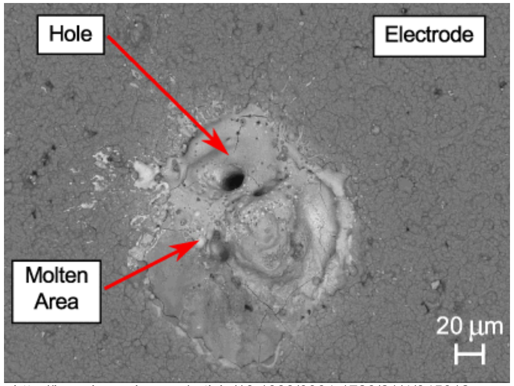


Electrode Diameter	Weibull α	Weibull β	ΔE_b
6.3mm	6021.5	7.7	0
9mm	5941.9	10.7	-600.3
12mm	5775.9	7.1	-748.3
18mm	5522.0	9.2	-1002.2

As the electrode diameter increases the defect density per electrode increases as well, increasing the probability of failure at lower fields.

Summary and Conclusions

- **Elevated Temperature**
  - *Permittivity increases as temperature increases, likely due to increased dipole mobility. Loss decreases with elevated temperature.*
  - *As temperature increases thermal breakdown pathways may be activated, contributing to the decrease in breakdown strength.*



http://iopscience.iop.org/article/10.1088/0964-1726/21/4/045012

- **Variable Relative Humidity**
  - *Decreases in breakdown strength is likely a result of increased thermal breakdown pathways.*
- **DC Voltage Ramp Rate**
  - *As DC voltage ramp rate in increased, the breakdown strength (Weibull α) of the materials increase as well. Breakdown can occur at lower voltages with slow ramp rates due to the increased time under electrical stress.*
  - *At higher voltage ramp rates, breakdown strengths of continuous ramps is greater than stepped ramps at the same rate. The stepped ramp applies the voltage increase instantly, causing more electrical stress than gradual increases of a continuous ramp.*
- **Electrode Area**
  - *No significant effects on permittivity and loss; however, there is a significant impact on the breakdown strength. Increased electrode area increases the defect density within the test area, leading to a higher probability of breakdown at lower fields.*

Future Work

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- **Variable Relative Humidity**
  - Further studies to confirm instrument accuracy, compare to previous measurements on the same samples.
  - Examine the effects of moisture at lower frequency ranges, and define frequency vs. humidity relationship.

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