Characterization of methods for surface charge removal for the reduction of electrostatic discharge events in explosive environments

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Abstract*—Electrostatic discharge (ESD) from charged dielectric materials used within explosive environments presents a significant hazard. To investigate dielectric surface charging, and methods of removing the charge, in detail and in a controlled way, a test stand has been built and utilized to study the behavior of several common dielectric materials used in such environments. A corona discharge source of the type used in electrostatic printing technology has been employed at normal laboratory temperatures and at low and high relative humidity in a controlled manner. Materials tested included black Kapton, yellow Kapton, Lexan, Delrin, and Adiprene with surface potentials (V_{diel}) ranging from -1 kV to -15 kV. Uniform charging and discharging of individual dielectric samples of varying thickness has been observed, as characterized by spatial scans of the surface potential at low voltages such as -1 kV to -4 kV. At higher charging voltages, the surface potential is found to decay or increase with time in complex ways, showing a dependence on the magnitude of the surface potential (V_{diel}), as well as two characteristic time constants τ_d (τ_1, τ_2) in some cases. The initial decay of V_{diel} (τ_d) is rapid, while the subsequent decay of surface potential is much slower. The decay time constant(s) is(are) found to be a nonlinear function of the surface voltage, V_{diel}. A conductive brush with a static dissipative handle, grounded to a metal backing plate proved the most effective method to remove surface charge (Q_S). Typically, 80-90% of Q_S could be removed, with a lower bound on the "discharged" surface voltage of -500 to -1000 V. Additionally, it was found that localized discharging results in an approximately constant electric field gradient, ∇E on the dielectric samples in 2D. Detailed experimental results, including the effects of humidity and temperature are presented.

I. INTRODUCTION

Dielectric materials are often used for packaging, assembling, and, handling of explosive materials in explosive environments. Unfortunately, these high resistivity materials are susceptible to triboelectric charging during handling, and the relaxation time of a typical dielectric is long enough that significant surface voltages can manifest. This can result in ESD that may be significant enough to cause explosive hazards [1]. A previous unpublished study by Martinez [2] utilized controlled frictional charging to investigate charging and discharging of a similar group of materials. However, the spatial uniformity obtained in these experiments was relatively poor. The experiments reported here have utilized a commercial corona charging source in order to improve uniformity.

In this work, several types of dielectric sheets have been uniformly charged using a commercial corona source, of the same type used in xerography. Using the corona source, negative charge is deposited directly onto the dielectric substrate by an accelerating electric field [3]. After charging the dielectric material, a grounded conductive brush (labeled “Conductive brush” in Fig. 1), as well as several other types of brush tools, was used to remove the surface charge [4]. Independent of brushing, it was found that materials discharge with time in complex ways and with widely varying discharge times.

For a better understanding of the charging properties of these dielectric materials and to develop a method to reduce/remove ESD within explosive environments, a test stand has been constructed, as shown in Fig. 1. This test stand is built around a corona charging source taken from a Tektronix Phaser 6120 printer. A dielectric sample is placed on the Cu plate (in Fig.1) and the source sits on a height-adjustable 8020 sliding rail with a spacing of (typically)1.5 - 5 mm above that dielectric sample. A noncontact electric field (E-field) meter (Monroe, M282) is mounted on an aluminum sliding rail which allows motion of the detector in the x-, y-, and z-directions. The meter has an accuracy of $\pm 5\%$ for high surface voltages [4]. The entire assembly resides on a ½ in. thick aluminum mounting plate. An earth grounded static-safe workbench with a static dissipative table mat is also used for ESD control and the Al plate is earth grounded. Relative humidity of minimum 16% and maximum 71%, and a temperature of $20^\circ C - 24^\circ C$ were maintained.

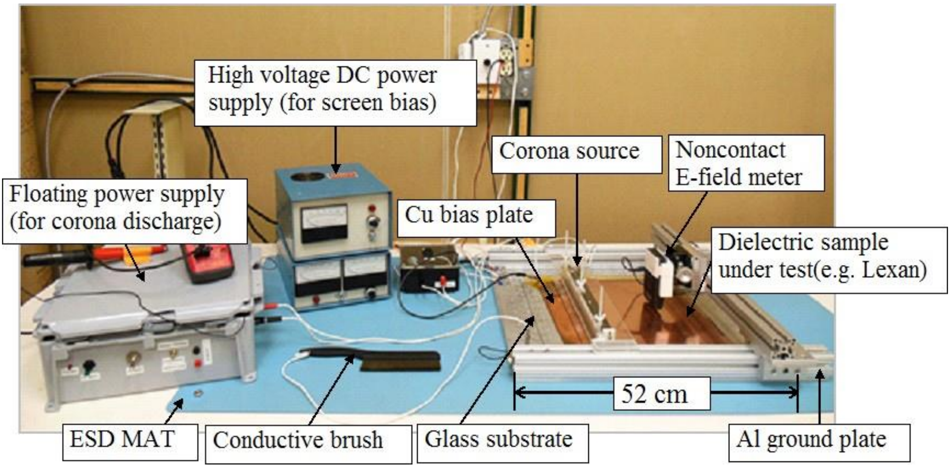

Fig. 1. Test set up for controlled surface charging, discharging, and measurement. Not shown: closed acrylic box, humidifier, and dehumidifier for relative humidity control.

II. EXPERIMENTAL DETAILS

The corona source operates with two DC power supplies (V_{disch}, and V_{scr}) as shown in Fig. 2. The electrically floating corona discharge voltage, V_{disch} (typically ~ 3 kV), connects between the corona "wire" and the screen-grid electrode. This creates corona discharge plasma which is the source of free electrical charges. The screen bias power supply, V_{scr} is connected between the corona source screen electrode and the Al ground plate under the tested dielectric. This voltage produces an electric field between the screen electrode and Al ground plate through the dielectric, which accelerates free charges from the source to the dielectric surface. The surface is charged until the E-field between the corona screen and ground plate is reduced to near zero so that no more free charge can be drawn from the source. The dielectric surface is found to charge uniformly in the area covered by the source. The power supply available for V_{scr} is limited to 10 kV. Therefore, to achieve dielectric charging voltages, $V_{diel} > 10$ kV, an additional Cu plate, V_{plate} is biased to a voltage with respect to Al ground (*cf.* Fig. 2) which results the surface voltage of $V_{diel} \approx V_{scr} - V_{plate}$. The corona charging time was 15-20s in most cases at ($V_{scr} = -1$ kV to -15 kV). Unfortunately, positive charging with this corona source did not work reliably, so only negative charging voltages are reported here.

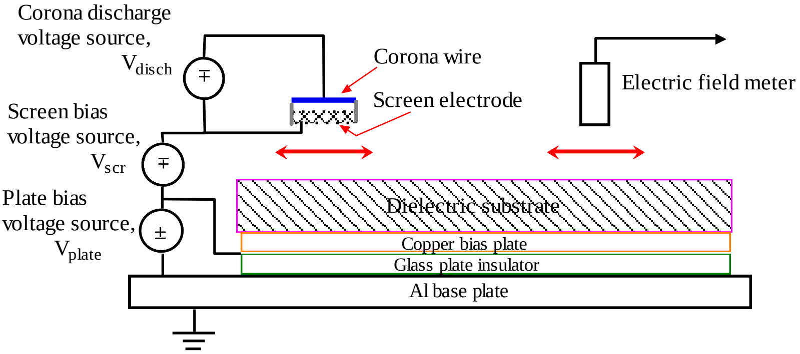

Fig. 2. Schematic of corona source-based controlled charging of dielectric materials.

Six dielectric sample sheets (red Adiprene, black Kapton, semi-black Kapton, yellow Kapton, white Delrin and transparent Lexan) were tested. Sample thicknesses were 0.005/0.010 inch (0.127 – 0.254 mm), or 2 mm/3mm, based on the availability in the market. The test dielectric samples were typically 12 inch × 12 inch (30.5 × 30.5 cm), and all materials were cleaned with methanol and allowed to dry before each test. The sample sheet was laid on the Cu plate (*cf.* Fig. 1 or 2) and the corona source was passed slowly twice without contact over the sample while both applied voltages ($V_{disch} = -3$ kV, $V_{scr} \approx -1$ kV to -15 kV) remained constant. After charging the dielectric material, a few commercially available brushes were utilized to remove the surface charge from dielectric [4]. Among these three brushes, two are manufactured by Gordon Brush Mfg. Co. Inc, and both brushes (grounded Brush #1, and ungrounded Brush #2) are designed with a static dissipative handle, while the third (ungrounded, Brush#3) brush utilized an aluminum handle [3]. Both brush #1 and #2 are considered "conductive", with a resistance of approximately 1 MΩ between the bristle end and brush handle. Each brush is passed manually one time (1x), two times (2x), or three times (3x) for few seconds (≤ 5 sec) over the sample in order to test the effectiveness of charge removal from the surface. The grounded brush#1 appeared more effective than brush#2, or brush#3, and thus, grounded brush#1 was utilized for all experiments reported here.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Uniform charging (negatively) and discharging after brushing

The dielectric surface just after exposure to the corona source at lower screen voltages charged approximately uniformly for all dielectric materials except Adiprene, as shown in Fig. 3 where $V_{scr} \approx -1$ kV. Measurements were obtained by the 282M E-field meter scanned to nine randomly chosen positions on the surface. Note also that, while the applied charging voltage, V_{scr} was approximately –1 kV, the E-field measured 1 cm away on both yellow Kapton and Lexan was nearly –2 kV/cm – greater than the applied source voltage.

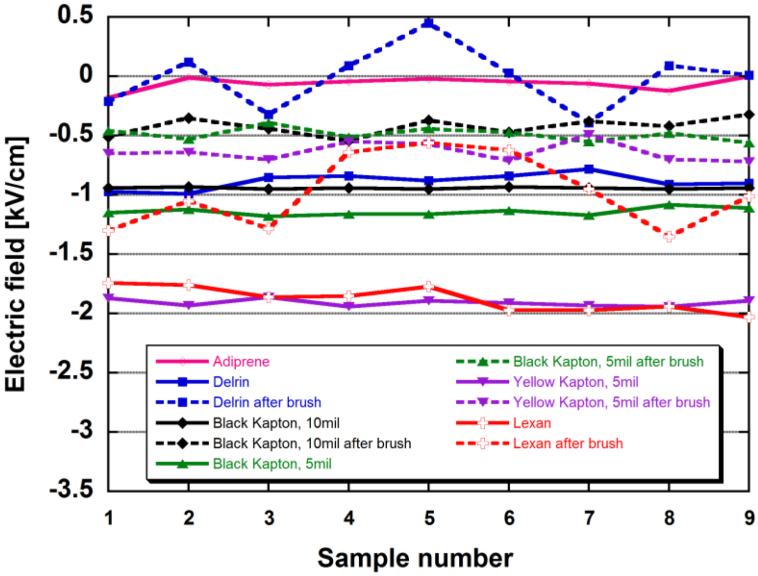

Fig. 3. Measured surface electric field after charging with $V_{scr} = -1$kV, and after brushing for several materials.

The dielectric sample thicknesses were as follows: black Kapton: 0.010 inch, semi-black Kapton: 0.005 inch, yellow Kapton: 0.005 inch, Lexan: 2 mm, and white Delrin: 3 mm. After charging, the grounded brush#1 tool was passed one time (1x) over the surface manually. As the brush approached to the charged surface, a spark/crackling could be heard in the region of the brush hair which is closest to the dielectric surface, however, no visible discharge was observed. As can be seen in Fig. 3, the grounded brush#1 removes approximately >50% surface charge from all dielectric materials except Lexan. Lexan shows a significant discharging nonuniformity (*cf.* Fig.3). That is, the brush eliminates almost 75% of the surface charge at few points but only 50% of the charge at other points. Adiprene did not charge appreciably, as shown in Fig. 3. Also, several attempts using positive screen bias voltage, $V_{scr} \approx +600$ V to +15 kV, were made. However, no reliable positive charging was obtained. Note here that we infer surface charge removal by assuming that surface charge, $Q_{sample} = C_{sample}V_{diel}$, where, C_{sample} = capacitance of dielectric sample, which remains constant and V_{diel} is the surface potential of the dielectric sample. Thus, the surface charge removal is proportional to reduction of the surface potential ($V_{diel} = E_{diel}\times 1\text{cm}$). It appears that there may be a lower limit to the amount of charge that can be removed by brushing, corresponding to an E-field ~ 0.5 kV/cm.

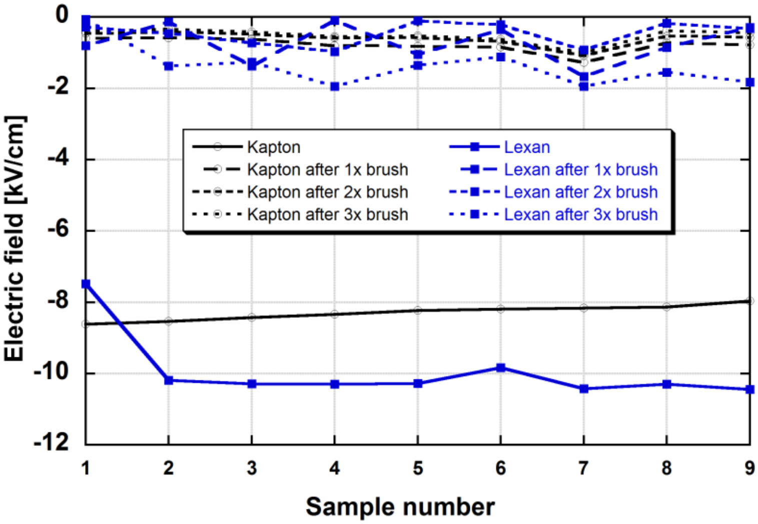

Fig. 4. Surface electric field after charging by corona source at –10kV (solid lines) and after brushing (dashed lines) for black Kapton and Lexan.

However, subsequent brushings (2x, 3x) were observed to remove approximately 80-90% of the surface charge from the dielectric sample as can be seen in Fig. 4. Fig. 4 is similar to Fig. 3 for black Kapton and Lexan, but with higher screen voltage, $V_{scr} \approx -10$ kV, and the results of one, two, and three brushings. Several attempts were made to charge other materials at higher screen bias voltage, ($V_{scr} \approx -6$ kV, –10 kV, –15 kV, and –18 kV). However, it was found that the surface potential on these dielectrics changed rapidly with time in complex ways at these higher screen voltages. Thus, only black Kapton and Lexan are shown in Fig. 4. We attribute the apparent spatial variation of E-field for black Kapton seen in Fig. 4 to a temporal decay of surface charge, as the E-field meter was scanned across the surface. The Lexan E-field, on the other hand, remains constant, or may actually become slightly *more* negative with time.

B. Passive discharging vs. time

It was found that after charging at higher voltage, e.g. $V_{scr} > -3$ kV, the surface voltage varies with time, as the materials discharged or relaxed. Furthermore, the discharge time, or relaxation time, varies as a function of charging voltage (V_{scr}). To quantify this behavior, immediately after charging surface, the corona source was removed and E-field measurements were recorded in intervals at a fixed position (typically near the middle of the surface). An example, cases of black, semi-black, and yellow Kapton, Delrin, and, Lexan is shown in Fig. 5. In this case, the samples were initially charged at $V_{scr} \sim -10$ kV, and corona source was turned off at t = 0. As can be seen, the surface potentials decrease from negative towards zero and the time responses are well fit by a single exponential decay $E = A - Be^{-t/\tau}$, where E is the surface E-field, A and B are the arbitrary constant values, and, t and τ are the time and time constant respectively.

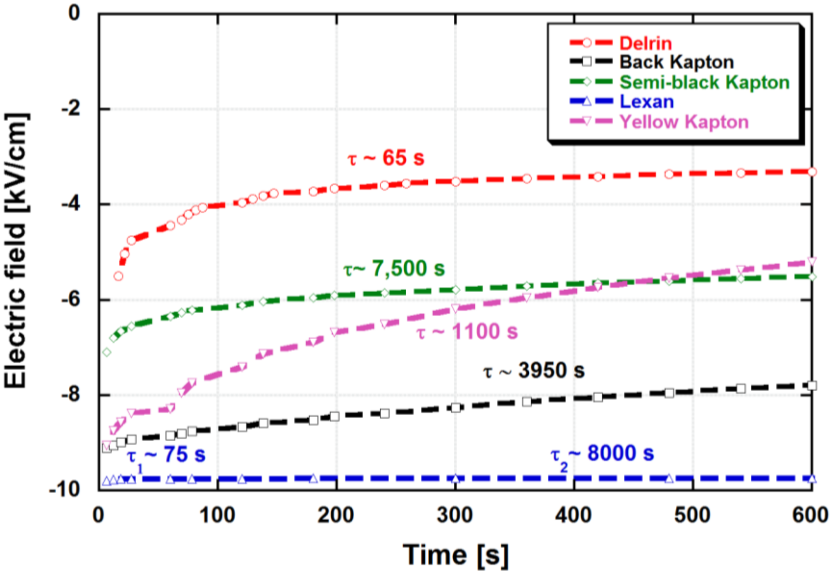

Fig. 5. Measured surface electric field versus time after samples were initially charged with $V_{scr} = -10$ kV (corona source was turned off at t = 0). Time constants shown are from exponential curve fits assuming final E-field values of 0. Two different time constants were required to fit the data for Lexan, as shown.

Another example can be seen for black Kapton at $V_{scr} \sim -3, -6, -10, -15$ kV in Table 1, where time constants were calculated from the curve fit to the experimental data for three cases of final voltage, $V_{diel}(\tau \rightarrow \infty)$: 1) an arbitrary asymptotic value determined from the curve fit ($\tau_{arbitrary}$ in the table), 2) $V_{diel}(\tau \rightarrow \infty) = 0$ (τ_0 in the table), and 3) for the final estimated value of $V_{diel}(\tau \rightarrow \infty) = -3.5$ kV ($\tau_{estimated}$ in the table). The estimated final value was taken as $V_{diel}(\tau \rightarrow \infty) = -3.5$ kV for black Kapton from observations after 4 hours from t = 0, when the corona source was turned off. Additionally, it was found that for charging voltages < -4 kV, time constants were too long to measure. While we believe that the most accurate values of discharge time, τ, is given by $\tau_{estimated}$, these three values serve to bound τ due to experimental uncertainties.

TABLE 1: TIME CONSTANT VALUE FOR BLACK KAPTON

Charging voltage (V_{scr}) [kV]	Time constants [second]
-4	$\tau_0 > 1900$ $\tau_{arbitrary} \sim 950$ $\tau_{estimated} \sim 4500$
-6	$\tau_0 > 10{,}000$ $\tau_{arbitrary} \sim 950$ $\tau_{estimated} > 4900$
-10	$\tau_0 \sim 3400$ $\tau_{arbitrary} \sim 380$ $\tau_{estimated} > 2200$
-15	$\tau_0 \sim 2000$ $\tau_{arbitrary} \sim 333$ $\tau_{estimated} > 1500$

In contrast to the other materials tested, Lexan exhibits much different relaxation behavior, as shown in Fig. 6. First, while surface potential on black Kapton reduces toward zero with time (at least at higher voltage, e.g. $V_{scr} \sim -10$ kV or -15 kV), the surface potential on Lexan *increases* in magnitude with time (becomes more negative) for cases of lower charging voltage ~ –3, –6 kV. Thus, Lexan appears to further charge itself on the surface. Probably this is due to an internal relaxation of bound charge within the material as it moves to a lower energy state.

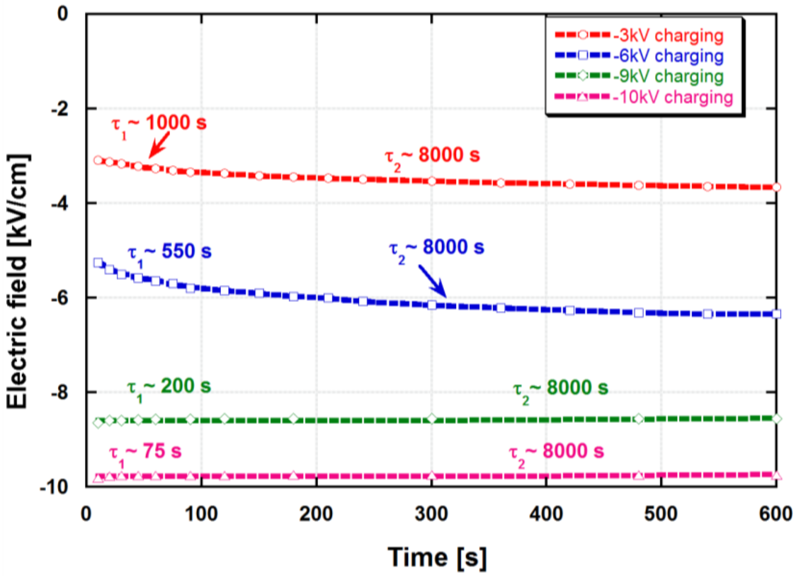

Fig. 6. Measured surface electric field versus time for Lexan at various charging voltages, V_{scr}, of the corona source.

However, at higher charging voltages (–10, –15 kV), Lexan seems to discharge with time toward zero, as in the case of black Kapton. Secondly, while V_{diel} vs. time (relaxation) curves for Kapton were well fit by a single exponential $\propto e^{-t/\tau}$, two exponential regions with different time constants are required to reasonably fit the data of Lexan. As can be seen in Fig. 6, the Lexan data are well fit at early times (t < 100 s, roughly) by one exponential, $\propto e^{-t/\tau_1}$, and at late times (t > 100 s, roughly) $\propto e^{-t/\tau_2}$. Furthermore, the primary time constant (τ_1) varies with charging voltage (V_{scr}) but the secondary time constant (τ_2) is independent with V_{scr}. This seems to suggest that two different physical processes are at work in the relaxation of Lexan. In should be pointed that these experiments were repeated several times, all with consistent results.

C. Humidity variation of passive discharging

Discharging surface electric field measurements of the charged dielectric were also obtained in a closed acrylic box at a lower range of relative humidity of 16-22% and at a higher range of 27-37% and effects of humidity were observed. All dielectric samples (except Adiprene) were charged followed by the same procedure described above. Examples for the case of $V_{scr} \approx -10$ kV are shown in Figs. 7 and 8.

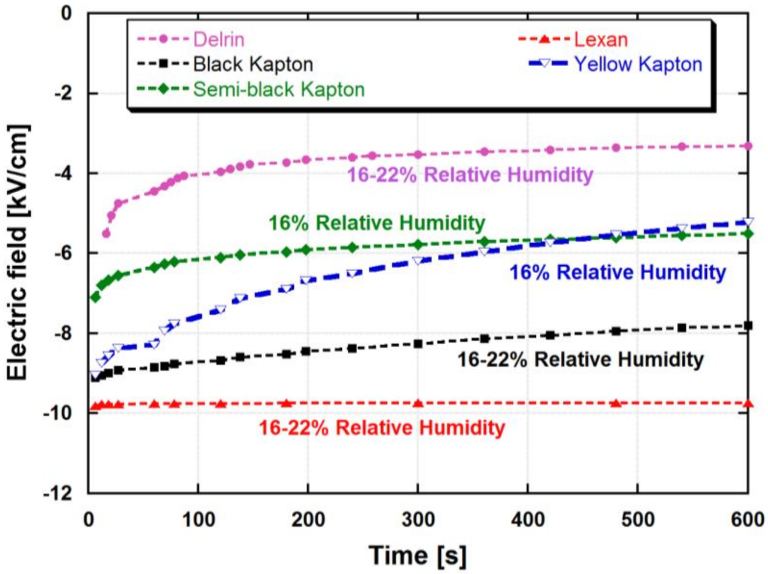

Fig. 7. Measured surface electric field versus time for various materials at -10 kV at lower ambient relative humidity.

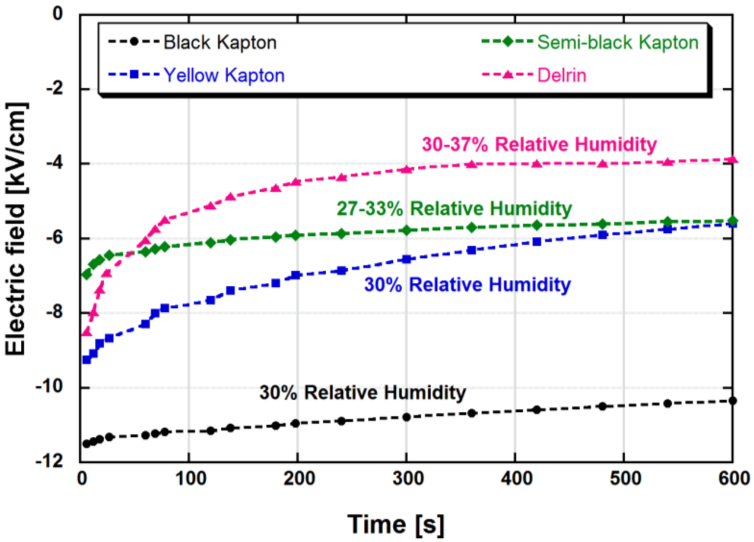

Fig. 8. Measured surface electric field versus time for various materials at -10 kV at high ambient relative humidity.

D. *Localized brushing*

The surface potential of the charged dielectric before and after using the brush tool in a localized area was also measured by brushing a relatively small area and making surface E-field measurements in the X- and Y- directions, as illustrated schematically in Fig. 9. Localized brushing was investigated in order to understand the effects of the localized discharging of a uniformly charged (approximately) dielectric surface. Localized discharging was mainly done using grounded conductive brush #1 (see details above). After charging the entire surface uniformly with the corona source as described above, the E-field was scanned in the x- and y-directions, as indicated in Fig. 9, before and after brushing in the corner.

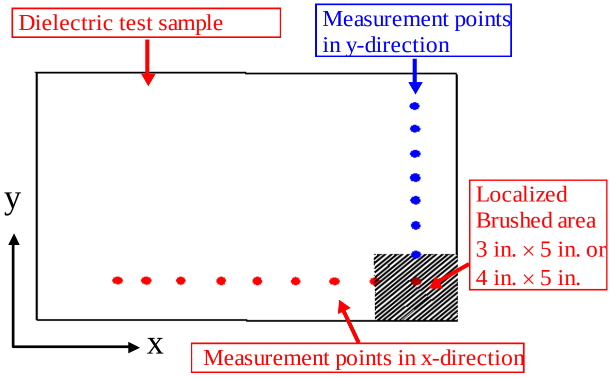

Fig. 9. Schematic of localized brush discharging at the corner of the material sample.

A ‘rectangular corner’, as indicated in Fig. 9, (labeled ‘localized brushed area’), of size 3 in. × 5 in. for Kapton and 4 in. × 5 in. for both Lexan and, Delrin, was selected for localized brushing. The rest of the surface sample remained untouched.

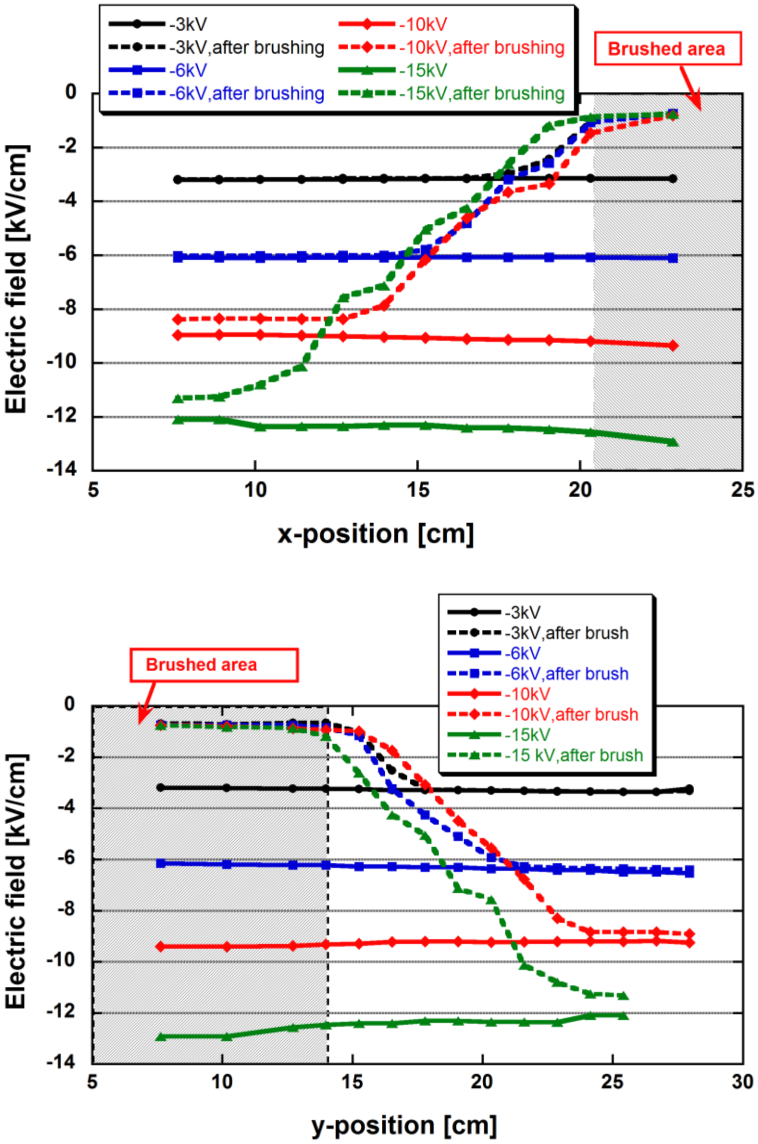

Fig. 10. Measured surface electric field in two orthogonal directions on black Kapton after charging at various corona source voltages, V_{scr}, and after localized brushing as indicated in Fig. 9. Upper: x-direction, lower: y-direction.

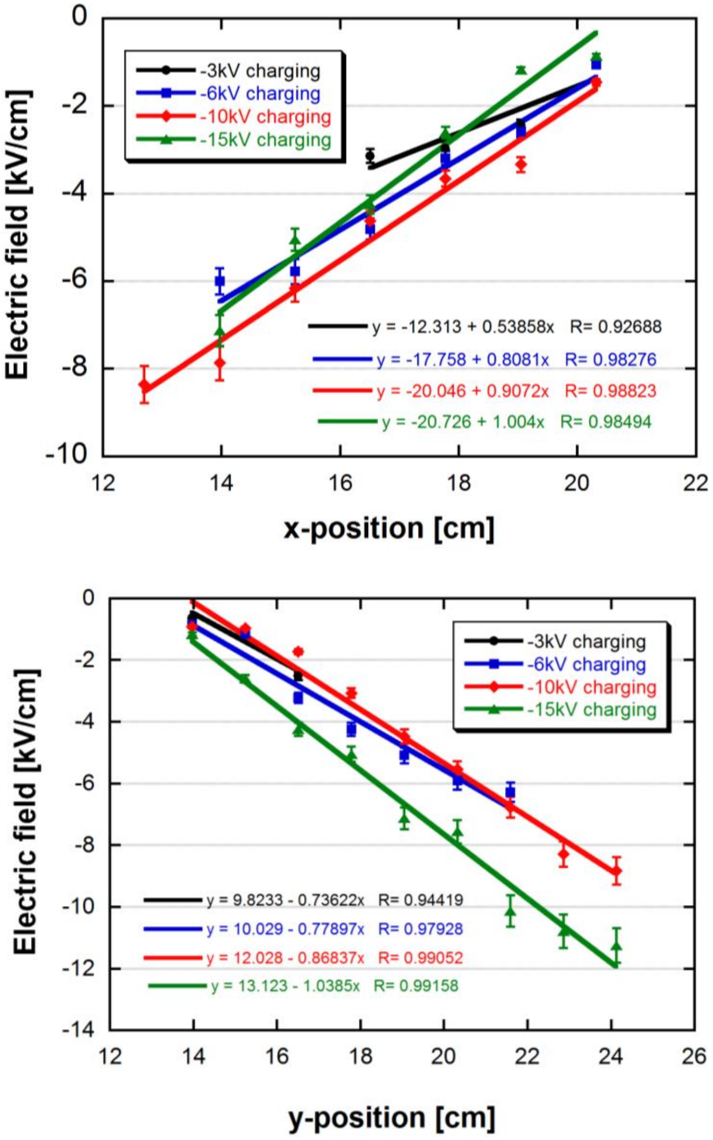

Fig. 11. Measured surface electric field in two orthogonal directions on black Kapton after charging at various corona source voltages, V_{scr}, then localized brushing as indicated in Fig. 9. Linear curve fits suggest nearly constant electric field gradients result outside the brushed area, as charge is redistributed across the surface over an area greater than the area brushed. Upper: x-direction, lower: y-direction.

Fig. 10 shows the results of localized brushing for black Kapton in two different directions (x and y). These experiments were performed on the black Kapton with the thickness of 0.010 in. at four different screen voltages, $V_{scr} \approx -3$ kV, –6 kV, –10 kV, –15 kV. The solid lines and dashed lines represent charged (after charging and before brushing) and discharged (after brushing) surface voltages (V_{diel}) respectively. As can be seen, it appears that the surface charge inside and outside of the brushed area redistribute themselves so as to result in an approximately constant electric field gradient, ∇E between the brush discharged and fully charged area on dielectric, regardless of the initial charging voltage. Linear curve fits on the region of electric field gradient give the values of gradient, between 0.538 and 1.00 kV/cm^2, with an average value of $\nabla E = 0.81$ kV/cm^2 as shown in Fig. 11 in x- and y-dir. There were no apparent differences in the x- and y-directions.

E. Other measurements

A limited number of experiments were conducted on a systematic basis to explore if there is any correlation between the tendency of a dielectric to charge and its surface resistivity. Example data is shown in Fig. 12, where it can be seen that yellow Kapton charges more than semi-black Kapton or Delrin, even though it (yellow Kapton) has lower resistivity. Even after 10mins, yellow Kapton still retains a significant amount of charge - more than Delrin. Similarly, semi-black Kapton charges more than Delrin, and after 10mins, semi-black Kapton still holds more charge than Delrin. Further investigation is required to elucidate the complete behavior of the other dielectric materials.

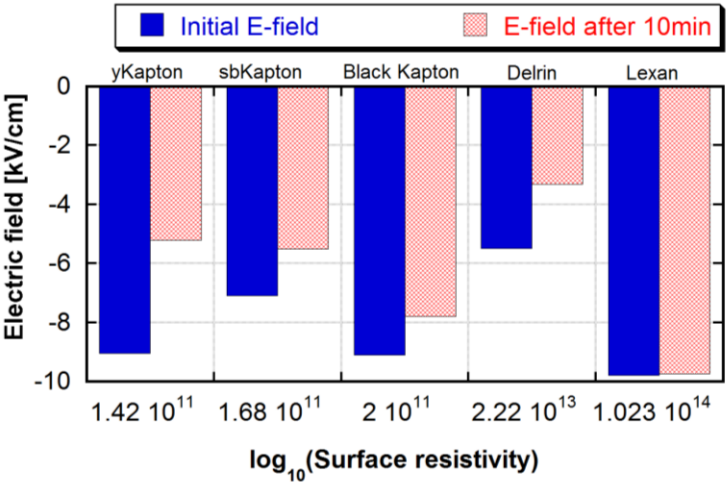

Fig. 12. Relationship between surface resistivity and chargeability of all dielectric materials at -10 kV at lower ambient relative humidity, RH (16-22%).

IV. CONCLUSIONS

The work presented here has reviewed the preliminary results of experiments to uniformly charge the surface of dielectric sheet samples and to develop methods for ESD-free charge removal. The conclusions may be summarized as follows.

i. A test stand has been constructed and utilized for the surface charge characterization and for the surface charge removal from dielectric materials at low (16-22%) and high relative humidity (>30%) in an ambient temperature environment. This test stand-

a) Allowed for uniform charging and discharging of solid dielectric sheets of area up to ≈ 30.5 cm × 30.5 cm (12 in. × 12 in.). (Exception is Adiprene)
b) Has successfully charged the dielectric materials up to surface voltages, $V_{diel} \approx -15$ kV ($E_{diel} = -15$ kV/cm).
c) Was used to test six dielectric samples: black Kapton, semi-black Kapton, yellow Kapton, Lexan, white Delrin, and red Adiprene (urethane).

ii. Detailed results are summarized in Table 2:

TABLE 2: SUMMARY OF EXPERIMENTAL RESULTS

Material	Basic Result/Comments	Range of Discharge Times [second]	Surface Resistivity [Ω/square]	Range of E-field gradient, ∇E, kV/cm^2
Red Adiprene	Did not charge	N/A	8.32×10^{10}	N/A
Black Kapton	Charged up to (-15 kV/cm) at low and high humidity, discharged E-field vs. time constant, τ	$\tau \approx 1900$ to 19,000	2.11×10^{11}	$\nabla E \approx 0.54$ to 1.0; Average $\nabla E = 0.81$
Semi-black Kapton	Charged up to (-15 kV/cm) at low and higher humidity, discharged E-field vs. time constant, τ	$\tau \approx 7{,}500$ to 20,000	1.68×10^{11}	$\nabla E = 1.08$ in x-dir; $\nabla E = -0.78$ in y-dir
Yellow Kapton	Charged up to (-15 kV/cm) at low and higher humidity, discharged rapidly, E-field vs. time constant, τ	$\tau \approx 245$ to >900	1.42×10^{11}	$\nabla E \approx 0.81$ to 1.5; Average $\nabla E = 0.99$
Lexan	Charged up to (-15kV/cm) at low and higher humidity, charge up itself, discharged E-field vs. two-time constants, τ_1, τ_2	$\tau_1 \approx 75$ to 19,000; $\tau_2 \approx 8{,}000$	1.02×10^{14}	$\nabla E \approx 0.74$ to 0.87; Average $\nabla E = 0.80$
Delrin	Charged up to (-10 kV/cm) at low and higher humidity, discharge rapidly with single τ, would not hold charge for $V_{scr} > -10$kV	$\tau \approx 65$ (at -10 kV) to > 20,000 τ too short to measure above -10 kV	2.20×10^{13}	$\nabla E \approx 0.19$ to 0.86; Average $\nabla E = 0.58$

iii. Three different brushes (see details above) were used for surface charge removal by an audible "crackling" sound when the brush approached the charged dielectric could be heard, but no visible discharge was seen. The best charge removal was obtained using a grounded commercial resistive brush (brush #1) with Thunderon® bristles. This brush could remove more than 90% of the surface charge from the dielectric.

iv. Multiple brushings had slightly effects in removing surface charge depending on the material, and in some cases increased the measured E-field, e.g. for Lexan.

v. All tested dielectric materials were found to discharge passively with time except Lexan. The decay time constant(s) is(are) found to be a nonlinear function of the surface voltage (applied voltage).

vi. Localized brushing in a 2D plane of a charged dielectric resulted in a charge distribution that suggests that each material may have a maximum ∇E that can be supported. No differences were observed in the x and y direction.

vii. A limited number of experiments on the surface resistivity have been conducted on a systematic basis to explore any correlations between the surface resistivity and surface voltage. It was found that there is no correlation between the tendency of a dielectric to charge more and the surface resistivity of the dielectric material.

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