3. MEASURING INSTRUMENTS

3.1 INTRODUCTION

Measurements are needed to show you the electrostatic conditions that are present, to help understand why these conditions are present, to help confirm that control measures put in place are continuing to work and to help select and develop suitable materials. Without measurements it is all guesswork!

The classical groundwork in electrostatics used instruments such as the gold leaf electroscope and the quadrant electrometer. These are perfectly valid measuring instruments - but they belong to the physics laboratory. The instruments described below are appropriate for use by non-specialists in industrial as well as laboratory situations.

An important area of measurement is assessing the characteristics of materials. Are materials in use, or being considered, suitable for their purpose? And when thinking about 'suitability' this is not only what is relevant for the immediate are of application (for instance within a processing operation) but also through to the final 'end user'.

Guidance is provided in a number of Codes of Practice [1,2,3,4] on arrangements and procedures designed to avoid static problems and risks. However, there are always situations and materials where there is uncertainty. Is there a problem, what is it due to, will suggested remedial actions work, are alternative approaches prospectively more suitable, are remedial actions continuing to work effectively?

In many cases measurements only need to be informative and to provide guidance. But measurements may have contractual, legal or safety implications. In such situations the instruments used need:

- to be appropriate for the measurements required
- to be formally calibrated
- to have their observed readings recorded and interpreted appropriately

The following sections describe the basic instruments needed for measuring electrostatic conditions that arise in various practical situation and also the instruments to assess the electrostatic characteristics of materials. These descriptions draw attention to the design features needed to ensure that measured values can be used with confidence. The ways in which these basic instruments may be used in practice are discussed in Chapter 4.

3.2 MEASUREMENT OF ELECTRIC FIELD

3.2.1 Basic aspects

The parameter of basic importance for static electricity is ‘charge’. In some practical situations this can be measured directly, however as it is via the electric fields created by charges that items nearby are influenced. Measurement of electric field hence provides the most generally applicable way to detect, locate and quantify sources of static charge and to assess the influence of static charge.

Measurement of electric field also provides the basis to measure a whole variety of other parameters of interest in electrostatics - voltages on surfaces, on people and in volumes, the density of charge on surfaces and in volumes, the nett quantities of charge on items and the ability of materials to dissipate static charge.

Electric fields may be measured by the mechanical forces created, but this has very low sensitivity and requires geometries that can define the electric field to be very uniform [5]. The more practical approach is to measure the charge induced on the sensing surface of a ‘fieldmeter’ instrument.

An electric field is associated with a distribution of charge at a conducting surface is – as discussed in Chapter 2.8.

$$E = \sigma \;/\; \varepsilon_o$$

Where E is the electric field (V m^{-1}), σ is the area charge density (C m^{-2}) and ε_o is the permittivity of free space (8.854 10^{-12}). This relationship forms the basis for all 'fieldmeter' instruments – instruments to measure electric fields.

3.2.2 Induction probe type fieldmeters

The simplest form of fieldmeter is the 'induction probe'. This is illustrated in Figure 3.1. It has an exposed conducting sensing surface on which the electric field to be measured induces a charge. The charge held at the surface is matched by an equal charge repelled to the measurement circuit.

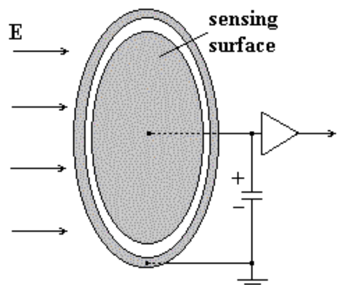

Figure 3.1: Induction probe type fieldmeter

The quantity of charge induced on the area of the sensing surface can be measured in two main ways:

- from the voltage developed across an input capacitor
- using a virtual earth charge measurement circuit

Two basic input stage circuits are shown in Figures 3.2 and 3.3.

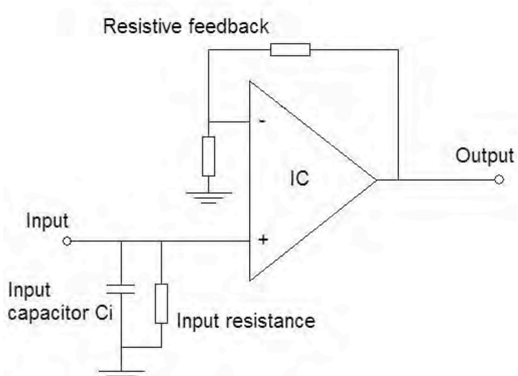

Figure 3.2: Measurement of charge via voltage on a capacitor

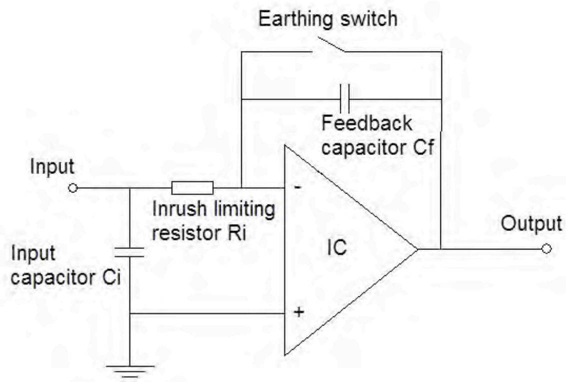

Figure 3.3: 'Virtual earth' charge measurement circuit

The main limitations of induction probe instruments are that they cannot be used for long term continuous monitoring and that they are they are not very sensitive. If an induction probe is presented with a step function of electric field the output will step in proportion to the input variation of field, but will then decay away in relation to the RC time constant of the input or feedback capacitor and the total leakage resistance to the input connections. There will also be adverse influence from voltage and current offsets for the input amplifier stage. This leakage time constant limits the maximum time over which it is sensible to make measurements and the maximum sensitivity that can be realised. Higher sensitivities can be achieved where shorter observation times are acceptable.

Induction probe instruments need to be 'zeroed' in a region that is free of electric fields. If this is not done then the output zero will correspond to the level of electric field at which zeroing was performed. For voltage measurement instruments 'zeroing' is achieved in zero electric field conditions by simply shorting the input to the circuit earth. With virtual earth charge measurement circuits it is necessary to short out the feedback capacitor. In both situations the switch needs to avoid reducing leakage resistance.

The voltage measurement circuit approach requires the greater care in the insulation of the sensing surface and its direct connections. This requirement applies more within the circuitry for the virtual earth charge measurement circuit because the sensing surface is held at earth potential. Where very fast edge electric field transients may arise the voltage measurement circuit is to be preferred. The performance of the virtual earth charge measurement circuit is limited by the output drive current capability of the amplifier to charge the feedback capacitor sufficiently fast to prevent the input terminal going to the power supply rails.

Induction probe instruments are not suitable for measurements in the presence of ionised air. This is because unipolar ionised air will create a current flow to the sensing surface trying to neutralise the effect of the electric field and bipolar ionised air will provide an unquantified leakage resistance path between the sensing surface and earth.

3.2.3 'Field mill' fieldmeters

'Field mill' instruments overcome the limitations of simple induction probe instruments by using an earthed chopper to modulate the electric field inducing charge at the sensing surface [5,6]. The basic arrangement is shown in Figure 3.4. The charge induced on the sensing surface may be measured using either of the input circuits shown in Figure 3.2 or 3.3. The alternating signal can then be amplified and phase sensitive detected to provide an output in proportion to and of the same polarity as the incident electric field.

It is equally appropriate to work with a sectored chopper and sectored sensing surface or with a sectored sensing aperture plate, a sectored chopper and a plane sensing surface. Instruments are usually constructed with an axial geometry but instruments may equally well be made with radial geometry [7]. Axial fieldmeters are used (as discussed more fully in Chapter 4) either mounted in a large plane conducting to measure the electric field there or used on their own to measure voltages of surfaces nearby or local space potentials in a volume.

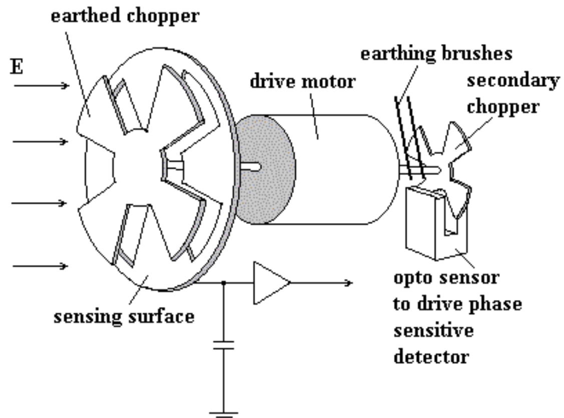

Fig 3.4: Basic 'field mill' fieldmeter

'Field mill' instruments are mechanically more complex than induction probes but provide much higher sensitivities, long term stable zeros and avoid the need to 'zero' the instrument in a region free of electric fields each time they are switched on. They are also suitable for use in the presence of ionised air.

The opportunity for much higher sensitivity arises because the input RC leakage time constant only needs to be suitably longer than the frequency at which the electric field is modulated. As the modulation time constant is likely to be say 0.05s it is easy to see that the basic sensitivity may easily be 1000 times greater than for induction probe instruments.

Measurements can be made to a few V m^{-1}, with response times down to a few ms and with accuracies to 1%. High useable sensitivities are useful because they enable even low levels of static charge to be detected with confidence at a good distance. High accuracy is often not necessary - but it is important when measurements with small differences are needed such as in measurement of very slow rates of change.

Fieldmeters are also available based on the use of 'voltage follower' designs where the voltage of an electric field sensing element within an earthed case is adjusted by servo control to null the electric field sensed [8]. The electric field at the instrument sensing aperture is then derived from the nulling voltage applied and dimensions of the sensing arrangement. The main limitation of this approach is that the sensitivity is much lower than for a rotating chopper type fieldmeter because the sensing aperture is much smaller because of limitations by the amplitude of vibratory movement. Internal gaps are also small, so there is also greater susceptibility to surface contamination.

3.2.4 General requirements for fieldmeters

The design and construction of fieldmeter instruments needs to be such that a definite relationship can be established between the reading, or output, and the electric field and that it can be understood and used easily by different users. For measurement of electric fields at conducting surfaces this requires, as specified in BS7506 [9], that the fieldmeter has a defined and recognisable ‘sensing aperture’. This might be the edge of the casing or a plane surface surrounding the sensing region. For the purpose of setting up and calibrating the electric field sensitivity it is this aperture that is mounted flush with a large surrounding plane conducting surface that is part of a large two plate parallel plane geometry in which the electric field can be defined with confidence from the spacing between the two plates, d, and the applied voltage, V, as: $E = V / d$. Arrangements for formal calibration are discussed in Annex 3. For fieldmeters used to measure electric fields in the atmosphere or in large volumes no mounting surface need be involved and alternative procedures for calibration are appropriate - as discussed in Chapter 4.5.

3.2.5 ‘Field mill’ fieldmeters without earthing of the rotating chopper

Traditionally ‘field mill’ fieldmeter instruments have been based on the use of an earthed rotating chopper to modulate the observed electric field at a sensing surface [5,6]. This approach works well, but has a number of limitations for practical and commercial instruments. Making a good low noise earthing contact to a rotating shaft is not easy. No lubrication can be used and the contact wears. Wear can be minimised by using a smooth shaft of small diameter and by keeping the rotational speed and the brush contact pressure down. The simple approach is a pair of thin spring wires resting on the side of the rotating shaft. For low noise a precious metal earthing brush contact is needed. The earthing problems become significant for instruments needed for long continuous operation (more than several months) and for fast response (below say 10ms). At the higher rotational speeds for fast response instruments a higher contact pressure is needed to avoid contact bounce – and this both exacerbates wear and increases the motor power required. In small scale instruments it may not be easy to mount and adjust suitable earthing brushes.

A ‘back to back’ fieldmeter approach, that was devised in 1990, overcomes many of the limitations of traditional ‘earthed chopper’ types of instruments [10,11]. Two fieldmeters are driven by the same motor with the two rotor assemblies electrically connected together and electrically isolated from the motor drive shaft. One fieldmeter observes the external electric field while the other, ‘secondary’, fieldmeter is in a fully shielded enclosure. By balancing the signal of the primary fieldmeter by an appropriate fraction of the signal observed by the secondary fieldmeter it is possible to fully compensate for the effect of any nett charge held on the dual rotor assembly.

A useful simplification for practical instruments is realisation that the function of the secondary fieldmeter is, in fact, just to observe the voltage variation of the rotor assemble arising from variations in capacitance of the rotor as it rotates. Figure 5 above shows the basic arrangement for a practical fieldmeter of the rotor assembly, the sensing surfaces, the motor drive and the phase sensitive detection.

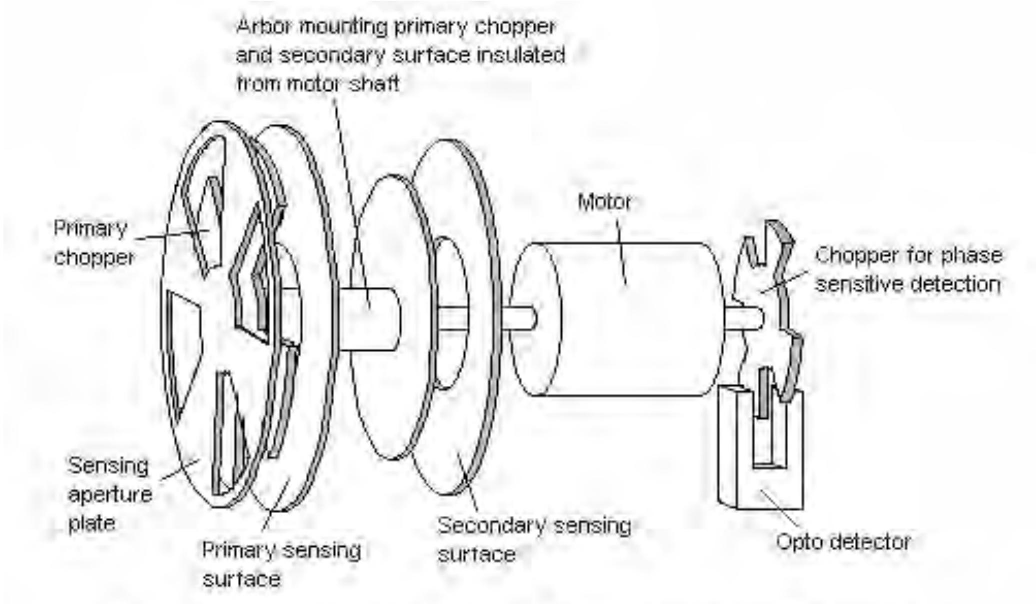

Figure 3.5: 'Field mill' fieldmeter with no earthing of the rotating chopper

The 'back to back' fieldmeter approach requires near zero end float for the rotor assembly drive and this requires care in choosing a suitable drive motor. All the normal requirements for good design and construction of fieldmeters (e.g. gold plating surfaces, etc) apply with this arrangement.

Immunity to charge on the rotor assembly is easily tested in setting up these instruments by observing the output after charge has been added to the rotor, by contact with a battery (e.g. 9V), and then after the rotor has been earthed. The contribution of the signal from the secondary sensing surface is then adjusted to achieve no change of output when charge is added to the rotor.

3.2.6 Zeroing fieldmeters

A sensitive fieldmeter will respond to the presence of conducting surfaces of different metals to its own near the sensing aperture. This is a consequence of contact potential difference effects. For a sensitive fieldmeter (say better than 2kV m^{-1} FSD) it is necessary for the cup to be sufficiently large so that no surfaces come within about 50mm of the sensing aperture. It is not satisfactory just to lay the palm of the hand over the sensing apertures or a metal surface. It is appropriate to use a suitably large and clean metal cup over the sensing aperture to check and set the zero reading and it is best if the cup surfaces are gold plated.

3.2.7 Calibration of fieldmeters

Calibration of the electric field sensitivity of fieldmeters is carried out in relation to the electric field over the sensing aperture with this flush to a large surrounding plane surface. Formal methods of calibration have been developed and documented [9,12] – and as outlined in Annex 3.

3.2.8 Factors determining performance of field mill fieldmeters

3.2.8.1 Introduction

Making a fieldmeter that responds to the strength and polarity of an electric field is not too difficult and many people have done this in various configurations. What is more difficult is to make fieldmeters with high sensitivity, low noise, fast response, long operational life and immunity to local environmental conditions – and to do several of these together in a single instrument. The following paragraphs outline some of the approaches that have been developed to tackle these objectives.

3.2.8.2 Earthing rotating choppers

Rotating choppers are usually earthed by brushes in rubbing contact with the rotating shaft. Neither sleeve nor ball bearings provide good earthing – basically because lubrication isolates the shaft and bearing surfaces. For low electrical noise to the fieldmeter input it is desirable that the contact brushes are made of a precious metal alloy spring wire (fairly hard) and resting with just a few grams force (say 5-10g) on a small diameter section of shaft. It is best to use a couple of brushes. The brushes wear with operation and need to be replaced from time to time. Experience has been that several months of continuous operation can be expected from a pair of brushes. If high rotational speed is needed to provide a fast response output then the brush pressure may be need to be increased to avoid the brushes bouncing during rotation. This will decrease the lifetime of brush operation and increase the drive power required.

3.2.8.3 Zero stability

Contact potential differences between chopper and sensing surfaces will give rise to a finite output signal even when the external electric field is zero. Such effects are best minimised by using stainless steel or gold plated surfaces, so there are no changes in contact potentials likely to result from corrosion in long term studies. It is also advantageous to have sizeable gaps between chopper and sensing surfaces to minimise the electric fields created by whatever electrochemical potentials are present. If the gaps are large compared to the size of the chopper sectors then there will be a sizeable reduction in depth of modulation and so a reduction in fieldmeter sensitivity.

A major factor affecting the zero in practical measurements is the influence of any contamination on chopper or sensing surfaces. This is a particular problem when measurements are made in situations where airborne particles of highly insulating powders are around. If these are deposited on surfaces in the sensing region then appreciable zero offsets can arise. The best way to combat this is to provide a flow of clean, particle free, airflow in the sensing region and out through the sensing aperture to minimise ingress of contaminants. It is also desirable to check the zero reading from time to time – see Section 3.2.6 above.

Zero stability can also be affected if signals can be picked up (via capacitance or inductive coupling) from the motor or the motor leads. While it may be feasible to balance out such signals when the instrument is initially set up they may change with time as motor commutation and bearings changes with wear in long term use. For fieldmeters without earthing of the rotating chopper this requires the capacitance between the chopper assembly and the motor shaft to be kept very low. It is also be useful to provide magnetic shielding between the motor and the signal connections and processing circuits.

3.2.8.4 Precision and Sensitivity

Achievement of a stable and precise relationship between signal output and the electric field at the sensing aperture requires good mechanical stability of all surfaces in the sensing region.

There should be no exposed insulating surfaces in the sensing region – so insulation mounting the sensing surfaces needs to be well shielded. There needs to be very little end float in the chopper drive system otherwise there will be a change in the depth of modulation as the chopper moves relative to the sensing surfaces. End float needs to be especially small with fieldmeters without earthing of the rotating chopper (Section 3.2.5 above). Where the chopper is mounted directly on the motor shaft this means choosing motors with preloaded bearings that eliminate end float.

Good precision requires careful attention to factors affecting signal to noise ratios throughput signal processing. This is of course a particular area of attention at the front end – and attention is needed to sources such as motor noise (3.2.8.3 above).

There are a number of ways the induced charge signals from the sensing surfaces may be processed – from the voltage developed across an input capacitor, by a direct virtual earth charge sensing circuit or by the current flow generated. Measurement of current flow is generally not a good approach as the current will vary with the speed of rotation and this may vary in battery powered instruments or with bearing or commutator wear. Voltage measurement has the disadvantage that it requires the input resistance to be very high – particularly high for high sensitivity. This makes operation sensitive to contamination and moisture on the insulation mounting the sensing surfaces and input to the preamplifier circuit. Use of the virtual earth charge measurement circuit minimises susceptibility to leakage from the sensing surfaces because these remain at earth potential.

The best way to process the alternating signals after amplification is phase sensitive detection. This gives low noise and a linear response. The signal for operation of the phase sensitive detector may be obtained in various ways - for example, an infra red opto detector or magnetic reluctance sensor operating in conjunction with a secondary chopper and arranged to be in exact phase relation to the observed electric field signals. It needs to be noted that infra red detectors may be susceptible to tungsten lamp and sunlight illumination – a problem that is avoided with magnetic sensing. An alternative approach can be to use an electronically commutated motor for chopper rotation and derive the phase sensitive detection drive signal from a rotation logic signal.

3.2.8.5 Response time

The response time of a 'field mill' type fieldmeter is determined by the frequency of modulation of the electric field at the sensing surface. With rotating chopper fieldmeters the frequency of modulation relates to the number of chopper sectors and the speed of chopper rotation. Rotational speeds of 10,000 to 15,000 rpm (170 to 250 rps) are reasonable to achieve in practice. The number of sectors is limited by the need to retain a sensible ratio between the aperture of chopping sectors and the spacing to the sensing surface or the sensing aperture so there is adequate coupling of the external electric field to the sensing surface. With say 10 sectors this means that the chopping frequency is not likely to be greater than 1.7 to 2.5kHz. On this basis one might expect to be able to achieve a response frequency up to say 0.5kHz.

When the response time of the signal output only needs to be slow compared to the time for chopper rotation then it is easy to filter out signal variations arising from irregularities in chopper geometries, etc. affecting phase sensitive detection. However, where the timescale of response needs to be comparable to, or shorter than, the time for rotation of the chopper and where a high sensitivity and high resolution is also required then special care is needed. The alternating signal generated at the primary sensing surface will be the average of the signals from all the chopper sectors during a chopper rotation, so this smoothes out many irregularities. The phase sensitive detection signal however is usually generated from interaction of a localised detector with just an individual sector of a secondary chopper. In this situation the matching of the timing of phase sensitive detection to the modulation of the electric field signal will depend on the angular precision of the sensed chopper and the detection arrangement and of influence from swashplating over the period of rotation. A good way to achieve a stable and uniform mark-space ratio is to link the detector signal to a phase locked loop circuit which drives the phase sensitive detection switch. This can provide a uniform mark/space ratio stable over many chopper rotation periods and so be a better match to the averaging of electric field signals from all the sensing surface elements.

The signal from the phase sensitive detector comprises a sequence of half sinewaves. To get the maximum frequency response from the fieldmeter the output needs to be filtered with as high a roll-off frequency as is compatible with achieving adequately low noise from the chopping frequency in the final output. One or two stages of Salen and Keys filtering may be suitable.

3.2.8.6 Adverse environmental conditions

Maintenance of performance in wet and dirt operating conditions is not easy and requires careful design and construction. To avoid water bridging between sensing surface sectors and nearby surfaces it is wise to have gaps larger than 5mm. This means that fieldmeters for situations where water is likely to get into the sensing region need to be fairly large. It is also necessary that insulation mounting sensing surfaces provide long tracking paths and that signal processing circuits are suitably protected.

Despite best precautions situations can arise when performance is degraded in adverse operating conditions. To give confidence against such risks through long term studies it is then desirable to include some form of operational health facility. This may conveniently be in the form of an independent local source of electric field whose amplitude can be monitored through the fieldmeter system [13,14].

3.3 MEASUREMENT OF CHARGE

3.3.1 Introduction

The nett charge on moveable items, conducting or insulating, that are separated or isolated from ground is best measured using a Faraday Pail. This is relevant to measurements on liquids and powders exiting from a pipe, on pieces of material and to falling particles – such as raindrops. The measurement of charge transfer in static discharges can be made directly by appropriate measurement of the voltage increase on a capacitor.

3.3.2 Faraday Pail

The basic concept of a Faraday Pail is a conducting chamber in which the electric field created by charge on the item to be measured is all captured on surfaces of the pail - and none couples to the world outside. In this situation if the chamber is isolated from earth then all the charge introduced into the pail also appears on the outside of the pail, where it can be measured. It is not necessary for the charge introduced to actually flow to the inside of the pail - so the method is equally useful for charge on insulators as on conductors. It is however necessary to note that the charge on an item or material put into the pail must be allowed to couple fully to the pail. Hence, it must not be, for example, mounted on an earthed retaining support that could affect free coupling to the pail. Nor may it be mounted on insulation that holds charge, as this could couple into the pail and affect observations.

The Faraday Pail may be used equally well to measure charge on individual items, on a collection of items, on a volume of liquid or on particles suspended or moving in air or a gas.

Basic features of a Faraday Pail are illustrated in Figure 3.6. The Faraday Pail itself needs to be provided with an earthed conducting shield to prevent charges being induced on the pail by electric fields from surfaces with charge or voltages in the surroundings.

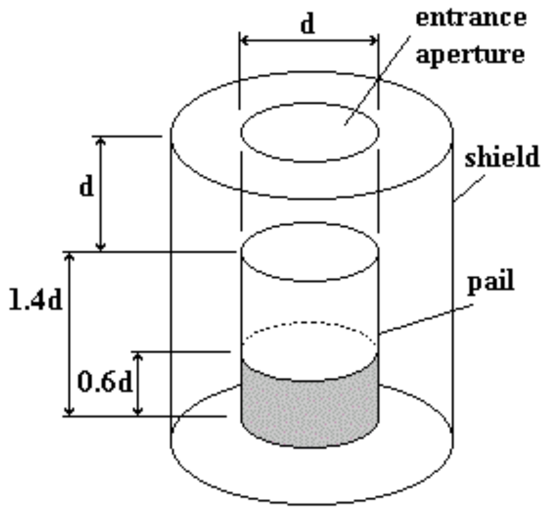

Figure 3.6: Basic features of a Faraday Pail

The pail needs to be designed and built with the following two main features in mind [9]:

- the geometry of the pail shall ensure that all charge introduced into the pail couples to the pail and none to the world outside. This means that a closed ended pail needs to be fairly deep (a height to diameter ratio of at least 1.4 to 1 with the charge retained within the lower 40% of the height). Similar considerations are needed to ensure full coupling of contained charge within double open ended and other shaped vessels
- the pail needs to be well shielded against the influence of charges in the vicinity.

3.3.3 Charge measurement

The charge induced on the pail is most appropriately measured using the virtual earth charge measurement circuit - shown in Figure 3.3. In this circuit the operational amplifier provides capacitance feedback to keep the input at earth potential. In this way all the charge on the source appears on the feedback capacitor and the quantity of charge is the product of the feedback capacitor and the output voltage. It can also be measured from the voltage developed across a capacitor on the input of a suitably high input impedance amplifier.

The virtual earth charge measurement approach is generally the most appropriate approach. The basic limitations are the maximum voltage swing available and the maximum rate of charge flow into the pail exceeds the output current capability of the amplifier stage. The virtual earth circuit aims to maintain the input at earth potential. However, if moisture and contamination are present on the input insulation then battery voltages generated will cause zero and reading values to drift.

If charge is measured by the voltage developed across a capacitor of known value then there is charge sharing and the voltage developed on the measurement capacitor depends upon the capacitance of the charge source. If C_s is the source capacitance and C_m the measurement capacitor then the voltage developed, V_m, will be:

$$V_m = Q_s /(C_s + C_m)$$

So long as $C_m >> C_s$ the voltage developed on the measuring capacitor will be a good measure of the quantity of charge entered in to the pail.

In both methods measurements need to be made with a sufficiently high input impedance that values can be noted or recorded within a small fraction of the RC time constant. An electrostatic voltmeter may be useful here.

Zeroing of a virtual earth measurement circuit is achieved by shorting the feedback capacitor – not by earthing the input connection! If it is desired to make measurements with stability and resolution down towards the picocoulomb range it is best to make circuit connections off the surface of a printed circuit board. Isopropanol make prove a useful cleaner for circuit components.

The performance of a Faraday Pail system for charge measurement may be checked and calibrated by charging a known value capacitor to a known voltage so as to inject a suitable and defined quantity of charge. It is important that a good quality capacitor is used and that the charging voltage is at least several volts – to minimise risk of influence by electrochemical effects. The charged capacitor approach is not so appropriate for calibration into the picocoulomb range because the value of a suitable capacitor is likely to be affected by proximity effects. An alternative approach is to create a defined flow of current and to switch this to the charge measurement input for a defined period of time. A defined and stable flow of current can be achieved from a referenced voltage source and a defined precision resistor to earth. The flow of this current at the earth connection point may be electronically switched to flow into the input of the virtual earth measurement circuit for a defined period of time. As the current flow is continuous there is no influence from any distributed capacitance in the precision resistor or its connections. The electronic switch and the layout of the circuit need to be chosen that gives negligible charge injection at operation. The period for current flow can be derived with high accuracy and stability by scaling down from a quartz crystal oscillator. Each of the 3 factors determining the quantity of charge output (voltage, resistance and time) can be formally calibrated with reference to National Standards. For circuits based on measurement of the voltage developed across an input capacitor the reference voltage needs to be suitably high. Formal calibration is described in Annex 3.

3.4 ASSESSMENT OF MATERIALS

3.4.1 Introduction

Static electricity arises on the surface of materials by contact or rubbing actions with other material surfaces or by the fracture of surfaces. The risks and problems created by static electricity and the opportunity for its constructive depends on four main features. The relative importance of each depends on the area of application.

1) voltages arising on surfaces when contacted or rubbed by other surfaces
2) ability of surfaces to drain charge away from conductors in contact
3) ability of materials to provide shielding against electric field transients
4) ability of a material to support an incendive electrostatic discharge

The first of these, the surface voltage that arises from charge retained on a material itself, is the root cause of most electrostatic problems and opportunities for applications. It is the surface voltage created that is responsible for the electric fields at nearby items and is responsible for attraction of dust and debris, for the clinging of thin films, for shocks, for the occurrence of incendive discharges and for risks of damage to microelectronic components and systems.

The ability of materials to drain charge from conductors in contact and away to earth is appropriately covered by resistance measurement [1,4] - for example for footwear and flooring to control body voltage during activities such as walking. Shielding and the support of incendive discharges are separate topics that require their own appropriate methods of measurement [15,16,17].

The voltages that arise on surfaces when these are contacted or rubbed will be influenced by the materials involved (triboelectric series). In practice, where materials and surface conditions cannot be defined, the voltages are determined by two main factors: first, how quickly charge can migrate over the surface compared to the time it takes for the surfaces to separate; and second, the capacitance experienced by the charge on the surface. The measurement of these parameters is the subject of the present paper.

3.4.2 Philosophy of assessment

Traditionally the suitability of materials to avoid problems from retained charge has been judged by measurement of resistivity. The view expressed in present Standards is that so long as the resistivity is below 10^{10} ohms there will be no problems [1,4]. This not philosophically appropriate and does not work for many modern materials. Composite and inhomogeneous materials may include both relatively insulating and relatively conducting parts. If the contact electrodes for surface resistivity measurement contact the conductive parts then low resistivity values may well be observed. It is clear however that such measurements will provide no information about the relatively insulating parts – which, of course, is where electrostatic charge may be retained.

The logical way to assess materials for the risk presented by retained surface charge is to put some charge on the material, by a contact or rubbing action, measure what surface voltage is created (per unit of charge) and measure how quickly this surface voltage falls as the charge moves away over the surface. These two measurements can then be compared to appropriate threshold acceptance level values. The values may be of general application or may be chosen for a particular area of application.

Studies on a variety of materials by the above ‘scuff charging’ approach have been carried out and published [18,19,20,21]. Such studies have indicated that decay times down below around 0.25 second are needed to limit surface voltages to low values against manual rubbing actions. This is in line with the expected need for the decay time to be comparable to the time for manual separation of contacting surfaces. These studies have also shown that maximum initial peak voltages can be held to low values if the charge experiences a high ‘capacitance’ at the surface [18,19,20,21]. The ‘capacitance’ experienced by charge on a surface is a feature of the dielectric constant of the material and, in particular, the proximity of any conductive features within the material. It does not seem practical to directly measure the capacitance experienced by surface charge. The problem is that in practical charging the charge density varies over the area charged so there is no defined boundary for the charge. The term ‘capacitance loading’ has been devised to describe the capacitance effect experienced by surface charge. ‘Capacitance loading’ is defined [18,21] as the surface voltage created per unit of charge deposited on a thin layer of a good dielectric surface divided by the surface voltage created per unit of charge with a similar spatial distribution on the test material.

Tribocharging is not an easy way to make measurements [18,22]. The charging action needs to be completed within quite a short time and the item used to achieve charging needs to move away very quickly so it does not affect measurement of the surface voltage created. The quantities of charge easily and quickly transferred to a surface in experimental studies may be quite a bit less than could arise in practice. Thus with materials that provide a high capacitance to surface charge it is necessary to be able to measure quite low surface voltages and to do this with a good time response. It is also necessary for the charging action to avoid mechanically impacting the fieldmeter used for surface voltage measurement instrument and for the charged rubbing material to be quickly removed well away to prevent any influence to the fieldmeter [18].

The alternative to tribocharging is to use corona charging to place a local patch of charge on to the surface of the material [21]. Studies with a variety of types of material have shown that measurements of decay times and of capacitance loading with corona charging give a reasonable match to these characteristics measured with tribocharging [20,24]. Corona charging provides the basis for compact and easy to use instrumentation that can be used directly on a wide range of materials - including powders and liquids.

3.4.3 Comments on methods for charge decay measurement

Several methods for measurement of 'charge decay' are described in various 'Standards' and in published literature [9, 18-38] and comments on these have been published [39]. The methods are very different in principle, do not in general agree with each other and in general do not provide the information likely to be useful for uninitiated or unskilled users because they are susceptible to the construction of the materials tested.

It is proposed [39] that methods of charge decay measurement need to satisfy the following requirements:

- give results comparable to measurements with practical tribocharging actions for a wide variety of materials
- the material is initially at near earth potential and is subject to a charging action in a central region near a surface voltage sensor. Measurements are made of the surface voltage created by the charging action and how this decays with time
- surface voltage measurements are made without contact directly on the area charged
- measurement should be made on the same side of the material as that charged
- independent of constructions or features of materials
- minimal modification of the material and decay characteristics by the conduct of the test (and this should also apply to tribocharging methods).
- the method should be easy to use and interpret by non-specialist staff
- suitable equipment should be easy to construct and/or commercially available.
- approaches should also be backed by peer reviewed published papers describing the equipment and giving supporting experimental measurements. Where appropriate these papers should be referenced in the 'standard' document.

The following notes describe a number of methods of charge decay measurement in use with their strengths and limitations. It may be argued that many of the methods mentioned are 'well established', in common use and are specified in 'standards'. However, this does not make them right – and it is hoped the following comments will clarify strengths and weaknesses!

Corona charge decay

The corona charging approach to charge decay measurement offers many practical advantages and has been implemented in compact easy to use instrumentation. It is in use by non-specialist staff with many types of materials in a wide variety of industries around the world.

It is included in formal standards documents [9,28]. The method can be used in conjunction with measurement of the corona charge transferred to give values for 'capacitance loading'

[18,20,21,25]. This is of practical relevance as it shows the surface voltages expected from practical quantities of tribocharge [19,21,25]. Corona charging gives a generalised way to assess the suitability of materials, including films, layers, liquids, powders, small items and installed surfaces. Suitable equipment is available commercially.

Studies have been reported that show comparability between corona and tribocharge decay times for a variety of materials [18,20,21]. These have shown it is important with short decay time materials to compare decay rates at comparable times after the end of the charging action [20]. Lack of any significant modification of the surface by the action of corona ionisation has been shown [40] by constancy of charge decay performance at a single location from an initial low corona charge exposure through a high exposure and back to low exposure.

The method needs to be checked more extensively by different workers – in particular for different areas of charge on surfaces and with further comparisons to tribocharging results.

Federal Test Standard 101C

Federal Test Standard 101C Method 4046 [29] has been around for many years and has been subject to a number of comments and refinements [32,36]. The basic approach involves mounting a 5” long and 3” wide strip of material between supporting clamps in front of a fieldmeter.

A voltage of 5000V is applied to the clamps and the build up of fieldmeter signal observed to achieve a reading equivalent to the applied voltage. The clamps are then earthed and the decay of the fieldmeter signal observed and timed. It is noted in the specification that the method should only be used for ‘homogeneous materials’ - but no guidance is given on how to recognise such materials!

Comparative tests have shown much shorter charge decay times by FTS 101C than are observed with corona charge decay measurements with many practical materials [30]. These tests did however confirm that comparable results are obtained with truly homogeneous materials. It was concluded that FTS 101C basically responded to the fastest route for charge movement in the layer of material, whereas corona charge decay showed how charge moved on the surface of materials. The method of charging will not ensure full charging of insulating components in a relatively conductive matrix or grid. The method requires use of a cut sample area. Equipment is available commercially.

ITV Denkendorf

ITV Denkendorf developed a tribocharging method (ITV-TEV) in which a nearly vertical strip of material is held between two earthed clamps and rubbed by polythene rollers on either side nipping the strip as these are moved down the strip under tension [38]. The rubbed area is held stable in front of a fieldmeter to observe the initial peak voltage and the rate of charge decay. The principle of the method seems sound. It is however only applicable to flexible layer materials and to materials with decay times longer than several tenths of a second. With fabrics rather different behaviour is observed in the warp and in the weft directions. The equipment is not now available commercially.

NASA

A tribocharging method for testing layer materials has been developed at NASA by Gompf [22]. This uses a rotating Teflon brush to tribocharge the sample surface that is earthed around its edge. At cessation of charging the sample is quickly dropped in front of a fieldmeter so the initial peak surface voltage and the rate of decay of this voltage can be measured. This seems a good, valid and useful approach. Results are reported to correlate well with safety experience at

NASA. There also seems reasonable correlation with two other test methods [24]. The approach had been limited by using an induction probe type fieldmeter, rather than a field mill (now in use [24]), and by the time taken to move the sample at the cessation of rubbing to the position of observation. Use of an induction probe limits the sensitivity for low surface voltages and the length of decay times that can usefully be measured. It is also, of course, limited to layer type materials that can be presented as cut samples and those not likely to be damaged by the tribocharged rubbing action. There is also a limitation in the minimum decay times that can be measured by the mechanical delay between the end of charging and the start of surface voltage observations. This equipment is not available commercially.

A modification has been proposed to the above approach [36] to try to simulate the risk from the charging of an unearthed person's body while wearing personnel protective clothing. An isolated pick up disc has been mounted as a backing support for the sample with 220pF capacitance to earth. The idea is that the electrostatic energy picked up by this disc will represent the energy available to create risks of ignition. However, if the sample is mounted on an earthy support then the presence of conductive threads in the test fabric could diminish the quantities of charge observed because of shielding effects. It needs to be recognised that risk may also arise if there are local areas of high voltage on garment fabric surfaces relative to the body – although the incendivity of such discharges will be affected by other characteristics of the fabric.

BTTG

A corona charging method is used at British Textile Technology Group (BTTG) for testing fabrics (Shirley Method 20). A 300mm diameter disc of material is held under radial tension in a circular conducting frame. The material is charged by a cluster of corona discharge points near one side of the centre of the disc and a fieldmeter observes the surface voltage on the opposite side. After the surface has been charged the mounting frame is connected to earth.

The observed charge decay behaviour after the mounting frame is earthed needs to be assessed with caution. First, observations with the fieldmeter are made on the opposite side to that charged. For materials including relatively conducting components within their structure (for instance conductive threads) there will be a shielding effect between the charge and the observations so observations will not directly relate to the behaviour of surface charge. Second, as for FTS 101C, the initial reduction of observed signal will be strongly influenced by capacitive coupling via high conductivity components in the material. It is then a matter of judgement as to when observations relate to the decay of surface charge on the fabric itself. It is only applicable for layer type materials that can be presented as cut samples. This equipment is not available commercially.

BTTG has also developed a corona charging method for testing whole garments (Shirley Method 137 for Charge Decay Time Measurement on a Full Garment [37]). This involves using a corona discharge to charge an area of the garment, while the garment is hung up vertically from insulated supports. The variation of the potential at the charged area is observed from the time the corona charging electrode system is removed. Charge decay behaviour is observed with four test procedures: charging with the garment unearthed and then earthed via the cuff and ankle area and then charged while continuously earthed via the cuff and via the ankle area. This equipment is not available commercially. Only the later two seem appropriate.

'Scuff' tribocharging

A simple method for studying tribocharging has been developed at JCI [18,20,41]. It involves scuffing the middle of a stretched area of film or fabric with a charge neutral Teflon rod. A fieldmeter above the struck area shows the initial peak voltage created by the charging action and the rate of decay of this charge. Measurement of the quantity of charge transferred at the scuffing action is made by putting the struck end of the Teflon rod into a Faraday Pail. Values for the quantity of charge per unit of initial peak surface voltage show the capacitance effect experienced by the charge on the surface. A similar approach has been used with inhabited garments [21].

It is felt that the main value of the method is to provide a tribocharging reference against which other test methods may be compared. It is only really suitable for research type studies with film and planar surface materials. No studies have yet been reported on results with charging of large areas or with repeated charging. It is not appropriate as commercial instrumentation.

STFI

A method for assessing materials has been developed by STFI [42]. This involves observation of the form of components of the signal observed on the far side of a sample in response to a step function potential applied to an electrode on the near side. With careful interpretation these observations seem to relate to the risk of occurrence of incendive electrostatic discharges from charged surfaces.

The method is not suitable generally for measuring the surface charge decay capabilities of layer materials. For instance it will not measure the decay of charge for a plastic layer on a metal sheet.

The method is not appropriate for measuring the surface charge decay capabilities of materials. The material is 'charged' by induction so components with long decay times will only be charged to a low level. This means that only small surface voltages will be available for surface charge decay time measurements. A field mill type fieldmeter is needed, rather than an induction type, to monitor charging and charge decay. If conductive threads or internal higher conductive components are included in the material tested then their influence will depend on the resistive and capacitance coupling to the earthed mounting. This will affect observations. The response time of observations to the fast rising applied electric field gives indication of the effective conductivity within the material providing shielding performance. It seems very reasonable that this has a relation to the opportunity for drawing incendive electrostatic discharges from the material surface [43]. Resistive and capacitance coupling at the earthed mounting of the sample will affect observations. It has been indicated that this equipment would become commercially available.

Charge plate monitor

Observations are often made using a metal electrode connected to an electrostatic voltmeter in contact with the middle of an area of test material [34,44]. A popular approach is to use a 'charge plate monitor' (an instrument designed for assessing the ability of air ionisation to remove charge from surfaces).

This approach may be useful for assessing how quickly charge may be removed from a conducting item in contact with a material - such as a person standing on flooring. It does NOT, however, measure the ability of a material to dissipate charge on its own surface. As with FTS 101C etc, the reason is that observations are strongly influenced by any conduction linkage to the fastest routes for charge migration and lack of fair representation of the influence of slow charge migration routes and the limitation on long decay times of the electrical leakage of the insulation mounting the plate. There is also an uncertain influence from the capacitance loading of the contacting electrode affecting RC time constant evaluation. Equipment is available commercially from several sources.

Eight methods have been described above for measurement of ‘charge decay’.

- Four of these are not appropriate for assessing how quickly charge can dissipate on a material itself – FTS 101C, BTTG, STFI and the Charge plate monitor. The basic problem with these methods is that their observations are dominated by the fastest route for charge migration in the material, and they do not show the behaviour of charge retained on the surface of the material - as after tribocharging. No attempts have been reported to relate such methods to tribocharging behaviour.
- None of the methods that start with the material already charged and tested by earthing the test area boundary can be considered valid because this situation does not match practical experience.
- Of the tribocharging methods only the NASA and ‘scuff charging’ approaches start with the sample initially earthed and with an earthed boundary. None of the three methods based on tribocharging is available commercially.
- Corona charging provides the basis for easy to use instrumentation and gives results that with a variety of materials match experience with tribocharging. It provides information both on how quickly charge can self-dissipate on a material and on the surface voltage likely to be generated by various quantities of charge. Instrumentation is commercially available.

The conclusion drawn from the above comments is that while assessment of performance with tribocharging is in principle the test method to be preferred the comparability of performance with corona charging and the greater versatility, ease of use and commercial availability make this a good practical alternative.

3.4.4 Corona charge decay measurement

Corona charge decay measurements are made using a high voltage corona discharge to deposit a small patch of charge on the material to be tested with a fast response 'field mill' electrostatic fieldmeter used to measure how quickly the deposited charge migrates away by the decrease in the surface voltage.

A physical arrangement for corona charge decay measurement is shown in Figure 3.7. This arrangement has been described in a number of papers [18,23,26,40,41] and is included in a British Standard [9] and an international standard [28].

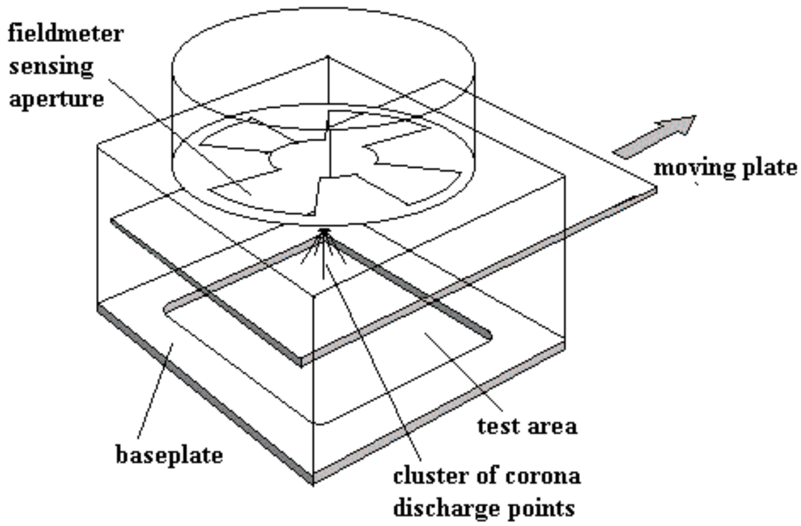

Figure 3.7 Arrangement for measurement of corona charge decay

The corona discharge is created by a brief pulse of high voltage (in the range ±2.5 to ±10kV) applied to a cluster of discharge points mounted on a moveable plate a short distance above the surface to be tested. The corona discharge deposits a local patch of charge on to the surface without contact. As soon as charge has been deposited the moveable plate is moved away (in 20-30ms). A fast response 'field mill' electrostatic fieldmeter, that has been shielded by this plate, is used to measure, without contact, the voltage developed on the surface by this charge and how quickly this voltage falls as the charge migrates away. If measurement is made of the quantity of corona charge deposited then the effective capacitance experienced by the charge on the test surface can be derived from the initial peak surface voltage created by this charge – as is discussed later. A full description of the design and test procedure for corona charge decay measurement is given in Annex 2 [45]. A paper has been published on the background [46].

The important practical features are that the times over which the corona charge is deposited and the time taken by the plate carrying the corona discharge electrodes to move fully out of the way for full view of the test surface by the fieldmeter are both short compared to the minimum decay time to be measured. To avoid problems from static electricity it is desirable that charge decay times are short compared to the times for separation of surfaces after mechanical tribocharging actions. This means decay times should be less than ½ second. To cover this and fast manual actions it is desirable to be able to measure decay times to 0.05s or below – and for this the times for charge deposition and plate movement need to be down around 0.02s.

Experience from many studies on a wide variety of materials shows that the form of charge decay curves a) rarely follow an exponential form, and b) that they depend little, if at all, upon the quantity of charge transferred to the surface and hence the level of initial peak voltage generated. In tribocharging situations it takes a finite time for the contacting surfaces to separate and for the separated charges to create an influence on items nearby. This time is typically 100ms or so. In the light of these points it is important that the performance of materials should be assessed in terms of the time for the surface voltage measured at this time (initial voltage) to fall to some specified fraction of this. The fraction chosen for the end point of timing may conveniently be 1/e (37%) and/or 10% of the initial voltage. The fraction chosen should be clear in the reporting of results. The advantage of using a 10% figure is that if the form of the decay curve flattens out significantly (as does happen with some materials) then by the time this level is reached there is not much charge left and little influence on items nearby. The disadvantage is that with some materials this may involve excessively long test times. It is suggested that measurement to both levels should be made whenever practical and also that the form of the decay curve is recorded to be available for any fuller analysis deemed necessary. This can be very useful for materials showing very slow charge decay as estimates of performance can be made with test durations much less than the time to reach the 1/e (37%) level. Examples of charge decay curves for copy paper are shown in Figure 3.8 with the start of analysis 100ms after the end of corona charging. The curves show a) reproducibility between repeat tests, and b) independence of decay times to 10% on initial surface voltage.

In practice materials may be used as supported freely and well away from any earthed surfaces or, at the other extreme, actually resting against an earthed surface. These two extreme situations may be described as ‘open backing’ and ‘earthed backing’. Charge decay measurements need to be made with both these test conditions in assessing general suitability of materials [9,28]. The longer of the decay time values with open backing and with earthed backing should be used.

It is considered generally most appropriate to make measurements on test areas that are initially charge neutral, or whose surface voltage is less than say 2% of the expected initial peak voltage.

Procedures appropriate for formal calibration of the surface voltage and decay time performance of corona charge decay measuring instruments are described in Annex 3 [45].

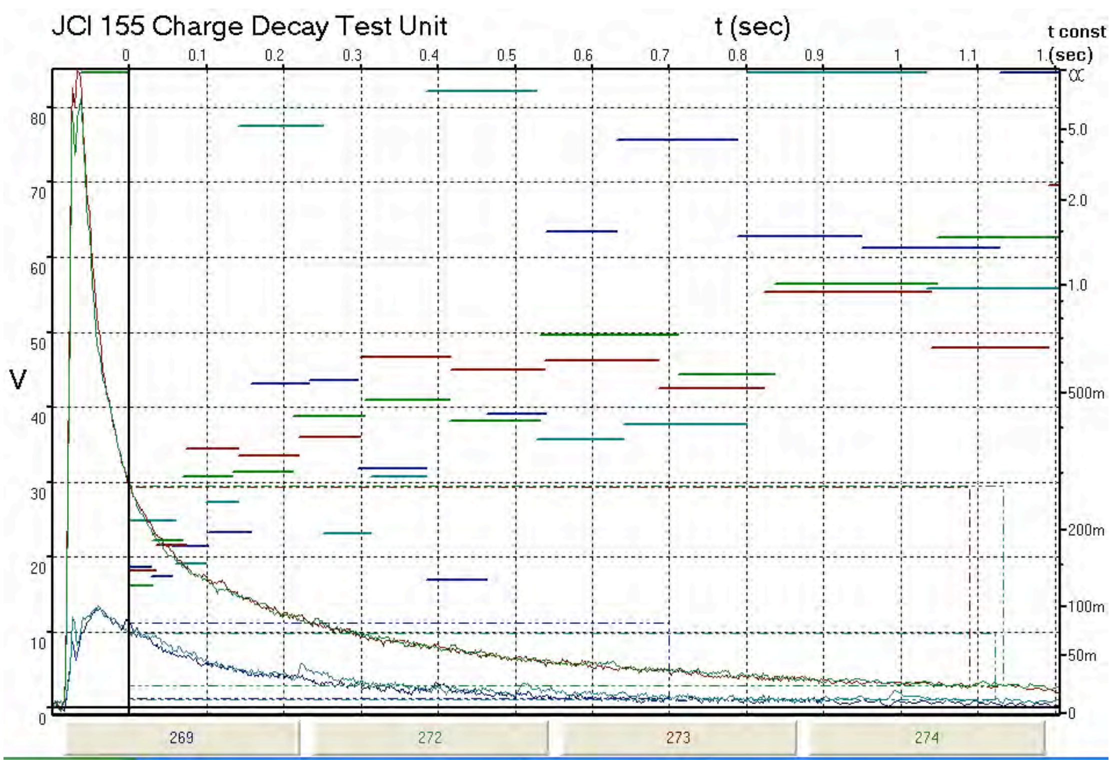

Figure 3.8 Examples of charge decay curves for copy paper with two levels of initial charge and start of analysis 100ms after end of corona charging

3.4.5 Capacitance loading

The influence of electrostatic charge on materials to items nearby depends on the level and on the time present of the surface voltage. The quantity of charge per unit of initial peak surface voltage is effectively a 'capacitance'. If this capacitance is large then only low surface voltages will arise from the quantities of charge likely to arise in practical tribocharging events. Conversely, if the 'capacitance' is low then high voltages will arise. For instance, fabrics that include conductive threads, such as for personal protective clothing and cleanroom garments, show high values of 'capacitance'. Although some such materials show long charge decay times they may present little risk of causing problems [18,21]. Thus for many situations it seems that the suitability of materials to avoid problems from retained static charge may be judged by both the charge decay time and by the capacitance exhibited to surface charge [45].

Calculation of 'capacitance' from the quantity of charge required to create a measured value of surface voltage is not fully valid. The area over which charge is deposited (by tribocharging or by corona) is likely to be much smaller than the area of material of uniform potential for which the voltage measurement instrument was calculated and the charge on the surface will not be uniformly distributed. The voltage will be non-uniform over the surface and with a peak value rather higher than the value interpreted from the fieldmeter measurements. Rather than guess an area for the deposited charge, in order to calculate a real 'capacitance' it is more practical to assess materials in terms of their 'capacitance loading' [1,2]. This is the apparent 'capacitance' as observed for the test material (as $C = Q / V_{pk}$) divided by the apparent 'capacitance' observed for a very thin dielectric layer, such as cling film. It is assumed that there are similar distributions of surface charge for the two materials. This ratio approach takes out concern over non-uniformity in charge distribution and differences between instruments and test arrangements.

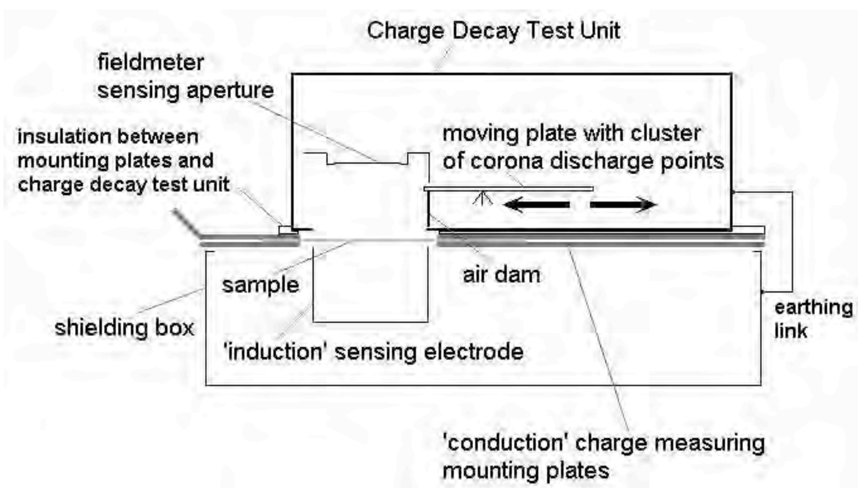

Figure 3.9: Arrangement for measuring received charge

The charge transferred to a test surface can be measured with the arrangement shown in Figure 3.9. The charge is measured as a combination of the conduction and induction signals [1,2]. The 'conduction' charge signal relates to the charge that moves or couples fairly immediately to the sample mounting plates. The 'induction' signal relates to charge held for a time near where it has been deposited and is free to couple up to the inside of the charge decay test unit and down to the induction electrode. The induction electrode may be made physically similar to the sensing region of the charge decay test unit so the induction fields from the retained charge is partitioned about equally between the two. The total charge may be expressed as:

$$Q_{tot} = Q_c + f\ Q_I$$

- where the factor f is expected to be about 2. This is because the induction sensing electrode arrangement below the test surface is made a reasonable match in form to the sensing region above the sample – so the influence of induced charge is split roughly in half.

With a simple dissipative sample material, such as paper or cling film, it is observed that nearly all the initial observations are associated with 'induction' charge effects and that this decreases while the conduction signal increases. The total corona charge deposited is of course constant, hence the fall of the induction signal, $Q_{i,}$ must match the increase in the conduction signal Q_c. A factor, f, may hence be found that gives a good constancy between the sum of the two signal variations.

Capacitance loading characteristics of materials often vary appreciably with the quantity of charge deposited [20,21,45]. It is desirable to make measurements of capacitance loading (and also to check charge decay times) with quantities of charge of both polarities over a wide a range of quantities of charge and down to as low levels as practicable. It has been found that the value of capacitance loading extrapolated to zero charge then provides a basis for predicting the surface voltages likely to arise on practical surfaces with tribocharging [21]. If decay times are longer than a second or so then the maximum surface voltage V_{max} (volts) that can be expected in practice for a quantity of transferred charge q (nC) can be calculated from the capacitance loading values extrapolated to zero charge ($CL_{q=0}$) as:

$$V_{max} = n\, q / (CL_{q=0})$$

- where n is a factor (typically around 75) [21,45]. Practical values for q are likely to be no more than 50nC.

For critical assessment of materials it is important that testing is done under well controlled and Standard values of temperature and humidity with adequate time (for example 24 hours) for accommodation to test environmental conditions.

3.5 MEASUREMENT OF SHIELDING PERFORMANCE

3.5.1 Introduction

The method of testing the shielding performance of layer materials that has been developed for the ESD Association Standard is based on measuring energy transfer [47]. This is appropriate for the area of interest of protecting semiconductor devices and assemblies in transport and storage packaging. However, it does not provide much information for other areas of application or for appreciating how shielding performance is achieved.

The ESDA Test Method for measuring the shielding performance of packaging bags used for microelectronic components and assemblies is illustrated in Figure 3.10. The basis of the test method is to apply a high voltage impulse across the outside of the bag and observe the energy received by a low impedance measurement circuit within the bag. The form of the impulse is what is called a 'human body model' discharge with a current risetime of 2-10ns followed by a 150ns fall time. 'Satisfactory performance' means the energy received within the bag shall be less than or equal to 50nJ for a 1kV discharge. The energy is derived by integration of the current waveform observed by the current transformer with the 500 ohm load resistor. The instrumentation for this test method requires a high quality current transformer and a high performance digital storage oscilloscope.

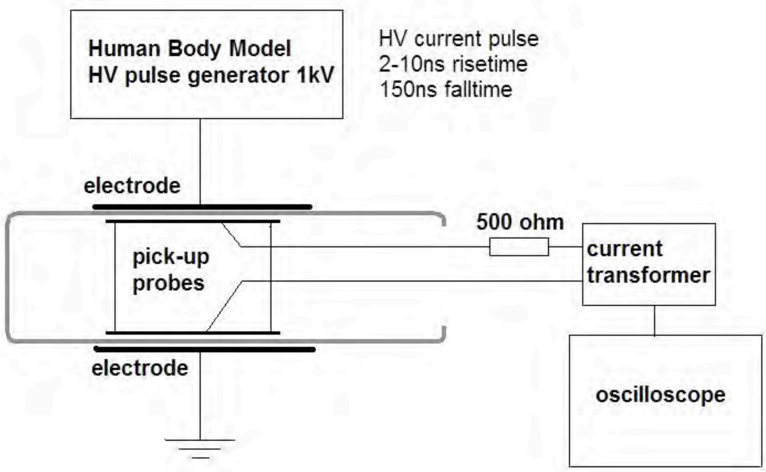

Figure 3.10 ESDA method for measurement of shielding performance

3.5.2 Alternative method of testing

An alternative method of testing has been developed that measures how the electric field shielding performance of materials varies with frequency [48]. The advantage of the method is that it provides a wider range of information about the characteristics of the material and, in particular, does not require any contact to the resistive feature or any earth bonding contact or connection. Studies with this approach have shown how the performance of some materials, such a 'black bag' films, falls away strongly as the test frequency increases whereas that of films with evaporated metallic coatings varies little with frequency. This suggested the idea that the variation of shielding performance with frequency might provide a unique and non-invasive way to measure the effective resistivity of materials.

The approach developed for measuring the shielding performance of film and layer materials [48,49] has five basic features:

a) a plane area of the test material, isolated from earth, is tested by applying a transverse electric field stress over a defined area by inductive coupling from a pair of nearby electrodes

b) the electric field stress is applied as a balanced bipolar signal relative to earth and covering a wide range of frequencies. Symmetry about earth potential ensures no common mode signal is impressed on the sample as a whole.

c) measurements are made of the signals inductively coupled to a pair of electrodes on the far side of the sample in positions matching those of the driving pair of electrodes. Observations can be made either as the difference signal between the electrodes on the other side of the sample or from either of these relative to earth

d) shielding is measured at a variety of frequencies as the ratio of signals observed with the material present compared to that without

e) shielding performance is presented as the variation of the ratio of signals as a function of frequency

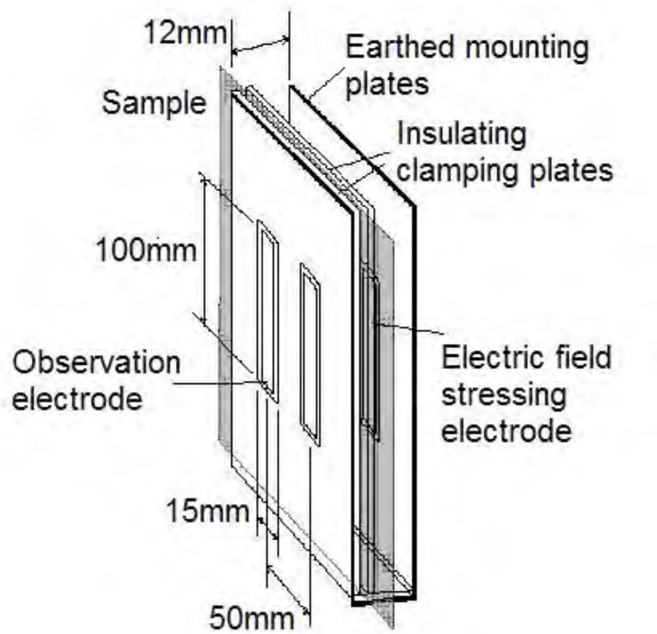

Figure 3.11: General arrangement for shielding measurements

The basic physical arrangement of the approach is shown in Figure 3.11. In the two test assemblies made to date the electrodes have been 15mm wide and mounted flush in earthed plates to be parallel and with their centre lines 50mm apart. In the first test assembly the electrodes were 50mm long and in a more recent assembly 100mm long. The 100mm length was chosen for studies on the characteristics of fabrics including conductive threads where the threads might be spaced as much as 25mm apart, so a rather wider area of test seemed wise. The arrangement of the observation electrodes matches the electric field stressing electrodes. The inner surfaces of the electrodes and mounting plates have been 10mm apart. The sample is clamped flat against a 3mm thick sheet of good quality dielectric (polycarbonate) on the observation side by a second sheet advanced from the driving electrode side. This arrangement ensures the sample is held flat and in a well defined position relative to the stressing and observation electrodes.

The initial test arrangement aimed to test the shielding performance of materials over the full range of frequencies relevant to risks of damage to microelectronic devices – 10Hz to 1GHz. The stressing electric field was generated by bipolar high voltage pulses of amplitudes up to 10kV. The rise time was around 3ns at 10kV and 1ns at lower pulse voltages. The fall time was over 0.1s.

The signal picked up by the observation electrodes was divided into 9 frequency bands using low Q bandpass filters centered on each decade of frequency from 10Hz to 1GHz. Because the filters needed to respond well to single pulse signals, and narrow bandwidths were not needed, the Q was hence set to unity for all channels except the GHz channel, where it was 0.7. The signals of each filter channel were held in peak detector and hold circuits and these were scanned by a 12 bit analogue to digital converter (ADC) and transferred over a serial data link to a local microcomputer within the time constant of the hold circuits. The computer analysed, stored and displayed observations.

Examples of the variation of shielding performance with frequency are shown in Figures 3.12 and 3.13. Figure 3.12 shows that the shielding performance of a metallised layer type material varies little with frequency, whereas Figure 3.13 shows that performance of a resistive material (black shielding bag) falls away rapidly with increasing frequency.

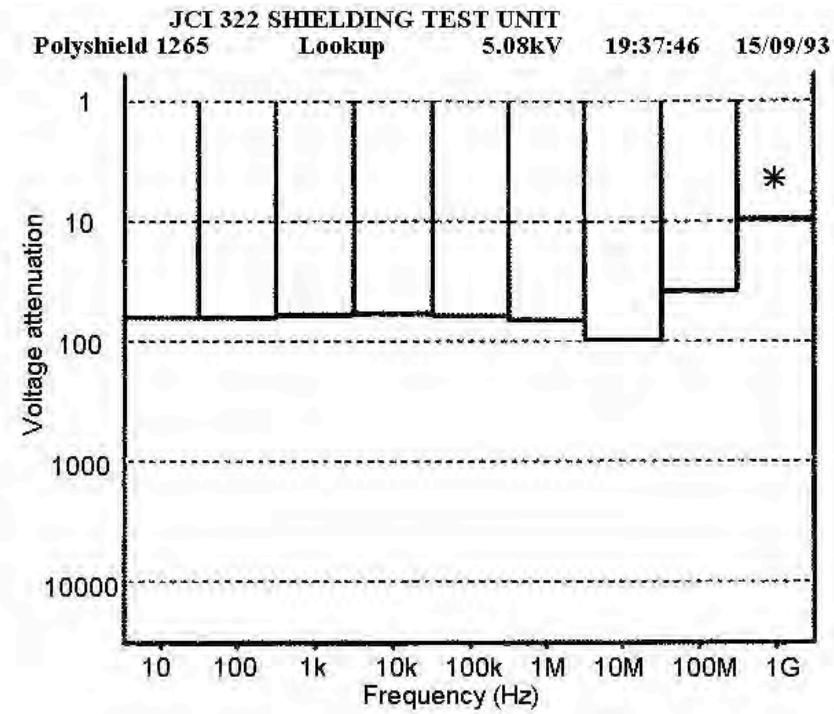

Figure 3.12: Variation of attenuation with frequency for metallised film material

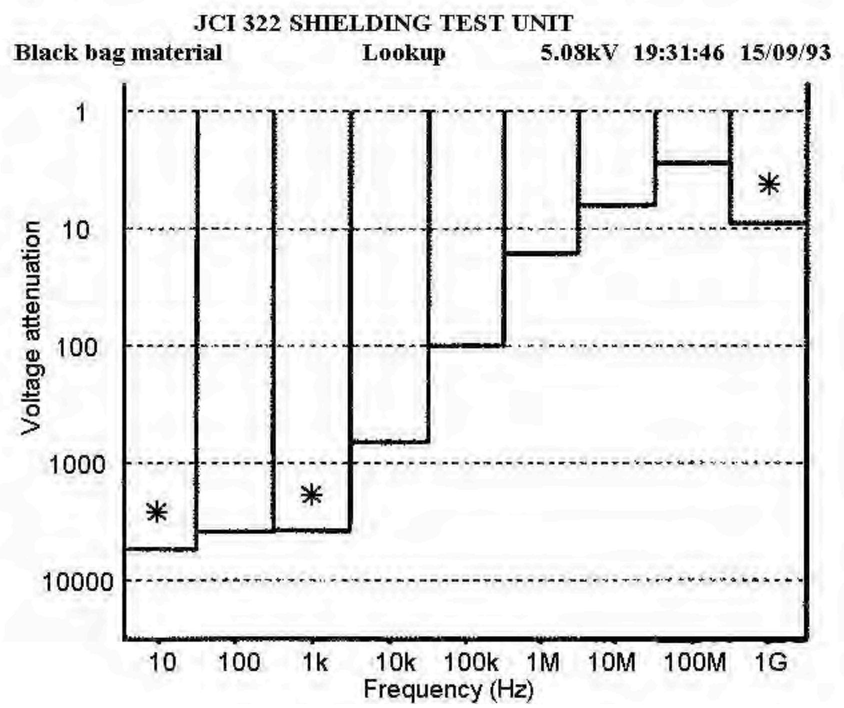

*Figure 3.13: Variation of attenuation with frequency for a carbon loaded 'black bag' resistive material (measurements marked * were somewhat uncertain)*

While the above approach was shown to be basically sound in philosophy the prototype hardware did not operate very stably at the higher frequencies – 100MHz and GHz. Studies on cleanroom garment fabrics, that included conductive threads, showed that attenuation was usually only significant at the lowest frequencies. With this in mind a much simpler approach has been developed to measure shielding performance on the more limited range of frequencies of 10Hz to 10MHz [49]. The same basic arrangement has been used for mounting the sample and test electrodes but the stressing electric field has been provided as balanced antiphase sinewave signals at a single frequency that is scanned over the range of interest. Because operation is more stable at these lower frequencies it has not been necessary to measure the reference signals at the same time as observations with the test material. The arrangement and basic circuits are shown in Figure 3.14. To give good signal to noise ratios at high attenuation the signals observed have been phase sensitive detected and filtered for measurement. To take account of the phase shift that occurs as attenuation rises the signals have also been phase sensitive detected in quadrature so the true attenuation can be derived as the square root of the sum of the squares of the two components.

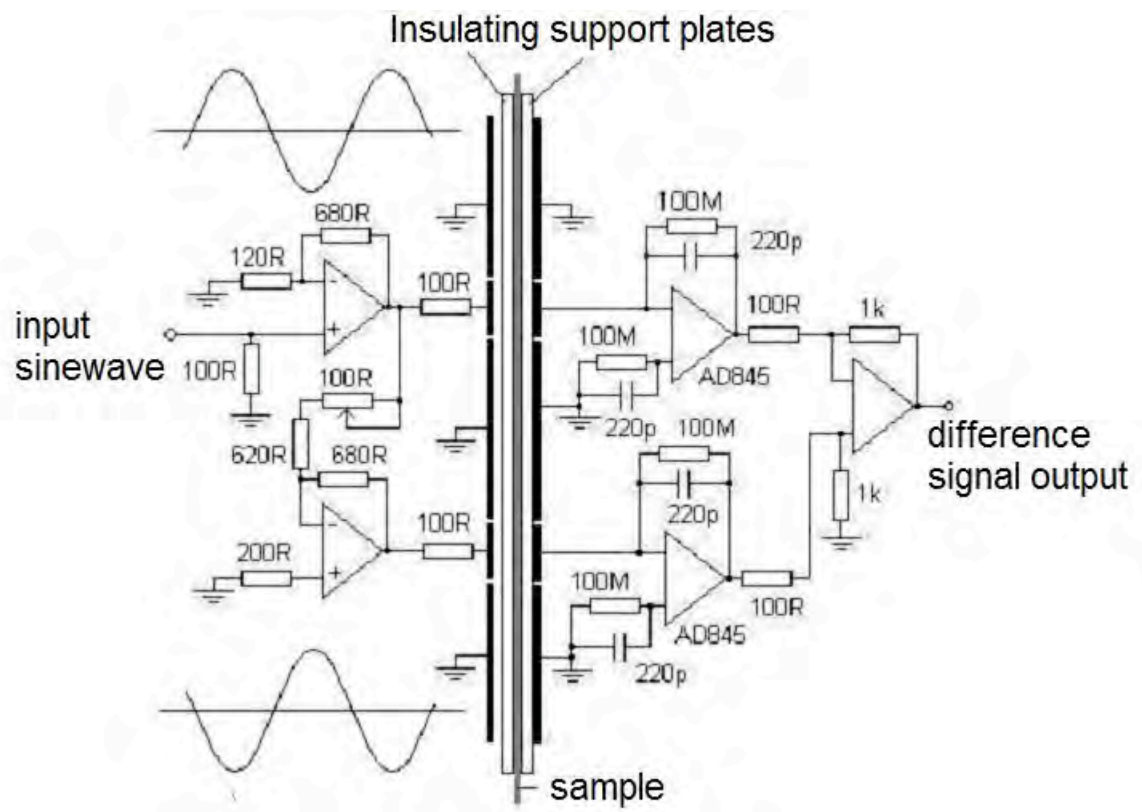

Figure 3.14: Bi-phase sinewave drive circuit and signal difference observation circuit

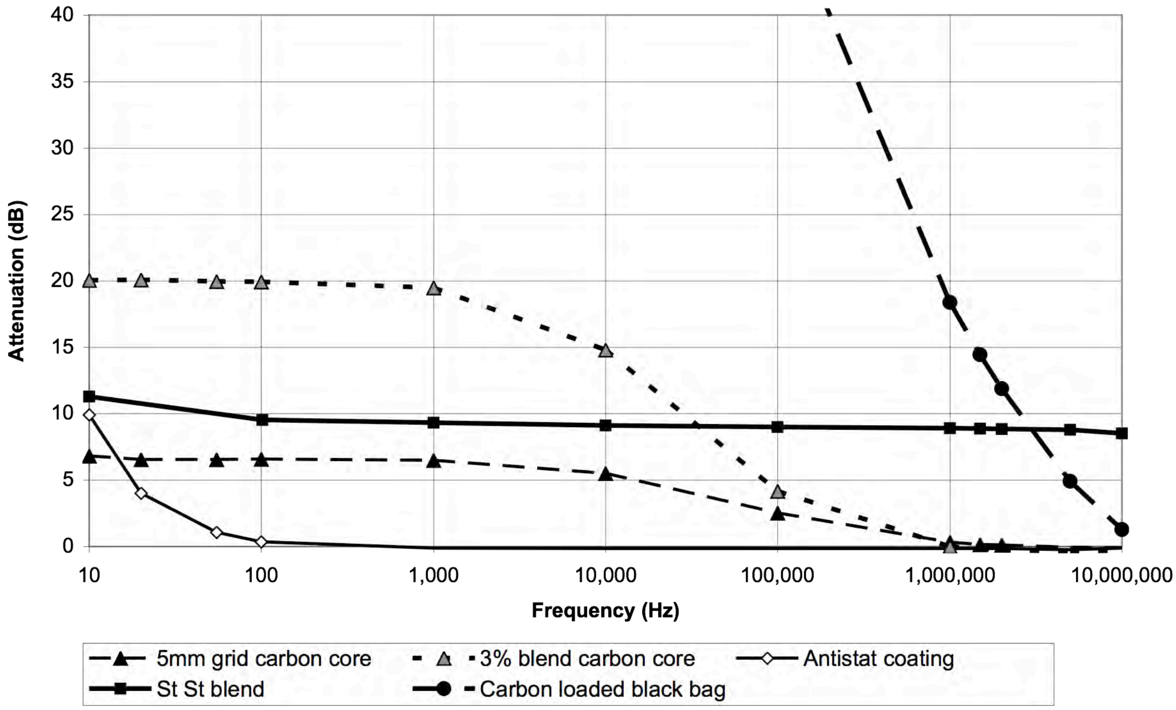

Figure 3.15: Shielding performance of a variety of fabrics and for black 'shielding bag' material

Figure 3.15 shows the variations of attenuation with frequency for two polyester based cleanroom garment fabrics that included core conductive threads, a fabric with stainless steel fibres blended in, a fabric with just an antistat coating and a piece of carbon loaded 'black bag' film from a shielding bag. The results in Figure 3.14 show that the attenuation of electric field signals by the material that includes metallic threads ('St St blend') is fairly independent of frequency whereas all others show a decreasing attenuation with increasing frequency. (The results shown in Figure 3.15 were taken before it was recognised that results should include measurement of quadrature components – as are included in the results shown in Figure 3.16. Figure 3.15 nonetheless shows real trends).

Measurements were also made with samples of single fine copper wires mounted across the interelectrode gap to examine the detection sensitivity for small quantities of conducting thread. A nearly uniform attenuation was observed over the frequency range, 10Hz to 10MHz, of around 0.54dB for a 0.5mm diameter wire and 0.42dB for a 0.2mm wire.

3.5.3 Relationship of shielding to effective resistivity

To relate the above characteristics to actual values of resistivity the planar samples of material were replaced, in the arrangement shown in Figure 3.14, by two 100mm long 15mm wide strips of brass foil mounted on dielectric sheets between the drive and observation electrodes and linked by a single resistor of defined value. Measurements were then also made with a layer of slightly damp paper whose resistivity could be measured from the resistance between two parallel contact bars.

The variations of attenuation with frequency are shown in Figure 3.15. (The finite attenuation shown by the brass strip and resistor arrangement at high frequencies is probably a result of fringing field coupling that was not present with the continuous area of slightly damp paper).

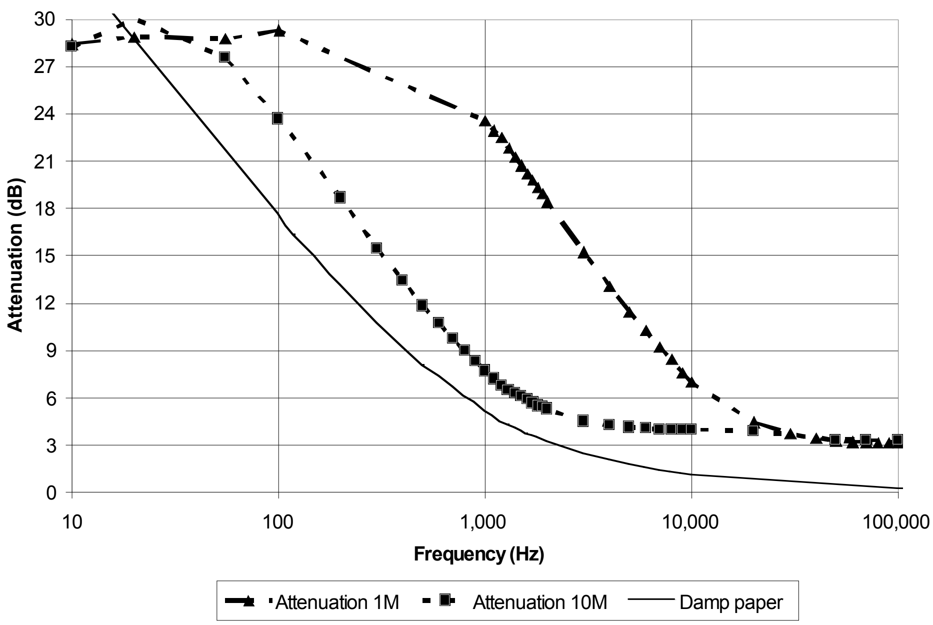

Figure 3.16: Variation of shielding performance with frequency for 1M and 10M resistors between brass strips and with damp paper

The variations of shielding performance observed with 1M and 10M resistors are similar in form but shifted in frequency by a factor of 10. The mid-range variation of attenuation with frequency is about 6dB per octave – which is what would be expected for an RC type filter. Comparison between these measurements suggested that the effective resistance presented by the 'damp paper' was around 20M. As the test area of the damp paper was that between the two 100mm long strips with 50mm separation the effective 'resistivity' appeared to be about 40M. Conventional measurement of the 'resistivity' of the damp paper sample with two contact bars gave values 30-50M - which is in at least reasonable agreement [49].

3.6 MEASUREMENT OF CHARGE TRANSFER AND CURRENTS IN DISCHARGES

Measurement of the charge transferred and of the current flow in electrostatic discharges, from charged surfaces and objects, are often made using quasi-spherical ended probes. The probe may approach the charged surface or the surface voltage may be allowed to build to the breakdown level. Many studies are conducted using unshielded probes and an unshielded probe design has been proposed for measuring charge transfer for a new IEC Standard IEC 61340-4-6 (as for example [51]). It has been argued before [52] that only shielded type probes will enable correct measurements to be made of charge transfer and of current flow. The need to use shielded probes was examined in a recent paper together with demonstration of performance for both conducting and insulating charged surfaces [53]. An example of a shielded probe is shown in Figure 3.17.

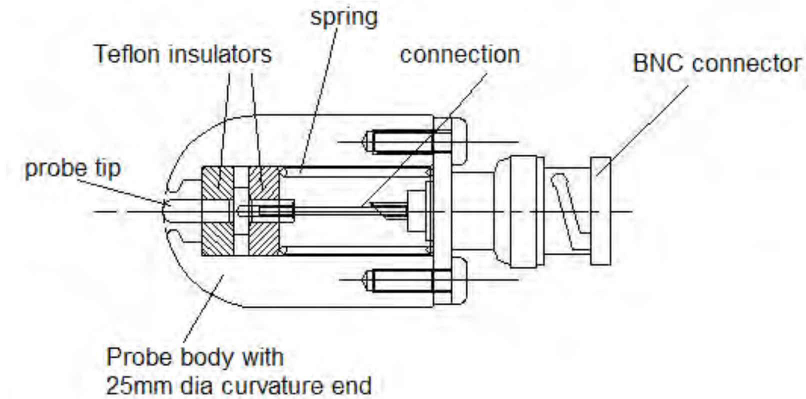

Figure 3.17: Example of shielded probe

Measurements of charge transfer and current flow in static discharges may be made by measuring the voltage developed across, respectively, a capacitor or a resistor to earth.

For charge transfer measurements the capacitor needs to be of good quality and of sufficient value to avoid generation of any significant voltage on the probe tip (for example less than 20V) to avoid changing the character of the discharge.

If a virtual earth is used for measuring charge transfer in discharges it is important to note that the performance of a virtual earth circuit is limited by the output drive current capability of the op amp used. If the output drive current is less than the input current then the input may not be held within the supply rail voltages and the output will not match the input. This of course is a particular problem with fast discharges (for example between conducting surfaces) as the amplifier then has to provide both high current and fast feedback. There are two ways round this problem for quantity of charge measurement: first, is to use a buffer capacitor on the input from the discharge probe with a feed resistor that limits the maximum current to within the feedback current capability of the amplifier. This is illustrated in Figure 3.18.

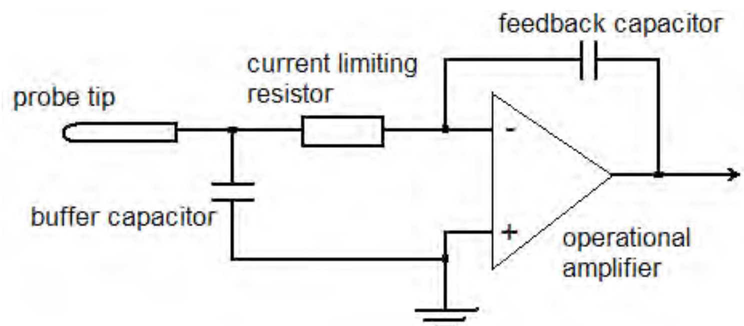

Figure 3.18: Example of buffer capacitor with virtual earth charge measurement amplifier

An input buffer approach, of course, slows down the response. This is not a problem just where total charge transfer is to be measured but it would be in current flow measurement.

For fast current flow measurement the resistor to earth needs to be of low inductance and care is needed to match the transmission line characteristics of the coax cable connection to the display and recording oscilloscope [51]. As discharge currents may be up to a few amperes it is important that the resistor has a low value to avoid voltages being developed that may affect the character of the discharge. Static discharges from small items at only a few kV have risetimes down below a nanosecond [54] so great care is needed in measurement arrangements.

Where good quality discharge current flow measurements are made and recorded with adequately high time resolution then the quantities of charge transferred can be obtained by integrating the current flow over the duration of the discharge.

3.7 MEASUREMENT OF RESISTANCE

There are plenty of commercial instruments available for measurement of resistance up to around 10^{14} ohms. Methods for measurement are described in a number of standards [1]. Instruments are available to measure much higher values but these need to be used with care and appropriate test procedures. One problem with measuring very high values of resistance is that the reading may change with time after application of the test voltage because the movement of charge is not necessarily linearly dependent on electric field and the distribution of charge varies as it migrates in relation to the capacitance it experiences. A decision needs to be made at what point to take the relevant reading.

In a number of instances it may be practicable to derive resistance and also current by measuring capacitance and voltage decay rate. An example is measuring the leakage resistance of an electrostatic voltmeter. The capacitance of the high voltage electrode system can be measured. A voltage can be applied and resistance derived from the RC time constant observed. It is not difficult to measure leakage resistance values in this way to over 10^{15} ohms. A special advantage in this situation is that the effective leakage resistance can be measured up to the maximum operating voltage of the voltmeter and so take into account any corona that may occur.

3.8 MEASUREMENT OF CAPACITANCE

There are plenty of commercial instruments available for measurement of capacitance and with the ability to make measurements with a resolution to around 0.1pF. The relevance in electrostatic studies is usually to assess the capacitance of a person standing on the floor, a container resting the ground or of an item of plant isolated from ground. It may also be necessary to measure the capacitance of electrode structures and low value capacitors involved with ignition testing.

An important point in measuring low values of capacitance (blow around 1nF) is to minimise the influence of varying capacitance to the measurement lead. The best approach is to hold the measurement lead via an insulator stand-off to minimise direct hand capacitance. The measurement electrode is held just out of contact with the test surface, the ‘zero’ reading is noted and the reading then taken after the minimum movement of the lead to make contact.

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