EXPERIMENTAL COMPARISON OF THE ELECTROSTATIC PERFORMANCE OF MATERIALS WITH TRIBOCHARGING AND WITH CORONA CHARGING

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Abstract: Experimental studies are reported comparing measurements of charge decay and capacitance loading for a variety of materials with triboelectric and corona charging. It is shown that comparable results are obtained if note is taken of the influence of the delay of around 100ms between the end of tribocharging actions and observation of the initial peak voltage of the surface. These results confirm the suitability of corona charging as the basis for assessing the suitability of materials to avoid risks and problems from static electricity. They also clarify how observations should be interpreted.

Keywords: charge decay, tribocharging, capacitance loading, materials testing

1. INTRODUCTION

The aim of this paper is to provide experimental justification for the use of corona charging for charge decay and capacitance loading[1] measurements for assessing the suitability of materials to avoid problems from retained static electric charge [1]. Previous studies have indicated comparability between the results of charge decay measurements with corona charging and tribocharging. The comparison has been fairly good with localised scuff charging studies [2,3] and moderate for more difficult studies involving inhabited cleanroom garments [4,5,6]. The precision of measurements has not been as good as desirable and the variety of materials has been limited. The studies reported here have aimed to provide information of better quality and on a wider range of types of materials. The emphasis has been on materials that have fairly fast charge decay times and values of capacitance loading as apply for materials of practical relevance.

The present studies are based on using the scuff charging test method used previously [2,3] and corona charging as used in several earlier studies [7,8,9,10]. The scuff charging method seems a reasonable simulation of practical single shot tribocharging events. The corona charging method of testing has formed the basis of convenient, compact, portable and easy to use instrumentation that is used for assessing materials in a wide variety of industries around the world. It is also included in a formal IEC Standard [11].

2. EXPERIMENTAL METHODS

2.1 Tribocharging

Tribocharging studies have involved, as illustrated in Figure 1, 'scuffing' the centre region of a 300mm diameter (200mm in earlier studies [1,3]) area of sample supported solely by radial stretching. Charging was by impact with an initially charge-neutral Teflon rod. The electric field created at a nearby earthed electrostatic fieldmeter (model JCI 140) was observed before, during and after impact [1,3].

Earthy surfaces are kept well away from the reverse side of the sample and any likely charged surfaces well away from the test area. The Teflon rod was charge neutralised by rotating it near

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[1] *'Capacitance loading'* is the capacitance experienced by charge on the material compared to that for a similar distribution and quantity of charge on a thin layer of a good dielectric - where the capacitance is essentially that of just the spatial distribution of charge and any influence of proximity of nearby earthy surfaces. The 'loading' effect probably arises from coupling of the deposited charge to some structural feature in the material. This might be a relatively conductive layer within the material or a pattern of conductive threads or a high dielectric constant feature. Coupling may link to nearby earthy surfaces or just to a larger effective area of material.

the side of a candle flame (as a source of bipolar air ionisation) with the remaining charge level checked under the fieldmeter until its transient contribution to observations was only a volt or so. The charge transferred to the sample was measured from the counter-charge created by the scuffing action on the Teflon rod by inserting the rod into a Faraday Pail (model JCI 147) positioned nearby.

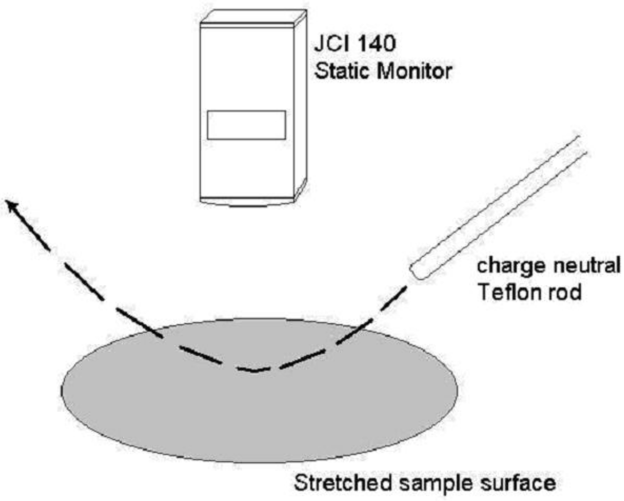

Figure 1: Arrangement for 'scuff charging' studies

The influence of a small initial area of surface charge on a nearby fieldmeter at 100 mm does not depend much on the area of the charge or its precise position. It depends on the capacitance experienced by the charge and the quantity of charge.

Observation of fieldmeter readings during the progress of each individual test were recorded on a digital storage oscilloscope (Picoscope ADC-212 connected to a Notebook computer). Figure 2 shows an example of a fieldmeter signal associated with a scuff charging test displayed using the JCI-Graph software developed for use with charge decay test units. The 'voltages' shown in the graph are fieldmeter response signals. A reading of '1V' corresponds to an electric field of 23V m^{-1} at the sensing aperture of this particular fieldmeter instrument

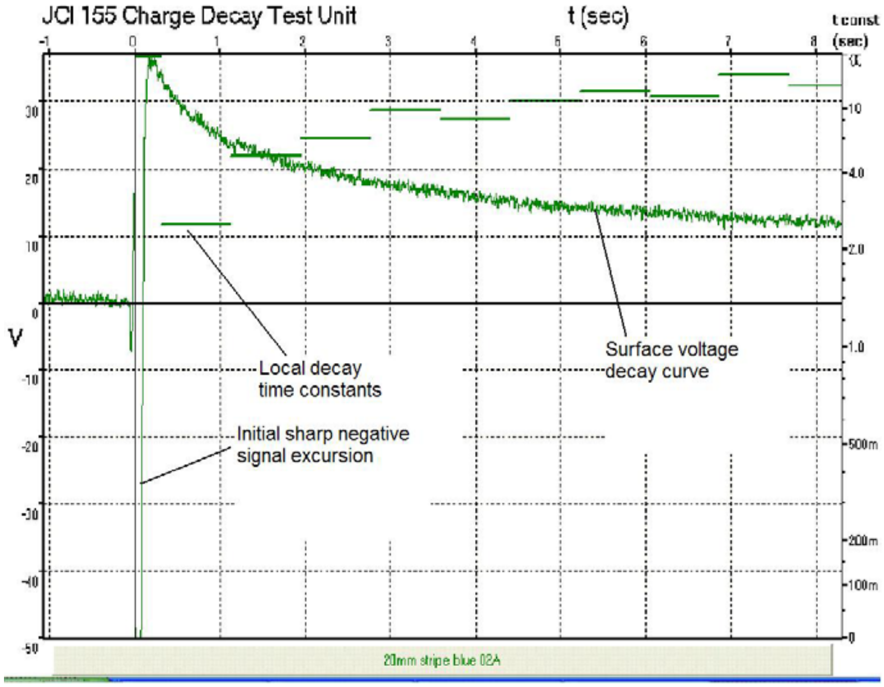

Figure 2: Example of fieldmeter response signal during scuff charging studies

The initial fast negative excursion of the fieldmeter signal arises in the following way: as the initially neutral Teflon rod approaches the test surface there is little influence on fieldmeter readings, during and immediately after scuffing while the rod is still in close proximity to the surface. The separated charges are close coupled and have little influence nearby, so the fieldmeter reading stays at zero. As the Teflon rod rises from the surface the charge on the rod gets nearer to the fieldmeter than the charge left on the surface, so the fieldmeter signal shows mainly the influence of the charge on the Teflon. As the Teflon rod swings quickly away the influence of its charge on the fieldmeter goes to zero and the fieldmeter comes to respond just to the charge left on the surface of the material. The positive peak of the fieldmeter signal shows the maximum influence of the surface charge on the nearby fieldmeter. The subsequent decay of signal shows how the local surface voltage decreases as the separated charge moves away over the surface of the garment fabric.

To get meaningful results it is necessary to observe the following points:

- the dynamic noise level of the fieldmeter needs to be low (typically around 1V p-p) and the zero needs to be checked to be within $\pm$½V
- the operator must be grounded and wear an antistatic coverall
- the fieldmeter response time needs to be adequately fast (e.g. -3dB at 30Hz)
- the fieldmeter signal from any residual charge on the test surface needs to be zero within $\pm$½V
- the charging rod (Teflon or other rubbing rod) must be charge neutralised to give a fieldmeter signal below 10V when just under the fieldmeter sensing aperture
- the charging rod needs to be of high quality insulation and well charge neutralised for a length at least longer than the depth of the Faraday Pail shielding enclosure
- it is appropriate to trigger the recording oscilloscope on the initial negative going part of the fieldmeter signal
- the charging rod needs to make a single clean scuff contact with the test surface directly under the fieldmeter sensing aperture
- the charging rod must be swung well away as quickly as possible so that charge on it can have no influence on fieldmeter readings
- the charging rod should enter the Faraday Pail without contact to any other surface and soon after completion of the scuff charging action

For each instance of striking the recorded observations were analysed to give values for the initial peak surface voltage and the quantity of charge transferred. Many decay curves were not recorded to a 1/e level or had relative noise levels that made such measurements of doubtful value. Presentation of decay graphs with JCI-Graph software enabled more meaningful comparisons in terms of local decay time constants during the progress of charge decays.

The simplest way to obtain values for capacitance loading is to make measurements of the 'apparent capacitance' ($C_{app} = Q / V_{pk}$) exhibited by the test material and divide this by the 'apparent capacitance' exhibited by a thin film of a good dielectric – for example cling film. For fieldmeter readings V_t and V_{ref} for the test material and for the thin dielectric film and corresponding quantities of charge Q_t and Q_{ref} the capacitance loading, CL, is derived as:

$$CL = (Q_t/V_t)/(Q_{ref}/V_{ref})$$

Instead of using the thin dielectric film as above, the fieldmeter reading (as equivalent surface voltage, V – where 1V corresponds to 23V m^{-1}) can be related to the charge on a small isolated surface at the location of the test surface. The fieldmeter reading observed for charge held on an isolated conducting disc (supported by a long small section charge neutral insulating rod) in the plane of the material is 108V per nC. The capacitance loading may then be calculated, from V_t and Q_t measurements as above, as:

$$CL = 108 * \text{charge } Q_t \text{ (nC) / (reading } (V_t))\text{.}$$

2.2 Corona charging

The time for static charge to dissipate over the surface of materials and the capacitance experienced by charge on the surface can be studied very conveniently using a high voltage corona discharge to deposit a localised patch of charge on to the material surface. The basic arrangement of the approach is illustrated in Figure 3. Measurements involve depositing a localised patch of charge onto the surface of the material to be tested, measuring the quantity of charge transferred and using a fast response fieldmeter to measure the initial peak voltage achieved and the time and manner of the decrease of surface voltage as the deposited charge moves away over and into the material [3,14].

To make useful and reliable measurements the apparatus needs to be fairly sophisticated:

- The fieldmeter observing the surface voltage needs to have a fast response (below 10ms) and the ability to measure surface potentials with resolution and stability of a volt or so. These are required to cover measurements of fast charge decays (to below 50ms) and to obtain useful observations on materials with high capacitance loading where only low surface potentials are created.
- The corona voltage supply, of both polarities, needs to be adjustable from near the corona threshold level to perhaps 8-10kV.
- Corona durations need to be short compared to the minimum decay time to be measured (5-20ms is a convenient range).
- The plate carrying the corona discharge points needs to move from fully shielding the fieldmeter to fully open in a time short compared to the minimum charge decay times to be measured (20ms is a sensible target).
- Measurement of the corona charge transferred [1] needs to cover a range from a nanocoulomb up to at least 100nC.
- The characteristics of most materials are significantly affected by temperature and humidity. It is hence important that environmental conditions inside the instrumentation remains similar to the surroundings in which samples have been conditioned. This means that power dissipation within the instrument need to be low.

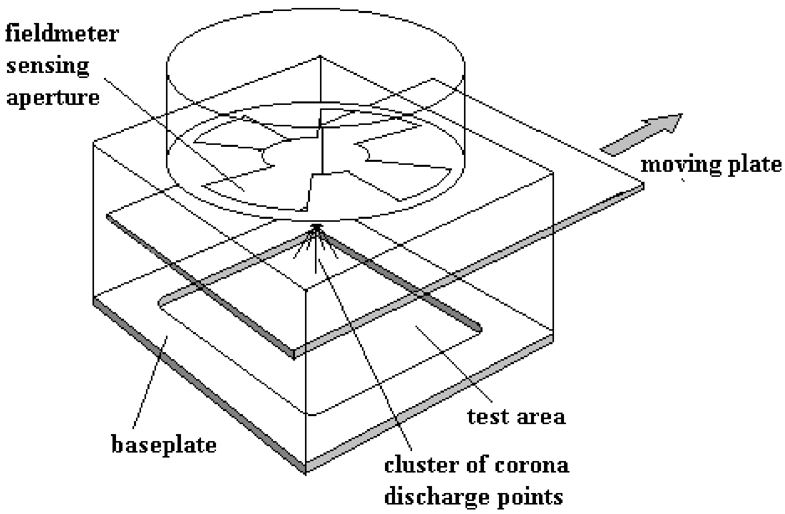

Figure 3: Basic arrangement for corona charge deposition for measurement of charge

decay time and capacitance loading

The reduction of surface voltage after corona charge deposition very rarely follows an exponential charge decay curve. Usually, the rate of decay decreases during the progress of charge decay. Simple comparison between the performances of materials is usually made using the decay time from the initial peak voltage to 1/e (37%) and/or to 10% of this. Examples of corona charge decay curves are shown in Figure 4.

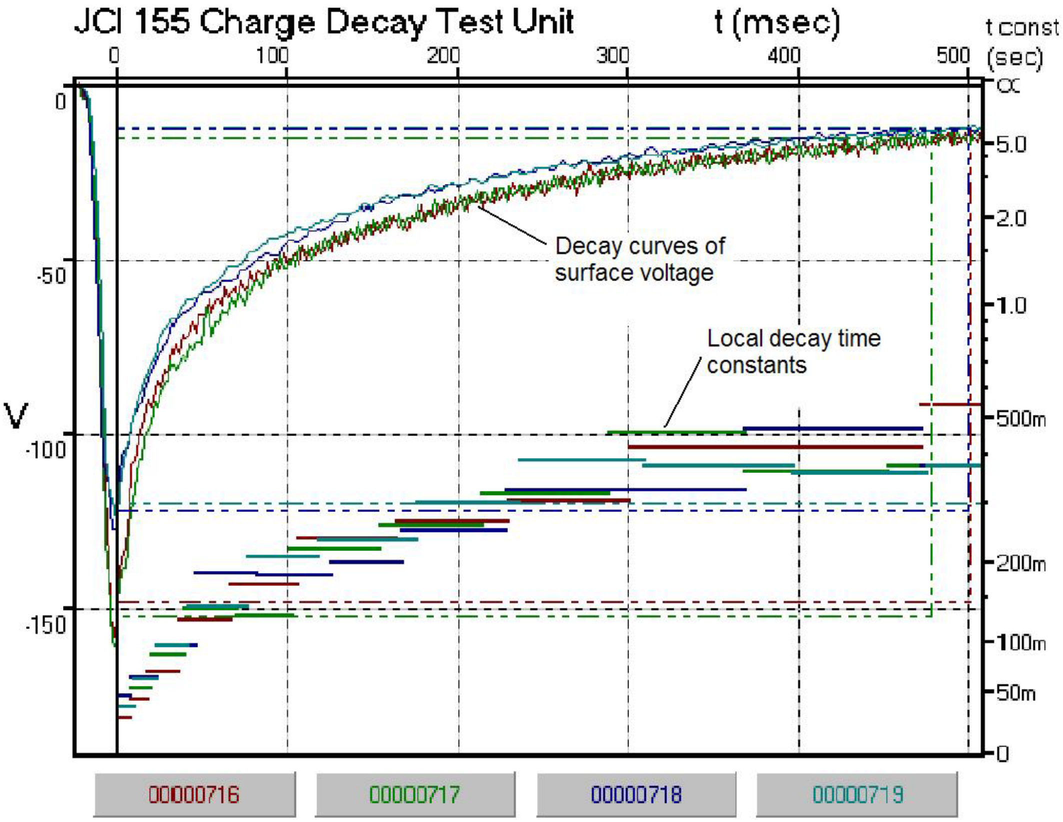

Figure 4: Examples of 4 charge decay curves observed with paper card samples

The surface voltage values in charge decay graphs (e.g. Figure 4) relate to the left hand axis. The short segments of horizontal line relate to the right hand axis and show the values of local charge decay time constants calculated for the corresponding segments of each decay curve. This is a convenient way to appreciate how rates of charge decay vary during the progress of decay and to compare tests with different polarities and different initial peak voltage values.

In making measurements it is important to ensure that the surface voltage before testing is low compared to the expected initial peak voltage. If measurements of decay time are to be made to 10% of the initial peak voltage then it is necessary that the pre-test surface voltage is no more than 2% of the peak voltage expected. With some materials it may be necessary to wait quite a time for any initial charge from even careful handling to dissipate away.

It is always wise to make several tests at each set test condition so the spread of results can be appreciated and values averaged.

Capacitance loading measurements are made basically in the same way as for tribocharging, by comparing the apparent capacitance observed with the test material with that observed with a thin layer of a good dielectric – for example cling film. To make such measurements it is necessary to measure the quantity of corona charge transferred. This is measured as a combination of ‘conduction’ and ‘induction’ charge [1].

Corona charge decay and capacitance loading measurements for the present studies were made using a JCI 155v5 Charge Decay Test Unit in combination with a JCI 176 Charge Measuring Sample Support. Results were analysed and displayed using JCI-Graph software.

It is observed with materials such as cleanroom garment fabrics that capacitance loading values vary linearly with the quantity of corona charge transferred [4,5]. An example is shown in Figure 5. It is thought this variation is due to a progressive focussing of corona charge flow to the vicinity of conductive threads in these fabrics as the surface potential builds up on the areas between the threads but not so much in the vicinity of conductive threads. In studies of capacitance loading it is hence important to make measurements for both polarities over a range of quantities of charge and down to low charge levels – comparable to those arising in tribocharging studies. The quantity of charge transferred is varied by changing the corona voltage level. With materials such as cling film, paper, lingerie fabric and plastic layers capacitance loading values have very little variation with quantity of charge.

For comparisons between tribo and corona charging results it is appropriate to find the intercept of the linear variations with the charge axis to get the value for CL @ q=0. This is sensible as the quantities of charge in tribocharging are usually much less than with corona charging. This was also shown as the best basis for relating the surface voltages experienced on inhabited garments to measurements of capacitance loading made on the garment fabrics with corona charging [4,5].

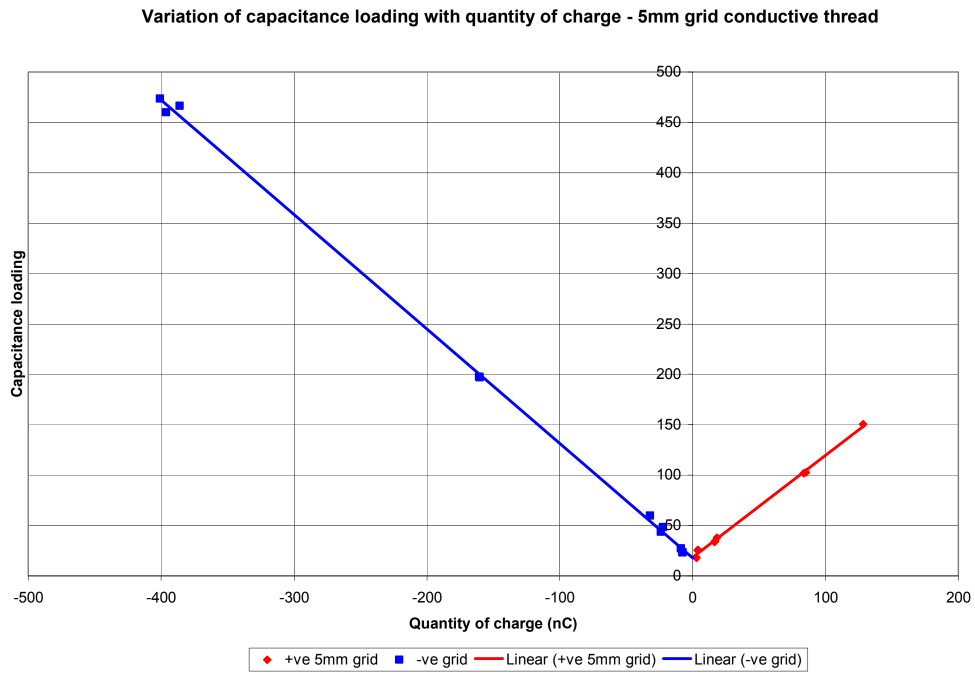

Figure 5: Example of variation of capacitance loading with quantity of corona charge

2.3 Materials and test conditions

Studies have been carried out using a variety of materials. Their features are summarised in Table 1 below. The aim was to examine both a number of rather usual materials (cotton, lingerie fabric) as well as some more specialised fabrics, such as are used in cleanroom garments. Concentration has been on materials with fairly short charge decay times and with high and low capacitance loading values. While these are the more difficult to study the prime concern has been comparison between tribocharging and corona charging results.

Table 1: Materials

Sample	grid/stripe	Conductive thread	Date tested
1	2.5mm grid	Yes	02/01/2004
2	5mm stripe (1)	Yes	04/01/2004
3	5mm grid (1)	Yes	05/01/2004
4	5mm grid (2)	Yes	12/12/2003
5	20mm stripe	Yes – surface conductor	14/12/2003
6	Blue lingerie fabric	No	20/12/2003
7	Cotton handkerchief	No	31/12/2003

Samples 2 and 3 were the same piece of fabric but one area was woven with a 5mm stripe pattern and the other with a 5mm grid pattern of the same conductive thread. Samples 3 and 4 had the same 5mm grid spacing in a polyester based fabric but were from different sources.

The present studies were made in open laboratory ambient conditions. The temperatures were somewhat low (10-15C) and the humidity often fairly high (70-80%RH). While this is important in terms of the absolute values obtained, it does not affect comparison between the two methods of charging. Studies on each material were carried out with the corona charging measurements following directly after the tribocharging studies (within minutes), so the same environmental conditions applied to both.

In all cases suitably low initial surface voltages were achieved by waiting. No air ionisation arrangement was used to promote surface charge neutralisation.

3 COMPARISON OF EXPERIMENTAL RESULTS

The following graphs (Figures 6-12) show comparisons of charge decay curves for each of the materials tested with tribocharging and with corona charging. Figure 6 shows only a single tribocharging result to avoid confusion.

In general 10 measurements were made with tribocharging. Somewhat more measurements were made with corona charging to get a good estimate with both polarities of capacitance loading values extrapolated to zero charge (CL @ q=0).

The time zero of the tribocharging curves is taken as being the edge of the sharp negative going signal associated with the rise of the Teflon charging rod from the test surface. It seems reasonable to consider this as the ‘end of charging’ time. With the corona charging curves the time zero has been set to be the beginning of data recording and this is close to the end of the period of charging (20ms).

The maximum surface voltages created by tribocharging were in many cases very low – only a few volts (for instance Figure 6). In these situations it was clearly not easy to make good quality measurements of peak voltages, for calculating capacitance loading values, or of local charge decay rates.

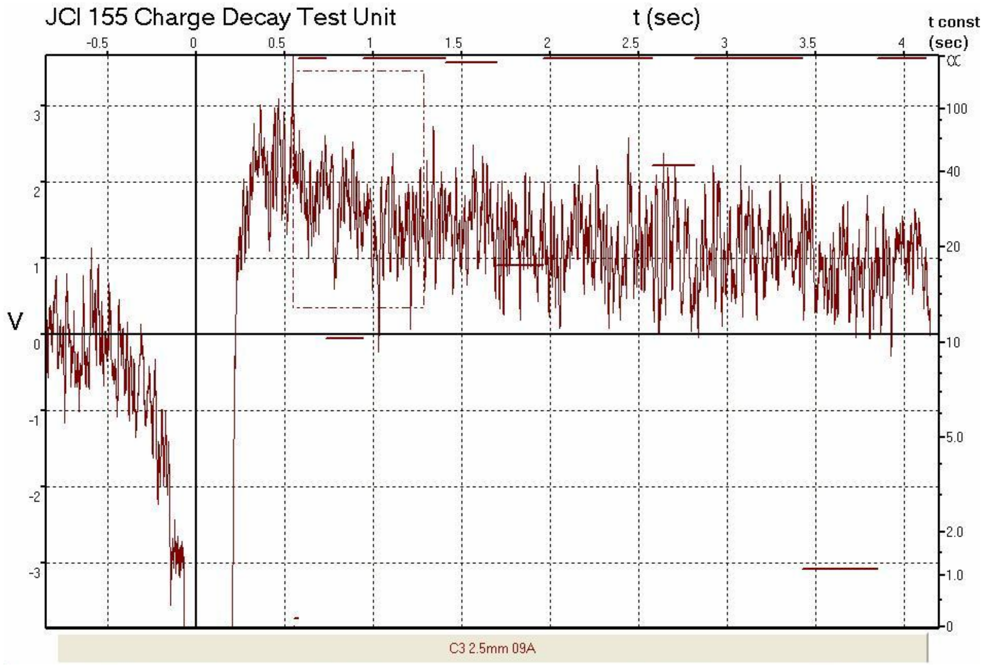

Figure 6: Fieldmeter response at tribocharging cleanroom garment fabric with 2.5mm grid pattern of conductive threads (Sample 1). 1.1nC of charge transfer

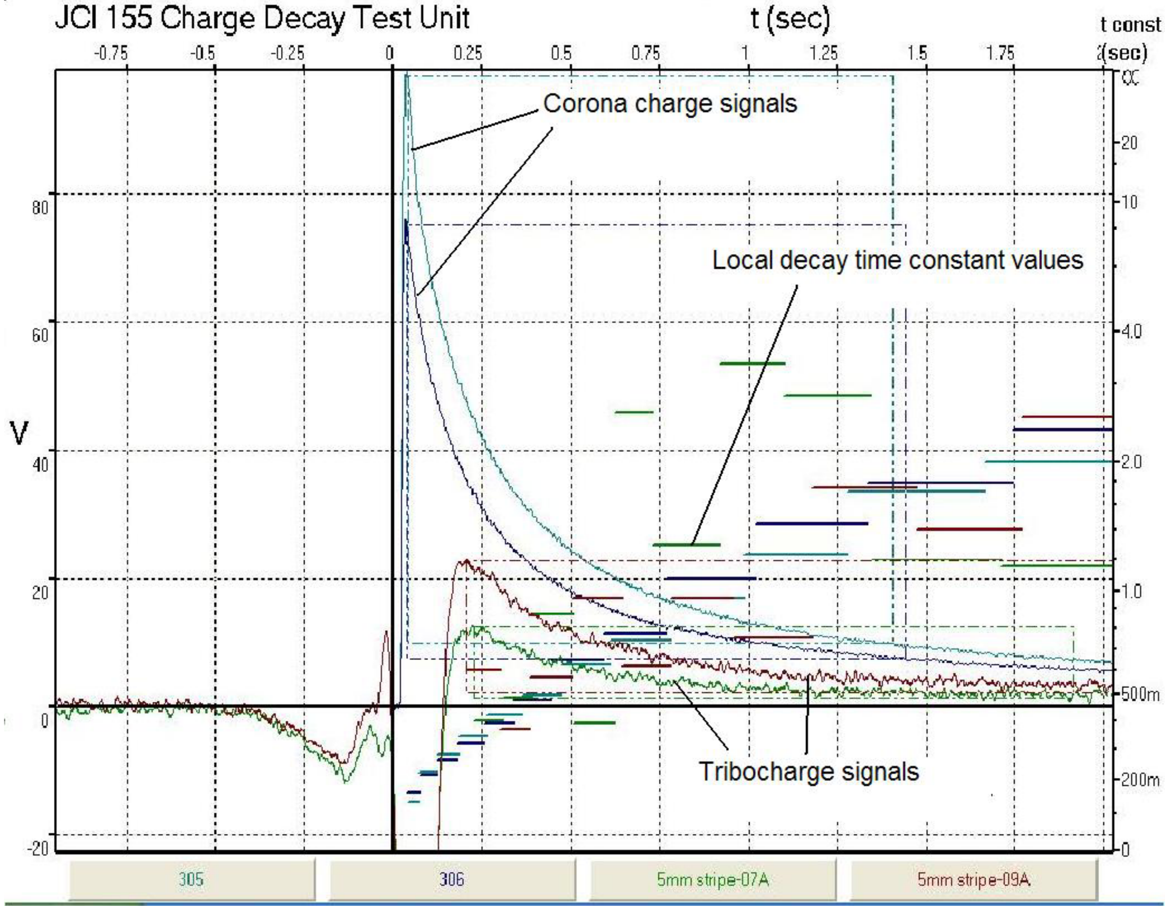

Figure 7: Response to corona and tribo charging of cleanroom garment fabric with 5mm stripe pattern conductive threads (sample 2)

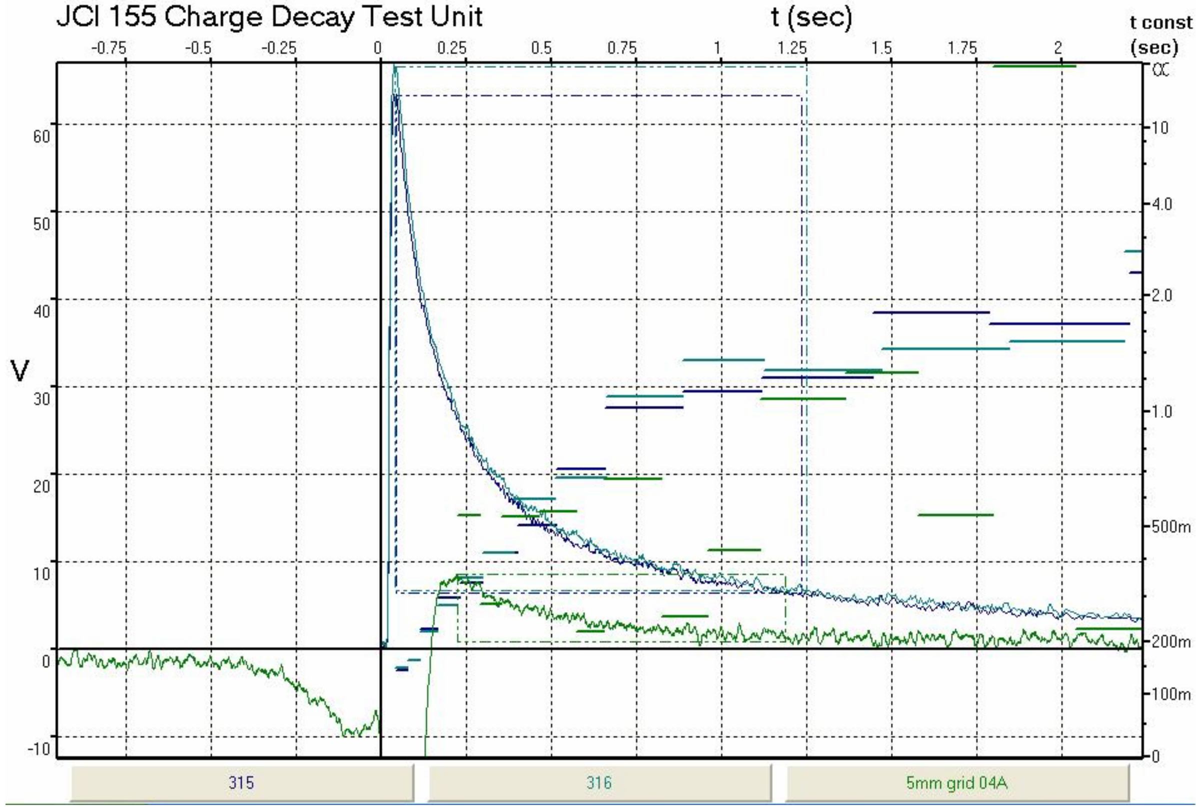

Figure 8: Response to corona and tribo charging of cleanroom garment fabric (as for Figure 7 above) with grid pattern of conductive threads (Sample 3)

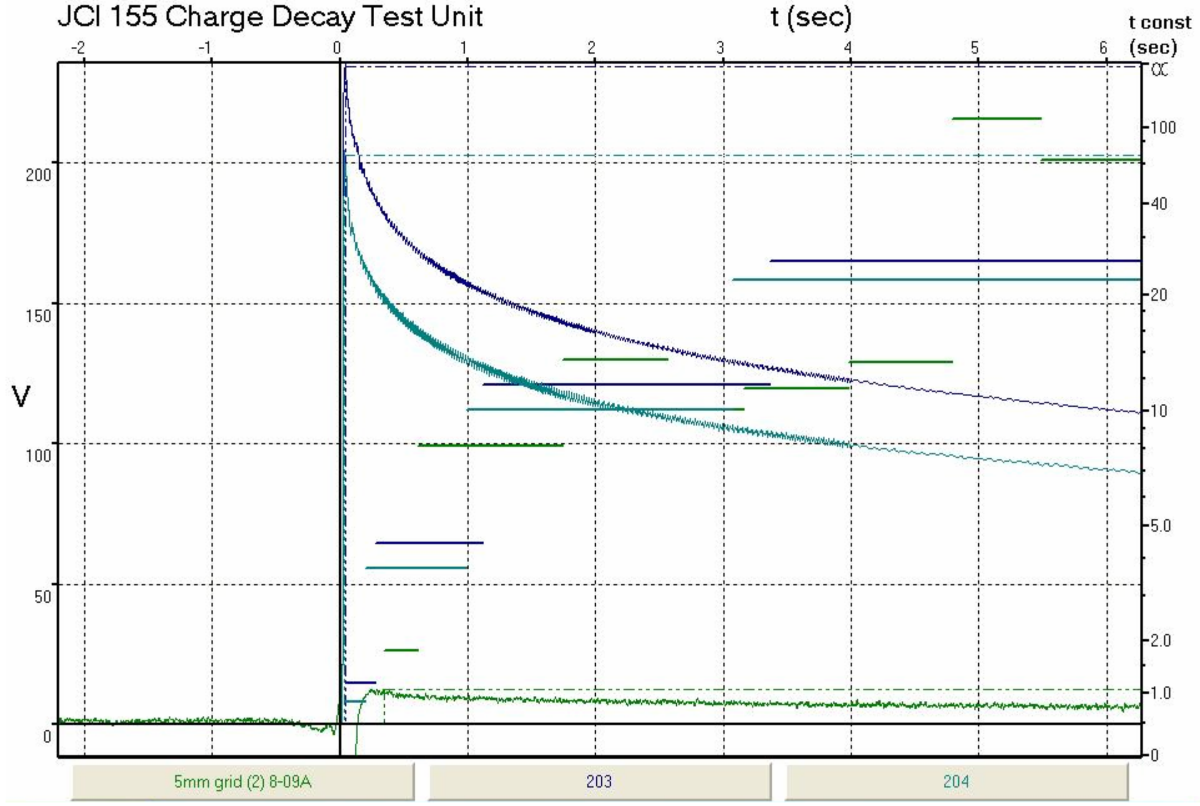

Figure 9: Response to corona and tribo charging of cleanroom garment fabric with 5mm grid pattern conductive threads (Sample 4)

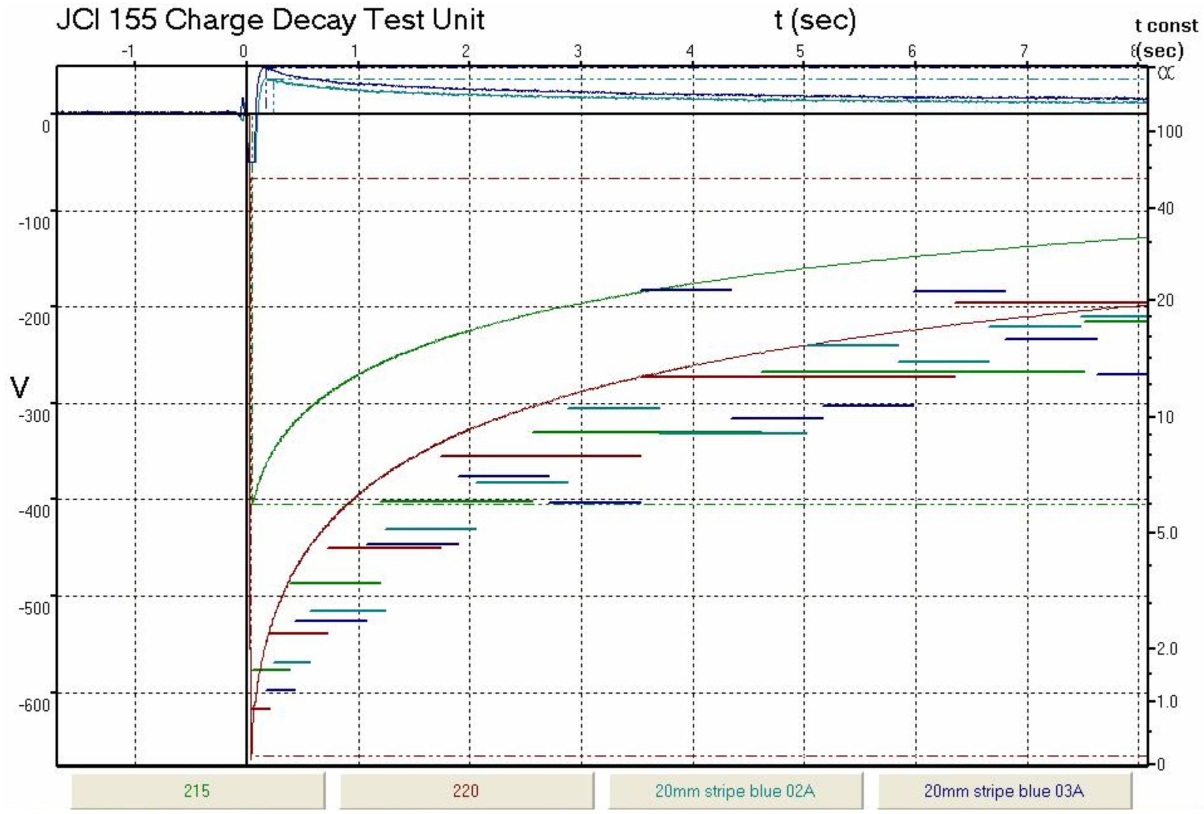

Figure 10: Response to corona and tribo charging of cleanroom garment fabric with 20mm stripe pattern of conductive threads (Sample 5)

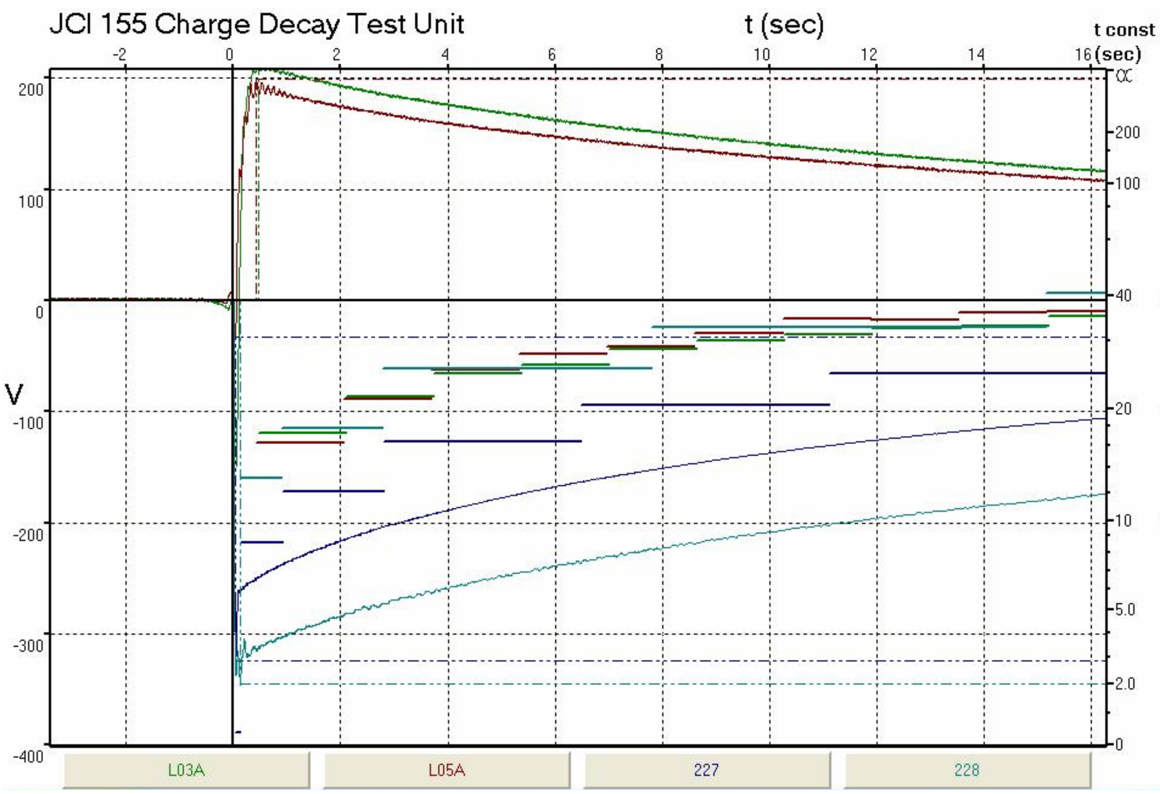

Figure 11: Lingerie fabric after 5 washes (Sample 6). Corona charge decay with JCI 155 supported 3mm above same sample area in scuff charging test rig (test 228) and in JCI 176 (test 227).

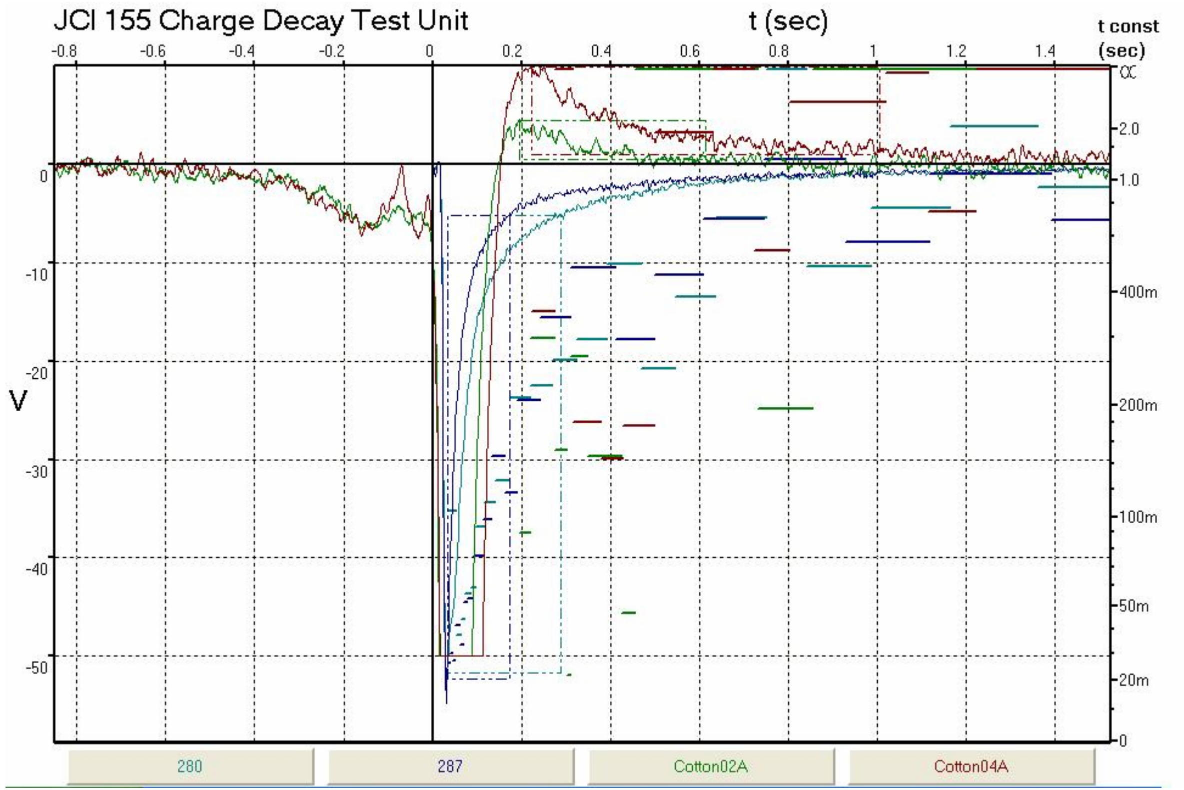

Figure 12: Cotton handkerchief (Sample 7)

The above graphs (Figures 6-12) show there is an appreciable time delay, typically around 200ms, between the end of the charging action with tribocharging and the peak of the fieldmeter signal. With corona charging the delay is about 20ms. Experience from corona charge decay studies indicates that it is during the initial period that the fastest rates of charge decay occur. Fair comparison between tribo and corona charging behaviour hence needs to be based on the rates of charge decay, as local time constant values, at a similar time after the end of charging. The end of the charging action is an appropriate and equivalent time zero. The influence of this delay to the peak fieldmeter signal with tribocharging will have the greatest influence on comparisons for materials with short decay times.

The form of the initial fieldmeter response signal in the scuff charging studies is a combination of the influence of charge on the sample surface and charge on the Teflon rod. It can be expected that the influence of the charge on the Teflon will hide the initial influence from the surface. To examine this some scuff charging studies were done with fieldmeters mounted in equivalent positions above and below the test surface. Studies with cling film and the blue lingerie fabric (sample 6) showed that there was good matching of the surface voltages achieved from topside and reverse side observations. Although reverse side observations are not generally appropriate (because they can be affected by shielding effects in the structure of the layer) they provide fair opportunity to compare the timing of topside and reverse observations. Figure 13 shows an example of observations with sample 2 (5mm stripe pattern of conductive threads). Such observations show that the peak response in topside observations is indeed delayed in comparison to reverse side observations which are much less influenced by charge on the Teflon rod. Hence in timing will better match observations at a time of say 50-100ms after then end of the charging action. This is the minimum practical time for occurrence of the peak of electric field influence on items nearby arising from topside rubbing by an earthed metal or very fast charge decay type rubbing material where there would be little influence on observation by charge retained on the rubbing material.

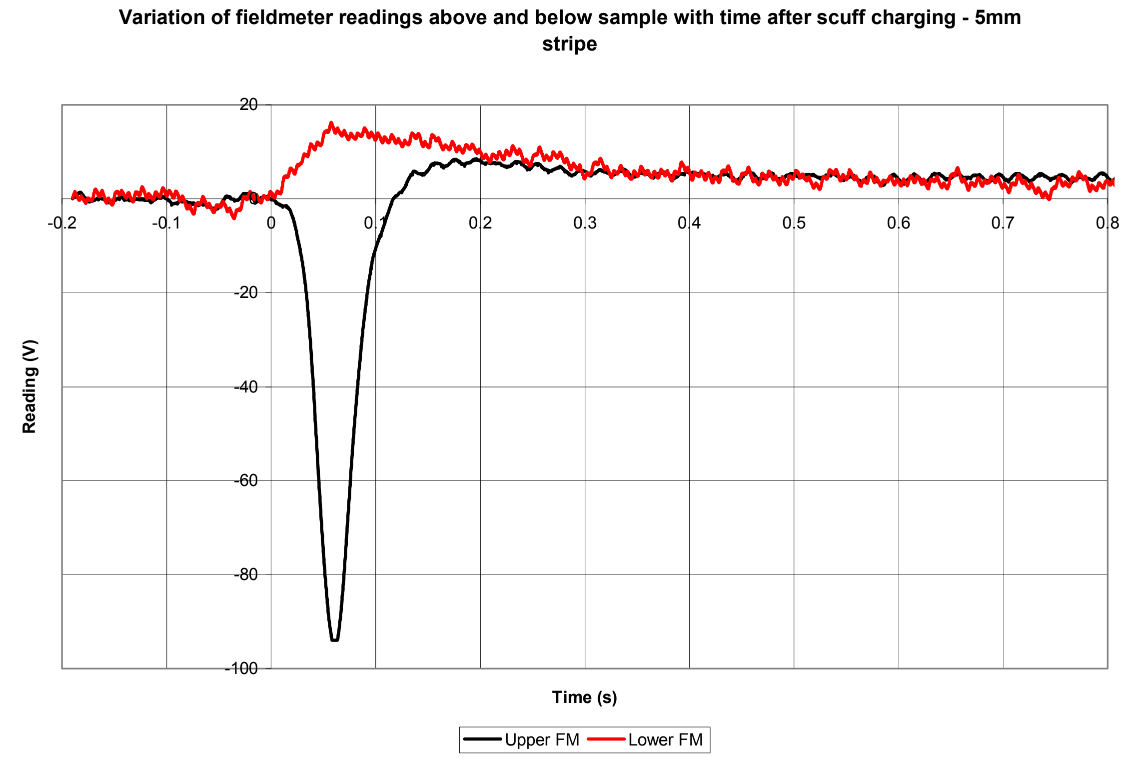

Figure 13: Comparison of topside and reverse side fieldmeter observations (sample 2, 1.07nC)

The above appreciation means that it is not appropriate to compare charge decay performance simply in terms of the time just from the initial peak of the observed voltage signal to a selected fraction of this (e.g. 1/e or 10% [11]). And this also applies to judging the practical significance of measured values.

For materials with short decay times the peak fieldmeter reading will be lower than it would have been without a delay after the end of the charging action. It can hence be expected that capacitance loading values will be higher with tribocharging than with corona charging where values have been derived from initial peak voltage values.

Results for the various materials tested are summarised in Table 2 below.

Table 2: Comparison of results for tribo and corona charging

Sample	Figure	Material	Tribocharging		Corona charging	
			Decay τ (s)	**Average CL**	**Decay τ (s)**	**CL@q=0**
1	6	2.5mm grid	2 @ 1s	50-150	5 @1s	40
2	7	5mm stripe (1)	1 @ 1s	23	1.3 @ 1s	8
3	8	5mm grid (1)	0.5 @ 0.5s	82	0.6 @ 0.5s	19
4	9	5mm grid (2)	2-8@1s	22	7 @1s	23
5	10	20mm stripe	2.5@1s	6.4	3.5-9 @ 1	4
6	11	Blue lingerie fabric	18@1s	1	15	1.9
7	12	Cotton handkerchief	0.25-0.4@ 0.5s	120-150	0.35-0.5 @ 0.5s	20-50

The results in the above summary Table show:

a) that with the longer decay time materials (4, 5 and 6) there is reasonable agreement between both decay time constant values, at a similar time after the end of the charging action, and of capacitance loading values.

b) that with shorter decay time materials there is reasonable agreement between decay times at the same time after the end of charging. Capacitance loading values are appreciably higher with tribocharging than corona charging. This is as expected because of the reduction of fieldmeter reading by the delay to the initial peak of fieldmeter reading used for determining capacitance loading values.

c) That there is a similar variation of local decay time constant values between tribo and corona charging after the peak of the tribocharging observations.

4. DISCUSSION

In assessing the suitability of materials to avoid problems from static electricity it needs to be recognised that with practical tribocharging actions there is a finite minimum time between the end of charging, when the surfaces first separate, and occurence of the maximum influence of the charge on the surface to items nearby – as illustrated by observations with a nearby fieldmeter. This is the time for the rubbing surface to move away at the speed of separation. Studies with topside and reverse side observations (e.g. Figure 13) indicate that this time is in the range 50-100ms. With direct, topside, observations delay times are typically a minimum of about 100ms. This has been illustrated in Figures 6-12. What this means is that corona charging observations during this delay time may be of scientific interest, in relation to the characteristics of materials, but they are not directly relevant to assessment of practical risks and problems that may arise from static electricity.

It is suggested that assessment of the suitability of materials is appropriately made on the basis of either, or both, of the following criteria:

a) the time for decay to 10% of the surface voltage observed 100ms after the end of a short charging action is to be less than 2s.

b) the capacitance loading calculated using surface voltage 100ms after the end of the charging action and extrapolated to zero charge (CL @ q=0), shall be greater than, for example, 40. (This value will limit surface voltages to 100V for a maximum charge transfer of 50nC).

The need to ignore observations over a finite period after the end of the charging action applies also to other charge decay methods for assessing materials. This, of course, is only relevant for the few methods [12] in which there can be confidence that the test surface is actually charged – as this does not reliably occur with many methods in use.

An interesting observation from the present and other recent studies is that either directly or after a short initial settling down the local decay time constant increases roughly linearly with time. This is illustrated in Figure 13 for three corona charging studies with sample 2. . If this variation applies fairly generally it will be very useful for predicting, from modest duration measurements, how long it takes for long decay time materials to discharge. The other value of this observation is that it eases comparison between tribocharge decay and corona charge decay observations. For example, with the material of sample 2 decay time constants were 0.25-0.43s for tribocharging from the initial peak voltage that occurred 0.2-0.25s after the end of charging. The data in Figure 14 indicates that at that time the decay time constant with corona charging was 0.35-0.4s.

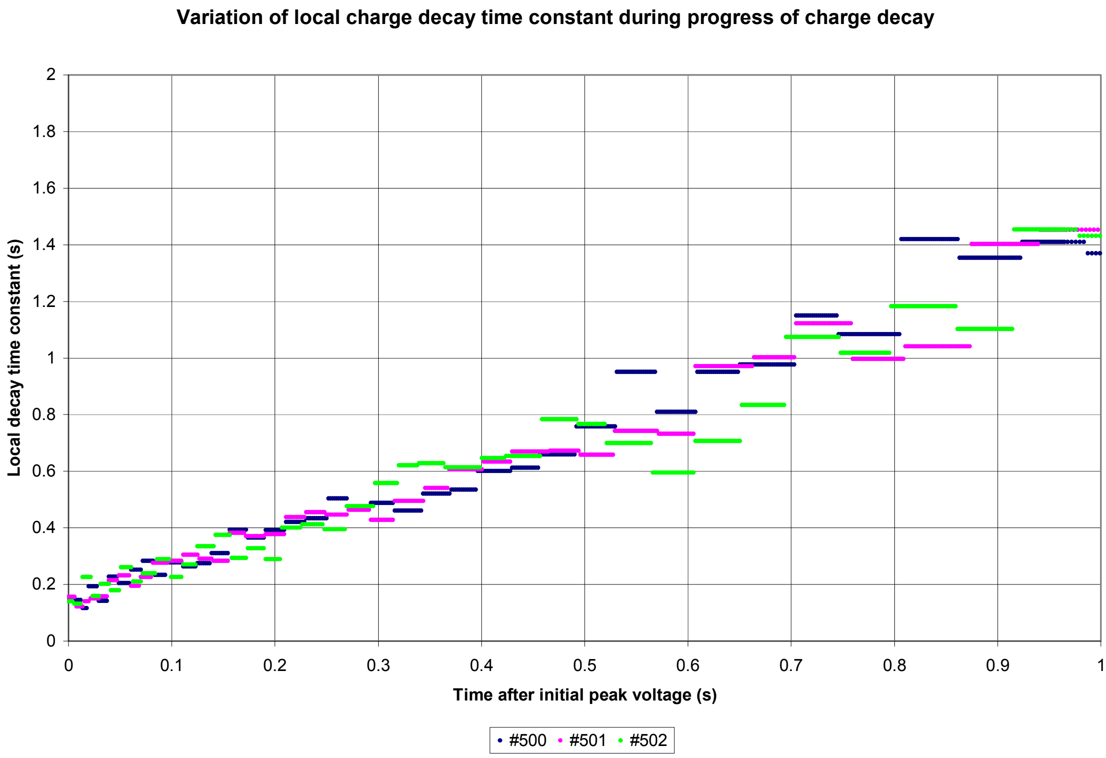

Figure14: Example of variation of local decay time constant during the progress of charge decay with corona charging with Sample 2

It is noted the response of a fieldmeter near an area of charge in free space does not depend much on the size of the area of charge, just on the total quantity in front of the sensing aperture. The overall capacitance of a disc of charge in free space can however be expected to increase in proportion to just the diameter of the disc. Where the charge is deposited on a layer with an appreciable capacitance loading then as the charge spreads out the area of coupling to quasi-earthed parts of the material increases in proportion to the area and hence the square of the effective radius. The contribution of capacitance experienced by the charge to the local decay time constant can hence be expected to increase. This will apply even for charge on materials having a linear dependence of charge migration rate on electric field – i.e. a 'resistive' material. This form of variation of local decay time with time is also observed with a layer of cling film when it is tested on an earthed backing.

4 CONCLUSIONS

It is concluded that the electrostatic behaviour of materials, in terms of charge decay times and capacitance loading, is the same with corona charging as with triboelectric charging. It is hence appropriate to take advantage of the ease of use of corona charging within suitable instrumentation to assess the practical performance and the acceptability of materials for avoiding risks and problems from static electricity.

The results of the present studies are relevant to the development of appropriate Standards for electrostatic measurements – and for discarding irrelevant standards.

Comparisons between charge decay time and capacitance loading results with corona and tribocharging need to be carried out with some care. This is because of the difference in the time of achievement of the initial peak voltages after completion of the charging action. A fair comparison requires use of a common time zero at the end of the charging action and with a charging time that is short compared to the minimum decay time to be measured.

Assessment of the suitability of materials in terms of charge decay time needs to be based on the surface voltage level achieved at an agreed time after the end of the charging action. This because with tribocharging it takes a finite time for rubbing surfaces to separate and the local influence of surface charge to reach a peak. The present studies suggest 100ms as perhaps an appropriate time for the start of decay time measurement. This is a change from previous recommendations [1,11] that decay times be measured from the initial peak of surface voltage. The variation of surface voltage with time earlier than this is of course of technical interest, but it is not relevant to the practical suitability of materials.

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