The Electrostatics of Charged Insulating Sheets Peeled from Grounded Conductors

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Abstract. The physics of a charged, insulating sheet peeled from a ground-plane conductor is examined. Contact charging is ensured by charging a sheet to 10-12 kV with corona to establish intimate electrostatic contact with the underlying conductor. The surface potential is next forced to zero by sweeping the sheet with a stainless-steel brush, and the surface recharged to a new potential between 0 and 11 kV. The sheet is then peeled from the ground plane and its residual charge density is measured. Results show that the residual charge equals the breakdown-limiting value, but its polarity depends on the surface potential acquired just prior to peeling. The results have relevance to studies of industrial webs and insulating sheets.

1. Introduction
In the processing of webs and films, charge often accumulates due to tribo or contact electrification [1-10]. Such charge, usually undesirable, may cause sheets to cling to surfaces, attract dust, and otherwise disrupt material motion [7,8,11]. Unwanted charge may cause detrimental spark discharges as the sheet is peeled away from a conductor such as a roller or platen, resulting in logic resets or damage to electrical components. In some situations, charge is intentionally deposited on a sheet, usually via corona discharge, for the purpose of a manufacturing process. Whether the charge is of accidental or intentional origin, its magnitude after the insulator is separated from ground is often of interest. This paper examines the subtly complex physics that governs a charged, insulating sheet peeled from a conducting surface.

When an insulating sheet is peeled from a conductor, a “triple-point” junction, comprising air, insulator, and conductor, develops at the peeling point. The susceptibility of triple-point junctions to microscopic discharges under high field stress is well known to those who design robust, high-voltage insulation systems [12,13]. For an electrostatically charged, insulating sheet, the source of a triple-point field will be surface charge acquired by triboelectric, contact, or corona charging. Our experiments suggest that electrostatic discharges at the peel point play a major role in determining both the magnitude and polarity of an insulator’s net, post-peel charge density. The results have relevance to studies involving industrial webs and insulating sheets.

2. Experimental Apparatus
To gain insight into the problem, we first used corona to intentionally charge individual insulating sheets placed on a 15 × 20-cm aluminum ground plate, as in Fig. 1a. For a variety of test conditions, charged sheets were subsequently peeled from the plate, as in Fig. 1b, and the residual charge on the insulator was measured. Sheet materials studied included 178-μm thick polyethylene-terephthalate
polyester (Mylar™) and 127-μm thick acetate derived from a common “overhead transparency.” The sheet under test overhung the edges of the aluminum plate by at least 4 cm on all sides. A 5 × 10-cm rectangular array of corona needles, spaced 1 cm apart, was swept over the insulator at a tip-to-surface spacing of 3.5 cm. The needles were energized to a positive or negative voltage in excess of corona onset, which occurred at about ±4 kV. The effective charging area was approximately 140 cm². Charge deposited on such an insulator causes its surface potential to rise. As a consequence, the corona discharge will quench when the potential difference between the insulator surface and needle tips falls below onset. By adjusting the needle-array voltage, we were thus able to control, to some degree, the density of charge deposited on the insulator surface.

Insulator surface potential was measured using a Trek Model 523 non-contacting voltmeter. The surface charge density \( \rho_s \) was then computed from the equation \[ \rho_s = \frac{\varepsilon_0 V_S}{d}, \] where \( V_S \) is the measured surface potential, \( \varepsilon_0 \) the insulator permittivity, and \( d \) the sheet thickness. To verify charge uniformity, \( V_S \) was measured at equally spaced points in the quadrants and center of the active area. If these measurements were not all within the desired range, the trial was abandoned and restarted.

As is well known in the field [1, 14, 15, 20], the operation of a non-contacting voltmeter is such that it does not affect the surface potential being measured. Rather, this type of feedback-null instrument re-establishes the conditions that prevail before its probe is introduced into the measurement space, and thus does not disturb the surface potential.

A Keithley Model 610C electrometer integrated the current flowing to ground from the aluminum plate during the peel event. Because the entire system must remain charge neutral, the magnitude of this charge quantity also represents the net charge on the peeled sheet. The post-peel charge carried away on the sheet was also measured using a Faraday pail and electrometer. The charges measured using these two methods were of equal magnitude, differing by no more than 1%.

Before each placement on the ground plane, the insulating sheet was first neutralized by grounded, stainless-steel brushes. To further ensure the charge neutrality of the sheet, it was then held in front of a Simco charge-balanced ac corona ionizer to remove residual charge. This neutralization method was periodically verified by dropping a discharged sheet into a Faraday pail connected to the electrometer.

3. Experimental Results
Sample sheets of Mylar and acetate were tested ten times each under four different test conditions, for a total of eighty trials, as follows:

- **Test 1:** Insulator charged to surface potential of −10 kV, then peeled from ground plane.
- **Test 2:** Insulator charged to −10 kV; charge removed by brush, sheet peeled from ground plane.
- **Test 3:** Insulator charged to +10 kV, then sheet peeled from ground plane.
- **Test 4:** Insulator charged to +10 kV; charge removed by brush, sheet peeled from ground plane.

In Tests 1 and 3, the sheet was charged on the ground plane via corona, then peeled immediately. In Tests 2 and 4, the charged insulator surface was first swept with a stainless steel brush, forcing its measured surface voltage to zero before peeling. Test results are provided in Table 1. Each entry
shows the average ground-plane charge measured over ten trials; given the earlier Faraday pail verification, the insulator charge was assumed to be equal and opposite to the ground-plane charge.

### Table 1. Measured Net Insulator Charge Density $\sigma_{PP}$ for Tests 1 to 4 (nC/cm²)

| Charging Polarity | Test 1 | Test 2 | Test 3 | Test 4 |
|-------------------|--------|--------|--------|--------|
| Surface Potential $V_P$ | negative | negative | positive | positive |
| Mylar | $-2.1$ | $+1.8$ | $-1.9$ | $+2.1$ |
| Acetate | $-1.7$ | $+1.8$ | $-1.8$ | $+2.8$ |

For either charge polarity, the magnitudes of the post-peel sheet charge densities were roughly the same. With the exception of Test 4 (acetate), all readings were within 15% of the 2 nC/cm² average. Interestingly, even the brushed sheets of Tests 2 and 4, which registered zero surface voltage prior to peeling, retained this net charge after peeling. This result is counterintuitive, because the pre-peel surface voltage $V_P$ is forced to zero by the brushing. One might expect the sheet to be charge neutral in this case. Even more significantly, however, the brushed sheets of Tests 2 and 4 acquired charge of polarity opposite that of their non-brushed counterparts, even for the same initial charge polarity. Clearly, something subtle and unusual is occurring at the insulator-conductor interface. To gain further insight into the physics involved, we performed expanded tests on Mylar sheets, as follows:

**Test 5**: Insulator pre-charged to $-10$ kV; charge removed by brush; sheet recharged to new surface potential; sheet peeled from ground plane.

**Test 6**: Insulator pre-charged to $+10$ kV; charge removed by brush; sheet recharged to new surface potential; sheet peeled from ground plane.

For these additional tests, the insulator was first charged to a surface voltage of about $\pm 10$ kV to force the sheet and the ground plane into intimate electrostatic contact, thereby ensuring contact electrification. The top surface was then discharged to zero surface potential by the brush. Subsequently, the sheet was recharged to a surface voltage of the same polarity as the initial $\pm 10$ kV charge, but at a new nominal value of $\pm 4$ kV, 7 kV, or 11 kV. In some trials, the second recharge was omitted, i.e., a “recharge” value of 0 kV. The sheet was then peeled, and the post-peel charge measured as before.

The results of Tests 5 and 6 are shown in Fig. 2. The horizontal and vertical axes indicate, respectively, the recharged insulator surface voltage $V_P$ just prior to peel, and the net, post-peel insulator charge density $\sigma_{PP}$ just after peeling. This net sheet charge was found by integrating the total plate-to-ground charge flow, assuming the insulator charge to be equal, opposite, and uniformly distributed, and dividing the result by the effective charge area. For $V_P$ magnitudes in excess of about 4 kV, $\sigma_{PP}$ saturates at about 2 nC/cm² at the same polarity as $V_P$. For $V_P = 0$ (i.e., no insulator recharging), $\sigma_{PP}$ attains the same saturating value, but of opposite polarity. The polarity transitions appear to occur at a $V_P$ of about $\pm 3$ kV. This general trend is shown by the dotted line for both polarities of surface charge.

### 3.1 Explanation of Results

These puzzling and counterintuitive, yet consistent, results can be explained by carefully considering the physics at the peeling point. For the purpose of discussion, we examine the case of positive deposited surface charge without loss of generality. In the geometry of Fig. 3, a positive charge density $\rho_S$ on the top insulator surface, together with its negative ground-plane image, produce a downward-pointing electric field of magnitude $E_{surface} = \rho_S/\varepsilon_0$. Just to the right of the triple-point junction, an air gap of height $h$ emerges, as in Fig. 3. Straightforward application of Gauss’ law shows the electric field in this air gap to be $E_{gap} \approx \rho_S/\varepsilon_0$, where $\varepsilon_0$ is the permittivity of air. Note that $E_{gap}$ is independent of gap height $h$, but will always be larger than $E_{surface}$ because $\varepsilon_0 < \varepsilon_1$.  

[3]
Next consider some fixed position A on the sheet. As the sheet is peeled, point A will break away from the ground plane, and the gap height h at A will grow as the peel continues. The breakdown field for the air gap, described by Paschen’s curve [3], will be large at first, but as h increases, it will eventually fall to the critical field value $E_c \approx 3 \times 10^6$ V/m at some critical gap length $h_c$ on the order of 50 $\mu$m [14]. (This value applies at standard temperature and pressure). If the deposited $\rho_S$ is of sufficient magnitude that $E_{gap}$ would otherwise exceed $E_c$ across $h_c$, local breakdown will occur, thereby bridging the gap with conducting pathways between the bottom surface of the insulator and the ground plane. Each local discharge will carry negative charge from the conductor to the bottom surface of the insulator, as in Fig. 3. As the negative charge is transferred, the net charge densities on either side of the gap will decrease, in turn reducing $E_{gap}$ to a quenching value just below $E_c$. The net charge density residing on both sides of the sheet will then fall just below that needed to sustain $E_c$ at the peeling point. This value will be equal in magnitude to the well-known charge limit of 2.7 nC/cm$^2$ equivalent to a gap field of $3 \times 10^6$ V/m, above which breakdown occurs in gaps longer than about 50 $\mu$m [16, 17]. Notably, the saturation values in Fig. 2 are approximately equal in magnitude to this limiting value.

Note that values of surface charge density much greater than 2.7 nC/cm$^2$ are needed to raise the potential of the insulator surface to the 10-kV level prior to peeling. The exact value of charge density required to reach 10 kV will, of course, depend on the insulator thickness. After the peeling event and the subsequent discharges that occur near the triple point, however, the net charge density on the sheet will be precisely the amount needed to hold the electric field in the air gap to just below the critical value of $3 \times 10^{-6}$ V/m. Because the net insulator charge determines the gap field, it is possible that the unipolar charge densities on opposite sides of the sheet may greatly exceed the 2.7 nC/cm$^2$ net critical value.
3.2 The Role of Intimate Electrostatic Contact

When charge is deposited by corona on the top surface of the insulator, it forces the sheet and conductor into intimate electrostatic contact, resulting in field-enhanced contact electrification. Previous studies have shown that when an electric field permeates a contact boundary, the magnitude and polarity of the field will alter the purely work-function related mechanism responsible for the transfer of charge between the surfaces [1, 4, 18, 19]. In our case, at a surface voltage of \( \pm 10 \) kV, the electric field caused by \( \rho_S \) is presumably so large that it dominates over the work function in the contact electrification process. If \( \rho_S \) is positive, as in Fig. 4, the downward-pointing, interfacial field will thus pull electrons up from the conductor into states on the insulator’s bottom surface, producing a negative contact charge \( \rho_C \) on the insulator. Conversely, if \( \rho_S \) is negative, the upward-pointing interfacial field will drive electrons from insulator surface states into the conductor, resulting in positive \( \rho_C \) on the bottom insulator surface.

Any \( \rho_C \) charge acquired in this way will induce its own image charge on the conductor, and the latter will be superimposed on the image charge induced by \( \rho_C \). This concept is illustrated in Fig. 5. The net field at the conductor-insulator interface will be comprised of two components: \( E_{\text{surface}} \) due to \( \rho_S \) and \( E_{\text{contact}} \) due to \( \rho_C \). For positive deposited \( \rho_S \), \( E_{\text{surface}} \) will point downward toward the conductor. The acquired \( \rho_C \) will therefore be negative, and \( E_{\text{contact}} \) across the conductor-insulator boundary will point upward away from the conductor. The converse will be true for negative \( \rho_S \), i.e., \( E_{\text{surface}} \) will point upward, \( \rho_C \) will be positive, and \( E_{\text{contact}} \) will point downward.

When the insulator is swept with a ground brush and recharged, it will acquire a new \( \rho_S \). When the insulator is peeled, as in Fig 3, the gap field \( E_{\text{gap}} \) will be the sum of the two components \( E_{\text{surface}} \) and \( E_{\text{contact}} \). Again focusing on the case of positive recharged \( \rho_S \) in Fig. 5, if \( E_{\text{surface}} > E_{\text{contact}} \), the net gap...
field \(E_{\text{gap}}\) will be directed downward. Conversely, if \(E_{\text{surface}} < E_{\text{contacts}}\) the net gap field \(E_{\text{gap}}\) will be directed upward. As noted previously, the magnitude of \(E_{\text{gap}}\) just to the right of the triple point in Fig. 3 cannot exceed \(E_c = 3 \times 10^6 \text{ V/m}\). If the net of \(E_{\text{surface}}\) and \(E_{\text{contact}}\) tries to exceed this value, discharges will occur during peeling, and charges will flow to limit the gap field to \(E_c\). The net charge density remaining on the insulator thus will be clamped to just that value required to produce \(E_c\). Of importance, however, is that the polarity of the gap field – i.e., the polarity of the net residual insulator charge – will be determined by whichever of \(E_{\text{surface}}\) or \(E_{\text{contact}}\) is larger prior to peeling. If the net \(E_{\text{gap}}\) points downward in Fig. 3, for example, then when discharges occur, negative charge will flow toward the insulator’s bottom surface as a result of peeling. Conversely, if the net \(E_{\text{gap}}\) points upward, then discharges will cause negative charge to flow away from the insulator bottom during peeling.

This theory appears to explain the plotted data of Fig. 2. Focusing once again on the case of positive charge, the force of the initial 10-kV surface voltage is assumed to establish “intimate electrostatic contact”, thereby producing negative contact charge \(\rho_c\) on the underside of the insulator. In our experiments, \(\rho_s\) is removed and then redeposited at some new value. If the new \(\rho_s\) is larger in magnitude than \(\rho_c\), then the gap field will point downward, and triple-point discharges will bring negative charge up to the insulator’s bottom surface. This flow will continue until the downward-pointing \(E_{\text{gap}}\) falls to \(E_c\). At this point, the net charge on the peeled insulating sheet will still be positive at about 2.7 \(\mu\text{C/cm}^2\), and \(E_{\text{gap}}\) will still point downward. The opposite scenario will occur if the redeposited \(\rho_s\) is positive, but smaller in magnitude than the \(\rho_c\) acquired by contact charging. In this latter case, the gap field will point upward. During peeling, triple-point discharges will force negative charge away from the insulator’s bottom surface until \(E_{\text{gap}}\) falls to \(E_c\). Now, however, \(E_c\) will point upward, and the net charge remaining on the insulator after peeling – just below the 2.7 \(\mu\text{C/cm}^2\) value needed to sustain \(E_c\) – will be negative. The net insulator charge density will vary from a negative to a positive saturating value as the pre-peel, top surface charge density is increased. Assuming a uniformly charged sheet, it follows that for some value of redeposited \(\rho_s\), the charges \(\rho_c\) and \(\rho_s\) will precisely balance, resulting in a charge-neutral peeled sheet. For the Mylar sheet tested, this transitional value appears to occur at around ±4 kV, as shown in Fig. 2.

4. Conclusion

We have examined the case of a charged, insulating sheet peeled from a conductor under various test conditions. Microscopic discharges at the triple point between conductor, insulator, and air occur until the gap field is reduced to the \(3 \times 10^6 \text{ V/m}\) critical breakdown strength of air. The balance of pre-peel charge acquired by contact electrification and surface deposition determines whether the insulator’s net, post-peel charge is positive or negative. For some value of deposited charge, the triple-point field will fall below the critical breakdown field, so that no peel-related discharges occur, leading to a charge neutral peeled sheet.

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