THE EFFECTS OF MATERIAL AT ARC SITE ON ESD PROPAGATION

Jason A. Young(1) and Mark W. Crofton(2)

(1)The Aerospace Corporation, 2310 E. El Segundo Blvd, El Segundo, CA 90503, USA, Email:Jason.A.Young@aero.org
(2) Email:Mark.W.Crofton@aero.org

ABSTRACT

In the past few years, the Aerospace Corporation and other labs have been exploring how an electrostatic discharges propagate over the surface of a positively charged dielectric surfaces, like solar arrays, on a spacecraft. One goal of these explorations is ultimately to aid in the extrapolation of transient currents measured on coupons in the laboratory to currents expected on full-scale spacecraft assemblies. In the popular plasma bubble model, the ESD plasma is expected to expand radially from a single arc initiation point at the ion sound velocity, which depends on the composition of conductor at that initiation point. In this study, we examine how changing the conductor material at the arc initiation site affects propagation on a positively charged Kapton surface. By measuring current flowing into a series of concentric electrodes beneath this Kapton surface, we can monitor surface neutralization as a function of time and radial distance from the arc site. Results will be presented for a selection of cathode materials, and implications for existing and future models will be discussed.

1. INTRODUCTION

It has been established that certain on-orbit conditions can result in positive charging of dielectric surfaces on a spacecraft relative to the conductive spacecraft body (see e.g. [1]). If the differential potentials are sufficiently large, this so-called inverted gradient (IG) charging condition can lead to a spontaneous discharge at a conductor-dielectric interface. This in turn leads to a “blowoff” of excess charge on the spacecraft structure and an outward propagating flashover that rapidly removes surface charge from the dielectric. This process is particularly concerning if the stored charge is on solar array coverglasses and the arc originates from a solar cell.

The rate at which surface charge is removed from the dielectric (e.g. coverglass) determines the magnitude of return currents flowing into the substrate electrodes (e.g. solar array strings). Furthermore, the sum of all these currents and the blowoff all flow into the arc initiation point. Hence, it is desirable to understand exactly how rapidly the flashover progresses over the surface as this determines the magnitude, shape and duration of the on-orbit current transients. These characteristics are needed to properly test the resiliency of the electronics (e.g. solar cells) [1]. They also inform the design of “flashover simulators,” which are designed to deliver a worst-case flashover current to trigger a secondary discharge [1,2].

There have been numerous past studies that tried to measure the “propagation velocity” of the inverted gradient flashover, with seemingly inconsistent results (e.g. [3-9]). Part of the issue with these tests as that they assume an idealized brushfire or perimeter model [10-12]. In this model, one assumes the flashover can be described by a uniformly expanding circular perimeter in which all of the surface charge within the perimeter is immediately removed or “neutralized” and flows into the arc initiation point. The problem with this assumption is that the neutralization does not occur within a narrow perimeter but is distributed over a broad radial span [9,6,7,13-16,18]. Hence, one can derive different velocity benchmarks depending on how one performs the analysis.

In order to provide clarity to this issue, we developed a custom test article for measuring flashover consisting of concentric electrodes covered in a uniform insulator (Kapton) [13-16]. A single region of exposed metal at this origin acts as an arc initiation point. By monitoring the current on these electrodes, one could construct a complete distribution of flashover neutralization current as a function of radius and time. In [15], it was shown that the neutralization wave front could be described by an effective velocity distribution.

In a follow-up study, the custom annular electrode test article was reworked to accommodate different cathode materials at the arc point [16]. The idea here was to test a hypothesis that trailing edge of the flashover should propagate at the ion sound velocity $v=\sqrt{(kT_e/m)}$ where T_e is the electron temperature and m is the atomic mass of the metal surface at the arc centre (i.e. the cathode) [17]. Three different cathode materials were used: Carbon, Aluminium, and Titanium. The longest duration discharges came from carbon, suggesting it had the slowest propagation in spite of having the smallest atomic mass. This contradicted the above hypothesis. However, there were confounding factors in this study: the surface finishes of each of the samples were vastly different.

In this paper, we examine more rigorously the effect of surface finish on flashover discharge characteristics. Samples were fabricated in which both composition and surface finish were varied in a controlled manner. In order to maximize atomic mass variation, Aluminium (27 amu) and Tantalum (181 amu) were used. In this way, we were able to separate the influence of each of these factors. As will be shown, cathode surface finish turns out to be just as important, if not more important, than cathode composition in determining propagation and discharge lifetime. We also examine the effect of varying capacitance (4nF and 100nF) and facility pressure on flashover characteristics.

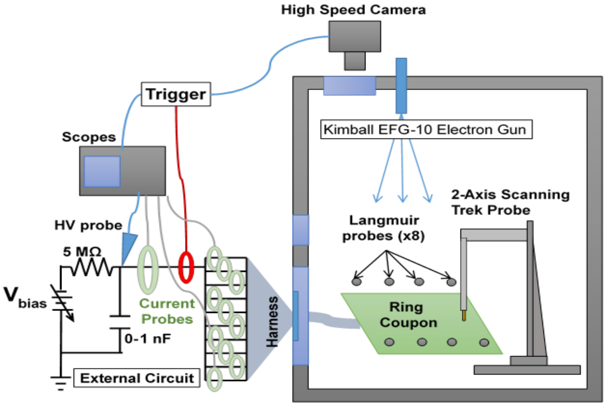

Figure 1: Apparatus for IG ESD testing

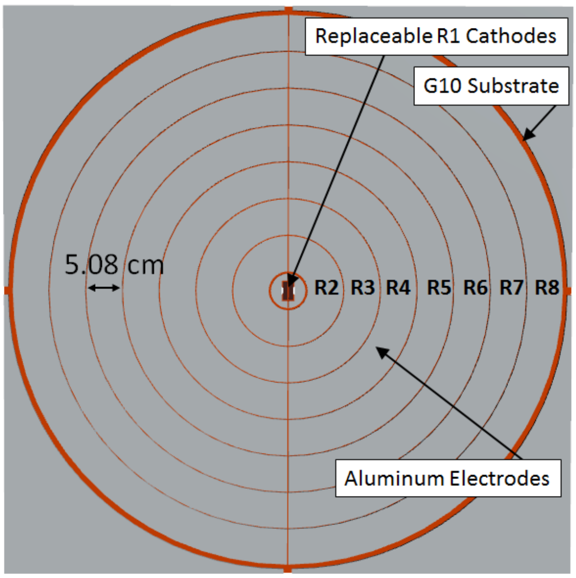

Figure 2: Diagram of Annular electrode test article

2. EXPERIMENT

The detailed methodology for performing radially and temporally resolved measurements of inverted gradient surface charge neutralization are discussed elsewhere (e.g. [13-16]) so only a brief summary will be provided here. Fig. 1 shows a schematic of the overall layout for inverted gradient measurements. The test article is biased to -4.75kV and exposed to a 5keV electron beam for ~8 hours at 2-5nA/cm2 (flux was increased over the length of the test to offset the declining arc rate). Transient current going into the 4nF structure capacitor was used to trigger capture on multiple Tektronix current probes monitoring segmented electrodes on the test article.

Similar to our most recent study [16], we used a custom annular electrode substrate coupon covered in 126 µm of nearly-seamless polyimide (Kapton) insulation (and 38µm of silicone adhesive). A schematic of this test article is given in Fig. 2. Return current on each electrode or pair of electrodes with like radius was recorded over the duration of the flashover, providing a radially and temporally resolved measurement of neutralization current density during the ESD flashover.

The central split electrodes, designated R1, each included a cathode sample, which was exposed on its inside face and top edge. The top of the sample was covered in a fresh layer of Kapton tape for each test to create the desired triple junction arcing point. For this test campaign, only two cathode materials were used, Aluminium and Tantalum. These were initially chosen due to the large difference in atomic masses: 27 amu and 181 amu respectively (as well as cost and machinability).

For each material, we generated samples with two different surface finishes. The first was a bead blasted finish (BB), produced by bombarding the surface with glass beads. The second was a so-called 250P mill finish, produced running a mill bit across the edge at a specific rotation speed and linear feed speed. In each case, care was taken to ensure the manufacturing methodology was repeatable. In this way, the sample surface finish was controlled so that the contributions to discharge behaviour from composition and surface finish could be separated.

Fig. 3 shows profilometry scans of Aluminium for the two different surface finishes, '250P' and 'BB'. The mill finish has the highest amplitude variation in height but the variation is slow and sinusoidal. In contrast, the 'BB' produces a highly random profile with much sharper changes in height compared to 250P.

This study also explores the effect of capacitance and ambient pressure on discharge characteristics. For the capacitance case, the external capacitance was increased to 100nF and a fresh sample was used with the same characteristics as a sample used for the nominal 4nF tests. For the pressure test, the chamber was backfilled with room air to the desired pressure and another fresh sample was used.

3. RESULTS

In this study we consider only discharges where R1 electrode acts as the cathodic source of the flashover. In a typical discharge, the radial distribution of neutralization current measured on the electrodes is observed to disperse outward sequentially from the innermost electrode (R2) to the outmost electrodes (R8). As radius increases, the duration of neutralization current flow increases, thus preventing the linear increase in peak current predicted by the brushfire model.

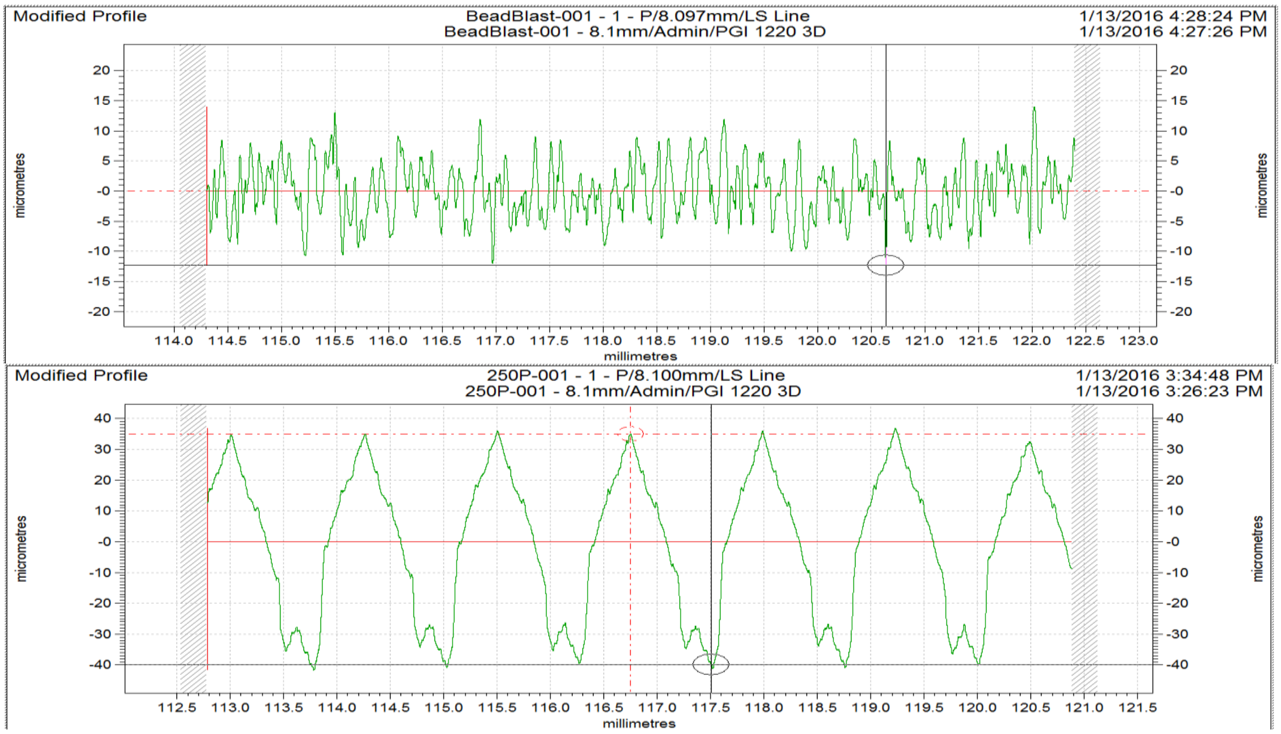

Figure 3: Surface profiles of bead-blast (top) and 250P mill (bottom) finishes on Aluminium

One simple way to compare different discharges is to examine their R1 discharge current waveforms. Fig. 4 shows the R1 discharge waveforms for Al with 250P mill finish, Al with bead blast (BB) finish, Ta with 250P mill finish and Ta with BB finish. The surface finish appears to be the strongest factor determining discharge duration and shape. The BB discharges were 50-65% longer than the corresponding 250P discharges. In contrast, The Ta discharges were on average only 10-20% longer than the corresponding Al discharges. The 250P samples also had more variable discharge durations than the BB samples.

By dividing the maximum radius of the coupon by the maximum duration of the R1 discharge, one can derive a minimum velocity which will be designated as the *effective* brushfire velocity V_{BF}. For an idealized plasma bubble model, the discharge ends when the bubble reaches the outmost radius and hence runs out of charge. Hence, this could also be considered an effective plasma bubble velocity. The values for the above samples are tabulated in Table 1. As expected, surface finish had the strongest influence on this effective velocity. Of course, this benchmark does not take into account the broadness of the neutralization front. In fact, the R1 waveforms suggest that the neutralization was randomly extinguished early for the 250P finish samples.

Table 1: Effective Brushfire Velocities V_{BF}

V_{BF}	**Al**	**Ta**
250P	6.1-11.5 km/s	5.1-12.3 km/s
Bead Blast	4.5-6.4 km/s	3.8-5.3 km/s

Table 2: Peak Current Velocities

	Al				**Ta**			
250P	16.8	+/-	5.6	km/s	10.9	+/-	3.2	km/s
BB	13.0	+/-	4.5	km/s	8.8	+/-	2.0	km/s

As discussed in [9,13,14], a more rigorous way to determine propagation velocities is by plotting for each discharge the time that a given milestone, like peak current, is achieved at each annular electrode vs. the mean radius of that electrode. This is shown for the case of peak current in Fig. 5. The inverse slopes of these curves, which appear fairly linear, gives a velocity. Table 2 summarizes the average fitted slopes of each sample using peak current on the electrodes as the time parameter. The velocities are larger than V_{BF}, since they correspond to features earlier in the discharge, but the qualitative trends are the same. In this case, material type seems to have a slightly stronger impact than surface finish, with Al having the higher velocities.

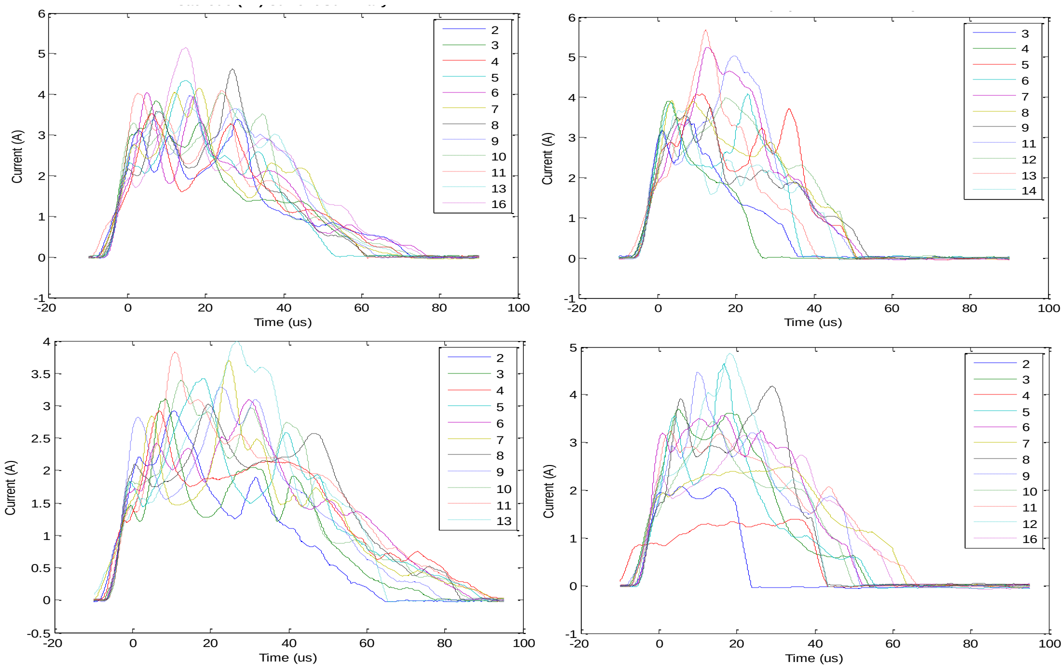

Figure 4: Discharge (R1) waveforms for multiple flashover events on Al-BB (top left), Al-250P (top right),Ta-BB (bottom-left), and Ta-250P (bottom-right)

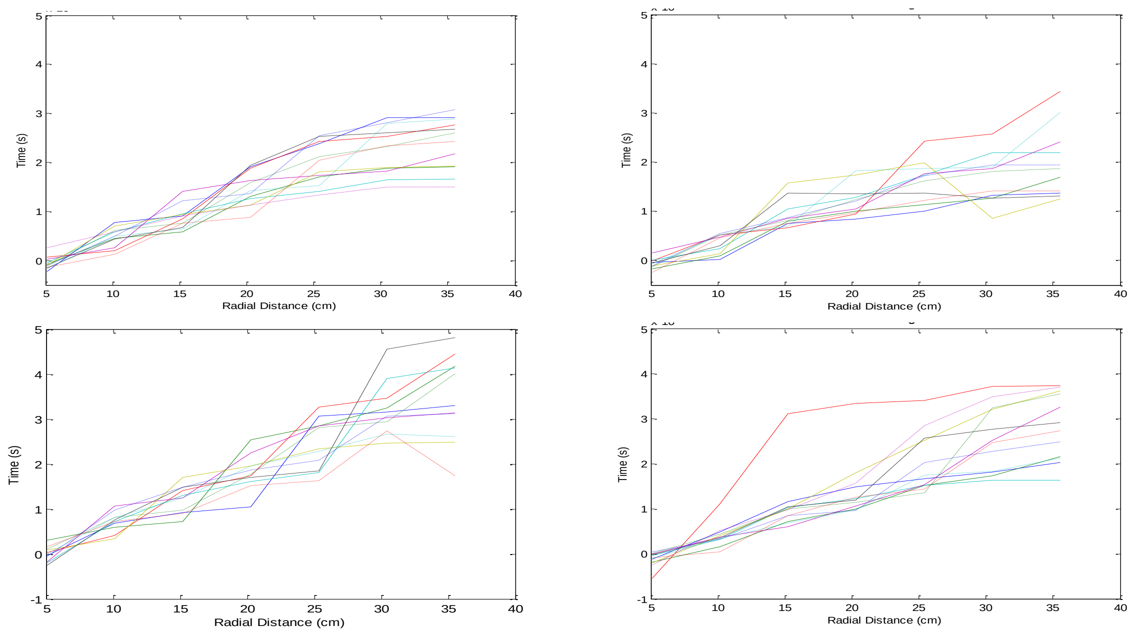

Figure 5: Peak current time vs. electrode radius for multiple flashover events on Al-BB (top left), Al-250P (top right),Ta-BB (bottom-left), and Ta-250P (bottom-right)

Another milestone in the electrode neutralization current waveform is the time when 50% of the final integrated charge is removed. This is essentially marks the time when the neutralization at that radius is halfway done. Velocities using this as a time parameter are given in Table 3. As discussed in [9,13,14], using integrated charge tends to reduce variability in the results. The overall velocities are lower than for peak current, indicating the peak neutralization occurs early in the discharge. The variation between samples is also much smaller but the overall trend is similar to that of peak current.

All of the results thus far have used an external capacitance of 4nF. This produces a modest blowoff current that brings the substrate to ground potential early in the discharge. Adding more capacitance increases both the magnitude and duration of the blowoff. Historically, additional capacitance has been

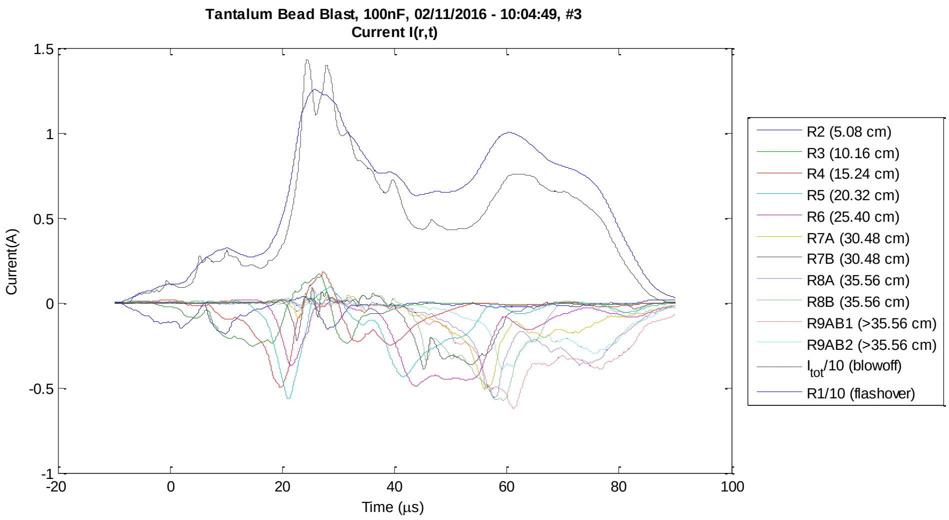

Figure 6: Typoical discharge for bead-blasted Tantalum with 100nF external capcitance

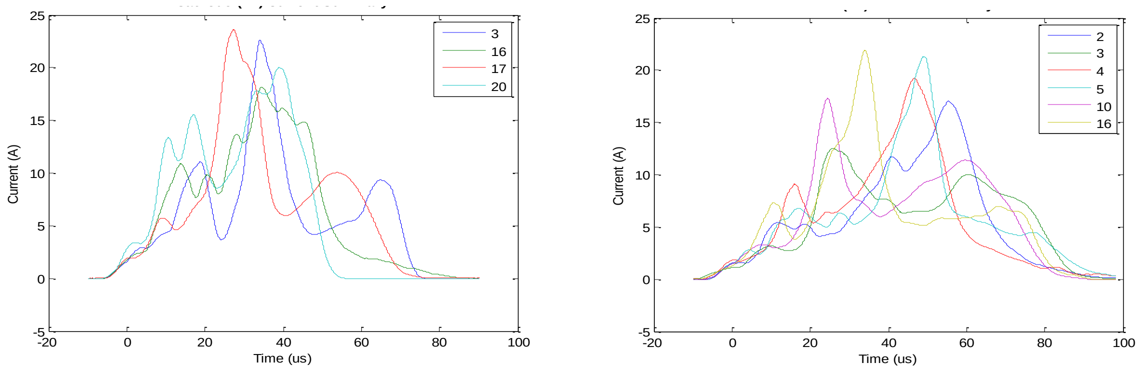

Figure 7: Discharge (R1) waveforms with 100nF external capacitance for multiple flashover events on Al-BB (left), and Ta-BB (right)

used to enhance the brightness of the discharge initiation point so one might presume that it might also increase the plasma density. Fig. 6 shows an example discharge from a bead blasted Tantalum sample with 100nF external capacitance. Of note, the R1 signal is dominated by the blowoff contribution, which remains strong throughout the discharge. Overall, the discharge progression on electrodes R2-R8 seems more highly structured than a typical discharge with low capacitance. Of note, there appears to be at least two distinct flashovers emanating from the origin, one starting at the beginning of the discharge and another at around t=25us. There is sharp disruption on all channels at this point, corresponding to peak blowoff.

Fig. 7 shows 100nF R1 discharge waveforms bead-blasted Al and Ta respectively. While the shapes and amplitudes are different, the durations are more or less the same as those for 4nF external capacitance. Because of the complicated structure of these discharges, calculating propagation in a manner similar to Tables 2 or 3 is beyond the scope of this paper.

Since some ESD tests occur in chambers with higher base pressure, we examined the effect of back-filling the chamber with air using a pristine bead-blasted Aluminium sample. Specifically, the chamber pressure was raised from 3e-8 torr to 7e-6 torr. While only 5 R1 discharges were collected, the R1 discharge durations appeared in family with those at low pressure. Furthermore, as shown in Table 4, the derived velocities were statistically identical to those at low pressure.

Table 3: 50% Charge Neutralization Velocities

	Al				Ta			
250P	12.6	+/-	2.3	km/s	10.5	+/-	1.7	km/s
BB	10.4	+/-	1.3	km/s	8.1	+/-	0.7	km/s

Table 4: Pressure dependence of derived velocities for bead-blasted Aluminium

	Peak current				50% charge			
3e-8 torr	13.0	+/-	4.5	km/s	10.4	+/-	1.3	km/s
7e-6 torr	13.6	+/-	5.7	km/s	10.2	+/-	1.0	km/s

4. CONCLUSIONS

It is clear from this study that one must carefully control for surface finish, among other characteristics, to properly elucidate trends in discharge evolution. The importance of surface topology has been known for decades in the general field of high voltage vacuum discharges but to our knowledge, has not been well quantified for inverted gradient ESD flashovers until now.

Overall, these results suggest that surface finish strongly affects the overall shape of the cathode discharge. Certain finishes, like bead-blasted finish, are more conducive to longer discharges whereas finishes like 250P mill-finish are more likely to result in random early extinction of the discharge. Propagation of the peak current density is more rapid for 250P samples vs bead blast samples. The same trend is observed for the "50% charge" velocity although the effect is more muted. At all radii, peak neutralization current occurs earlier in the discharge than 50% surface charge removal. Hence, the return current waveforms tend to have a long tail extending to the end of the discharge.

The variation in discharge duration associated with changing the composition of the cathode is slightly less than that due to surface finish. Across all benchmarks, derived velocities are generally larger for Al than Ta samples. For instance, the peak current propagation velocities are 30-55% larger for Al vs Ta. For comparison, the atomic mass ratio is 1/6.7. Hence, if flashover neutralization were dictated by a plasma expanding at the ion sound velocity $v_B=\sqrt{(kT_e/m)}$, the Aluminium cathode velocities should be 2.6 times larger than the Tantalum velocities (assuming similar electron temperatures). The effect we see is far more modest, suggesting different physics is involved.

In [16], a carbon sample produced even longer discharges than the bead blasted tantalum sample in this study, opposite to the prediction based on ion sound velocity. We now know that the very rough surface finish of the Carbon sample likely played a role here. If we attribute discharges to emission from sharp surface features at the cathode, it makes sense that the sharp variations in height like those observed in the profilometry of bead-blasted samples, produced longer discharges. It is worth pointing out that even though this study did show some effect on propagation due to composition, after controlling for surface finish, it is not clear how much of that difference is due to atomic mass, versus other characteristics like melting point. The work functions for Aluminium and Tantalum are similar so they can be ruled out as contributing in this particular case but they may contribute in other cases.

The effect of facility pressure seems to be negligible, as long as it is kept below 7e-6 torr for ~1m2 samples (one could argue the effect might be stronger for larger samples due to the longer path lengths traversed by the particles). The effect of external capacitance, on the other hand is less benign. Although the actual discharge durations do not change, the evolution of the discharge is significantly different. It seems as if when the blowoff peaks, the initial flashover extinguishes then restarts from the central cathode again. Since the substrate still has a net negative potential at this time, it seems plausible that plasma ions from the cathode are drawn back to the surface during this first extinction, partially restoring positive charge for the next flashover. Further research is needed to validate this hypothesis.

The upshot of this research is there appears to be only modest variation in worst-case flashover neutralization current densities with changes in cathode material, even including the effect of surface finish. It remains to be seen if changes in dielectric composition and thickness have similarly modest effects. It should also be pointed out that this study also does not include the effect of exposed conductors on the "anode" electrodes, like would be found on the edges of strings in a flight-like solar array coupon. To some degree this was studied in [19], but further research may be needed.

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