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A Dual-defect Model for Predicting Lifetimes for Polymeric Discharges from Accelerated Testing

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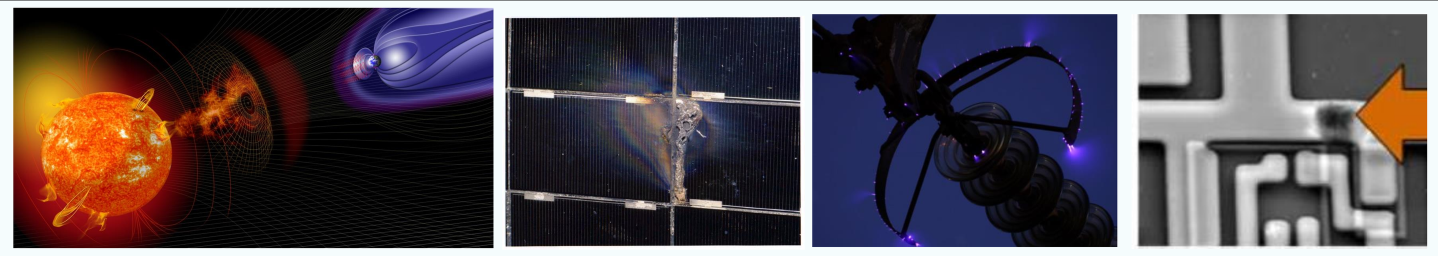
Introduction to the Problem of ESD



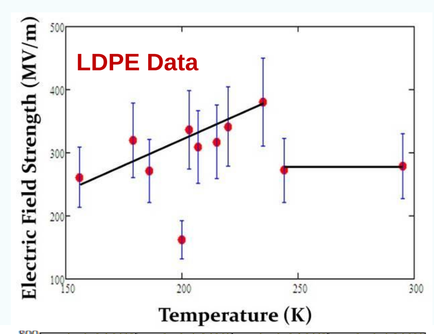
Enhanced Predictions of Dielectric Lifetime for Electrostatic Discharge (ESD) are Critical for Applications Such as:

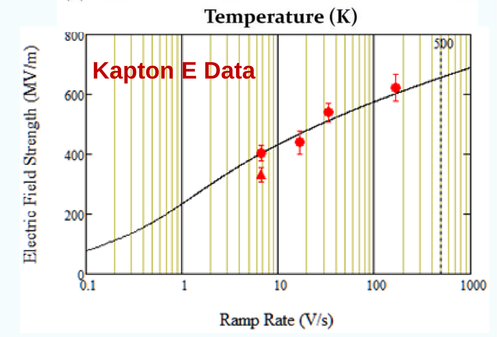
- Spacecraft Charging. ESD is the most common and most devastating result of interactions between spacecraft and the space plasma environment.
- High Voltage DC Power Transmission. ESD and coronal discharge can cause parasitic leaks and total failure of components.
- Any Electron Device. Especially as devices get smaller insulators are more vulnerable to ESD.

With $F_{ESD} \approx 10^8$ Vm^{-1}	Thickness (d)	Breakdown Voltage (V_{ESD})
Power Lines	$\approx 10^{-2}$ m	$\approx 10^6$ V
Spacecraft	$\approx 10^{-5}$ m	$\approx 10^3$ V
Circuits	$\approx 10^{-4}$ m	$\approx 10^4$ V
MOFSET	$\approx 10^{-8}$ m	≈ 1 V

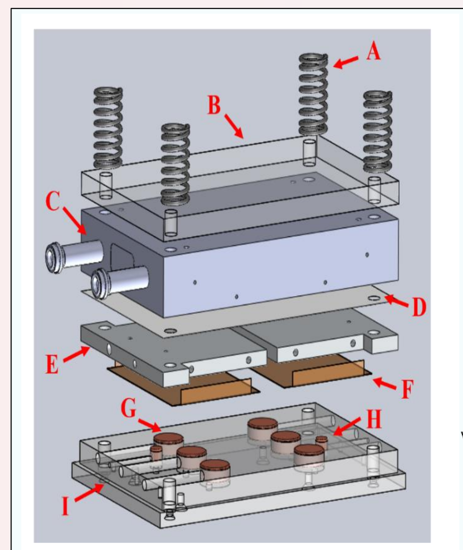
Variability of Dielectric Strength

- A material's observed dielectric strength varies significantly with
  - Temperature
  - Charging history and voltage ramp rate.
  - Surrounding medium e.g., vacuum, air, or oil.
- Dielectric strengths listed in engineering handbooks state values as constants or at best a range of values with a temperature but without other vital experimental conditions.
- ASTM standards for determining material breakdown strength using $\lesssim$ 500 V/s. Results from such tests have poor repeatability. Charging occurs much faster than in many real applications.

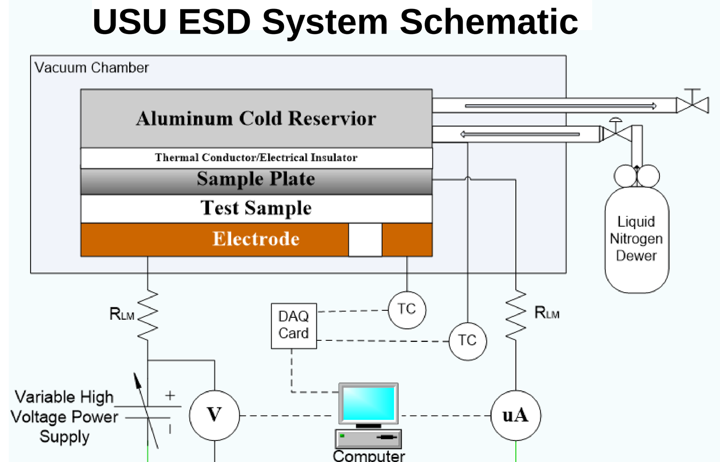




Experimentation



USU ESD System Schematic



- Simple parallel plate capacitor geometry applies V <30 kV (F <1000 MV/m)
- Variable dV/dt = 20 V / 3.5 s for tests shown
- ~100 K < T < 350 K with ℓ-N2 reservoir
- Vacuum < 10^{-3} Pa.
- All samples cleaned and subjected to vacuum bake.

ESD Test 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 HV polished Cu electrode
H Cu thermocouple electrode,
I Insulating base

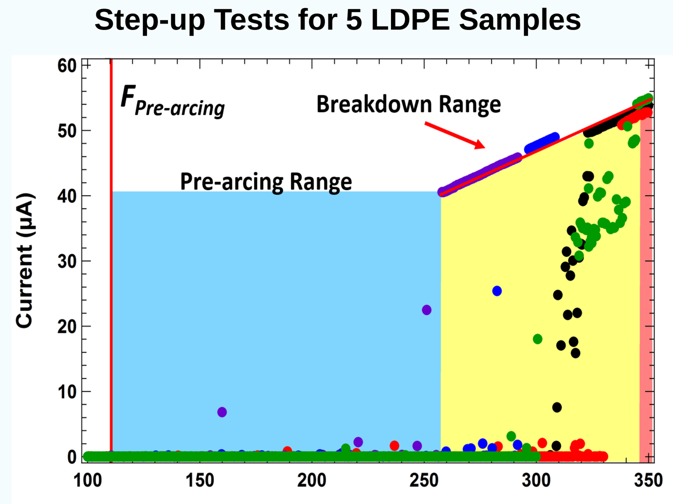
Features of Voltage Step-up Tests:

- Initial current is ≤ 10 nA, indicative of very high sample resistivity.
- Above $F_{Pre\text{-}arcing}$ small transient current spikes begin, increasing in amplitude and frequency as voltage increases.
- At ESD breakdown there is an abrupt transition to a linear slope:
  - A very low resistivity conduction path is created in the material.
  - Slope of graph corresponds to ohmic resistance of the circuit due to the current limiting resisters (200 MΩ).

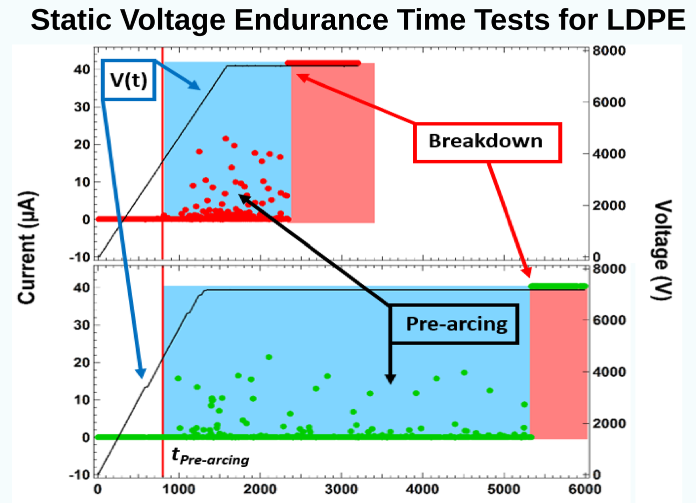
Features of Static Voltage Endurance Time Tests:

- Initial current again negligible (≤ 10 nA).
- Above $t_{Pre\text{-}arcing}$ pre-arcs are again observed.
- At ESD breakdown there is an abrupt transition to a constant current.

Step-up Tests for 5 LDPE Samples



Static Voltage Endurance Time Tests for LDPE

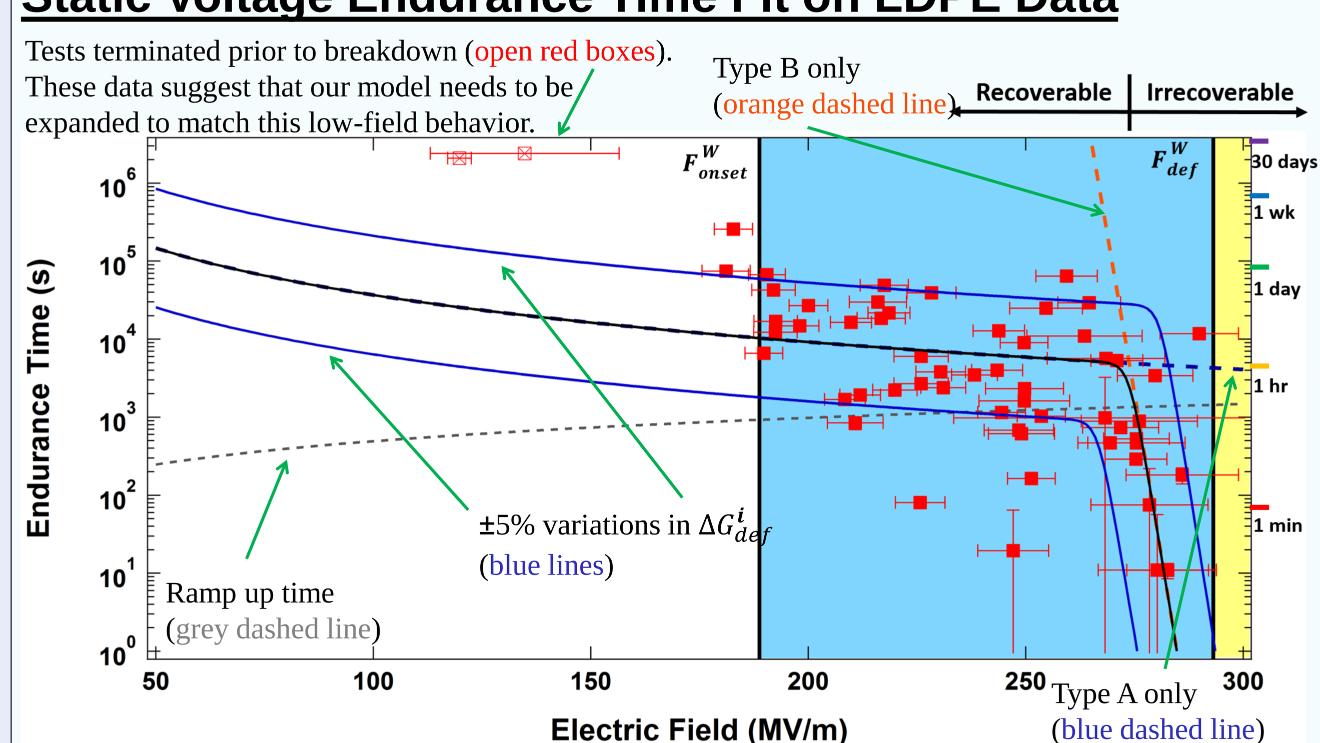


Abstract

Electrostatic discharge (ESD) can cause catastrophic failures in electronic devices. Estimating the lifetime of dielectrics under prolonged high field exposure is a major design concern for applications including spacecraft, high voltage DC power transmission, and semiconductor electronics. Dielectric strengths listed in engineering handbooks are primarily based on cursory measurements with poor repeatability and tend to overestimate ESD fields in real applications. Standard measurements subject test samples to ≈500 V/s ramp rates until breakdown. We present the results of ESD studies in two prototypical polymer dielectrics including ramp rate of ≈20 V/4s until breakdown, together with tests applying a static voltage and directly observing time-to-breakdown. Prior to ESD, transient current spikes, termed pre-arcs, were also observed. The results of these tests are explained in terms of a physics-based model of defect creation within the material from bond stress due to applied electric fields. A first order approximation is presented to develop an extended temperature- and ramp rate-dependent ESD model with both repairable and irreparable defect mechanisms. Repairable defects such as bond bending have energies on the order of thermal energies so that they can be readily repaired through thermal annealing; irreparable defects such as bond breaking have higher energies. We discuss how defect energies and densities, extracted from the results of accelerated laboratory tests, can be used to estimate fields with a satisfactory probability of material lifetimes of many years.

Electrostatic Discharge Test Analysis

Static Voltage Endurance Time Fit on LDPE Data



Data are fit (black line) with the dual-defect model prediction of endurance time (below) with ΔG^A_{def}=0.95 eV, ΔG^B_{def}= 3.65 eV from independent measurements, and fitting parameters N^A_{def}=7·10^{21} cm^{-3}, and N^B_{def}=1.75·10^{18} cm^{-3}.

$$t_{en}(\Delta t_{step}, V_{step}, V_{wait}, T) = \left(\frac{h}{2k_BT}\right)\left[\sum_{i=A,B} \exp\left[\frac{-\Delta G^i_{def}}{k_BT}\right] \sinh\left[\frac{\varepsilon_0\varepsilon_r {N_{step}}^2}{2k_BT\, N^i_{def}}\right]\right]^{-1} \times \left\{\prod_{j=1}^{N_{step}}\left[1-\left(\frac{2k_BT}{h/\Delta t_{step}}\right)\exp\left[\frac{-\Delta G^B_{def}}{k_BT}\right]\sinh\left[\frac{\varepsilon_0\varepsilon_r\left(\frac{j\Delta V_{step}}{D}\right)^2}{2k_BT\, N^B_{def}}\right]\right]\right\}$$

For the ramp rate used here the product term can be neglected.

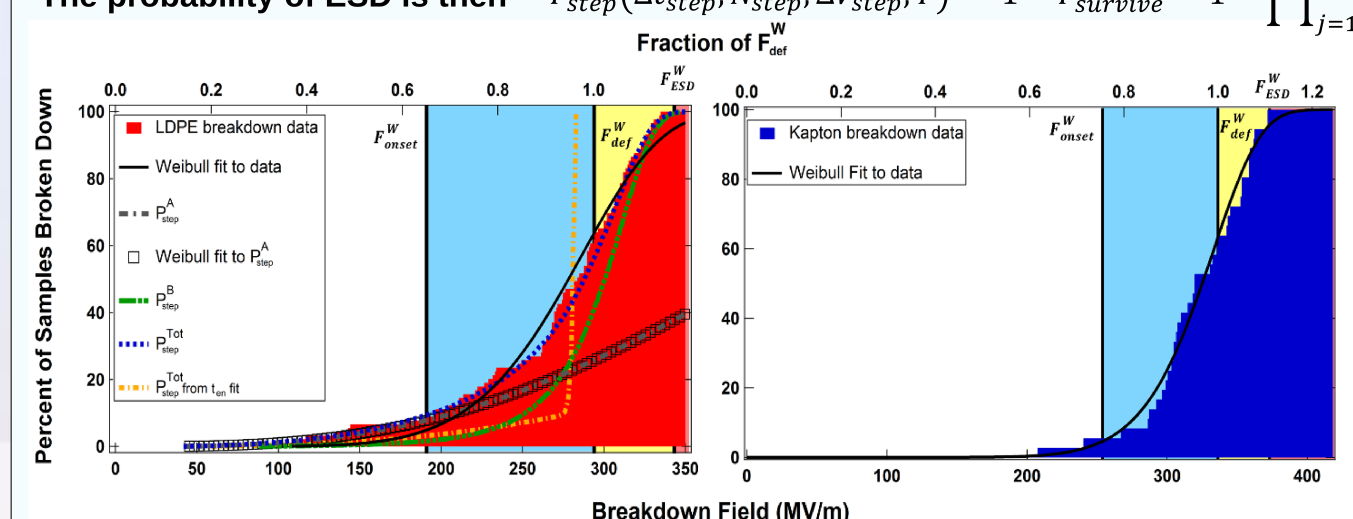
Both A and B type defects are needed to fit the data!

Statistical Fits to Voltage Step-Up Breakdowns of LDPE and Kapton

The probability of sample surviving the voltage step-up processes for N_{step} steps is

$$P^{Tot}_{survive}(\Delta t_{step}, N_{step}, \Delta V_{step}, T) = \prod_{j=1}^{N_{step}}\left[1 - P^{Tot}_{def}\left(\Delta t_{step}, \frac{j\Delta V_{step}}{D}, T\right)\right]$$

The probability of ESD is then $P^{Tot}_{step}(\Delta t_{step}, N_{step}, \Delta V_{step}, T) = 1 - P^{Tot}_{survive} = 1 - \prod_{j=1}^{N_{step}}\left[1 - P^{Tot}_{def}\left(\Delta t_{step}, \frac{j\Delta V_{step}}{D}, T\right)\right]$

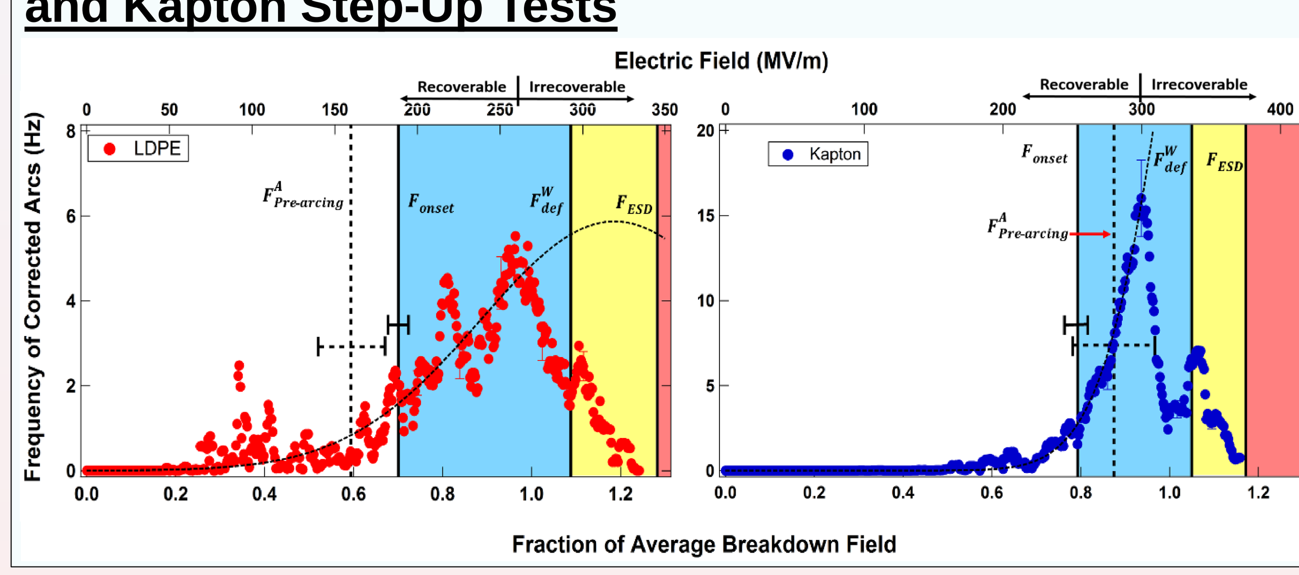


$$P^{Tot}_{step} \approx P^W_{def}(F) = 1 - \exp\left[-\left(F/F^W_{def}\right)^\beta\right]$$

The Weibull distribution (above) is commonly fit to ESD step-up tests.

- $P^W_{def}(F^W_{onset}) \equiv 4.6\%$ or 2σ below F^W_{def} (beginning of blue regions)
- $P^W_{def}(F^W_{def}) \equiv 63.2\%$ (beginning of yellow regions)
- $P^W_{def}(F^W_{ESD}) \equiv 95.5\%$ or 2σ above F^W_{def} (beginning of red regions)

Guassian Fit to the Frequency of Voltage Step-Up Pre-Arcs in LDPE and Kapton Step-Up Tests



$$f(F) = \frac{f_0}{\sqrt{2\pi}\Delta F} e^{\left(-\frac{(F-\bar{F})^2}{2\Delta F^2}\right)}$$

We estimate the field where pre-arcing is expected to begin, $F^A_{Pre-arcing}$, by defining $1 - 2\int_{F^A_{Pre-arcing}}^{\bar{F}} f\, dF = 4.6\%$. We can now quantitatively compare the field where ESD begins (F_{onset}) to the field where Pre-arcing begins ($F^A_{Pre-arcing}$).

- LDPE $F^A_{Pre-arcing}$=160 ±20 MV/m ≈ F_{onset} = 189 ± 6 MV/m.
- Kapton $F^A_{Pre-arcing}$=280 ±30 MV/m = F_{onset}= 253 ± 8 MV/m

These agree within the uncertainty.

Dual-defect Model

This dual-defect model is an extension of the single defect species mean-field approximation. For a single defect energy, *ΔG*, the hopping probability for a charge q_e in field *F* at temperature *T* with mean defect spacing a_0 is

$$P_{def} = \nu e^{-\left(\frac{\Delta G - q_e a_0 F}{2k_bT}\right)} - \nu e^{-\left(\frac{\Delta G + q_e a_0 F}{2k_bT}\right)}$$

$$P_{def} = 2\nu e^{\frac{-\Delta G}{k_BT}} \sinh\left(\frac{q_e a_0 F}{2k_bT}\right).$$

Setting probability to one and inverting

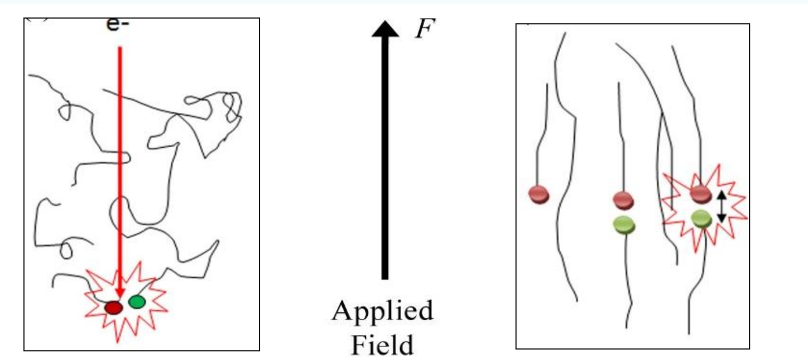
$$t = \frac{1}{2\nu} e^{\frac{\Delta G}{k_BT}} \cosh\left(\frac{q_e a_0 F}{2k_bT}\right).$$

Then for a 2D slab model define

$$E_{strain} = \frac{1}{2}\varepsilon_r\varepsilon_0 F^2 \Delta V$$

$$\Delta V = a_0^3 \equiv 1/N_{def}$$

Where N_{def} is the defect density.



Type A Reversible Defects

- Energetically ~ k_BT_{Room}
- Can be thermally annealed
- Strongly T dependent: thermally annealable
- Lower T can reduce recovery
- Due, for example, to charge injection, impact ionization, or kink formation.

Type B Irreversible Defects

- Energetically >> k_BT for any operational temperature for material
- Essentially non-recoverable
- Due, for example, to chain bond breaking from direct stress.

For two defect species (A and B), we simply add terms for each defect type

$$P^{Tot}_{def}(\Delta t, F, T) = \sum_{i=A,B} P^i_{def} = \left(\frac{2k_BT}{h/\Delta t}\right)\sum_{i=A,B}\exp\left[\frac{-\Delta G^i_{def}}{k_BT}\right]\sinh\left[\frac{\varepsilon_r\varepsilon_0F^2}{2N^i_{def}k_BT}\right].$$

Results and Conclusions

Predicting the Lifetime for ESD

- Polymeric insulators in applications need to last years or decades. Accelerated laboratory tests are imperative, especially when comparing many candidate materials.
  - The 58 static voltage endurance time data shown took nearly 68 days of instrument time. This time does not include sample preparation, vacuum breaks, etc. More long duration tests are needed to fully characterize long term behavior.
  - The 89 LDPE step-up tests shown took just over 3½ days of instrument time.
  - There was an average of 17 pre-arcs per LDPE step-up test. If the field where arcing begins is a good indicator of minimum breakdown field only about ½ day of instrument time could be needed per material. This is potentially ~2 orders of magnitude savings in test times!

Dual-Defect Model

- Dielectric strength is not a constant. ESD depends on temperature, charge history, and material structure.
- Our dual-defect model is consistent with measurements of pre-arcing, temperature- and ramp rate-dependent breakdown field distributions, and endurance times.
- The model provides tentative physics-based links between pre-arcing and ESD.

Future Work

- Acquire time endurance data for Kapton and extend the LDPE data sets to longer times.
- Extend temperature studies of ESD and pre-arcing.
- Perform ESD tests on other materials with very different structures such as SiO_2.
- Expand the model to include other dynamic density of state and defect occupation profiles.

References and Acknowledgements

[1] Allen Andersen, JR Dennison, Alec M. Sim and Charles Sim, "Measurements of Endurance Time for Electrostatic Discharge of Spacecraft Materials: A Defect-Driven Dynamic Model," *13th Spacecraft Charging Technology Conference*, (Pasadena, CA, June 25-29, 2014).

[2] Allen Andersen and JR Dennison, "Pre-breakdown Arcing and Electrostatic Discharge in Dielectrics under High DC Electric Field Stress," *2014 IEEE Conference on Electrical Insulation and Dielectric Phenomena*—(CEIDP 2014), (Des Moines, IO, October 19-22, 2014).

[3] ASTM D-5213-12, "Standard Specification for Polymeric Resin Film for Electrical Insulation and Dielectric Applications," (American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA, 2012).

[4] J.P. Crine, "On the interpretation of some electrical aging and relaxation phenomena in solid dielectrics," IEEE Trans. Dielectrics and Electrical Insulation, vol. 12, no. 6, pp. 1089-1107, 2005.

[5] P. Trnka, M. Sirucek, M. Svoboda, et al., "Condition-based maintenance of high-voltage machines-a practical application to electrical insulation," IEEE Electrical Insulation Magazine, vol. 30, no. 1, pp. 32-38, 2014.

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