4. PRACTICAL ELECTROSTATIC MEASUREMENTS

4.1 Introduction

This chapter is concerned with the use of electrostatic instruments, such as described in Chapter 3, for practical and experimental investigations and for measurements relevant to decisions on the suitability of materials and/or on the safety of situations.

Where work is carried out in a commercial environment it is necessary to recognize that customers are rarely interested in the physics of what is going on, in the theory of operation or in the technology involved. Customers are primarily concerned to achieve a solution to their problem or application and one in which they can have confidence. In this respect it is important to have clear objectives – what is going to be measured, how will the measurements be interpreted and how can results be used. It is usually helpful to work back from the end user requirements by considering how results can be used. This helps keep a proper focus and avoids spending time on just 'interesting' science! To ensure results can be used it is necessary to have a 'systems' appreciate of the problem – where, when and why the problem arises and its practical, engineering, economic context and the implications for personnel. It is also important to recognize that although the problem may be an electrostatic problem its solution need not involve electrostatics – so one needs to be aware of other problems, risks or relevant influences to the situation.

4.2 Fieldmeter measurements

Electrostatic fieldmeters are the workhorse instrument for electrostatic measurements. They provide the way to identify if, when, where and why there is an electrostatic problem. In many cases qualitative measurements are quite adequate to get a feel for where things are highly charged and to what features of an operation or activity does this charging relates. The following points need to be remembered in fieldmeter observations:

a) the fieldmeter must be bonded to earth throughout the time of measurement to define its potential. Do not rely on earthing via hand contact.

b) there needs to be confidence in the zero reading. This should not be a problem with 'field mill' type fieldmeters so long as they do not become contaminated (for example by charged dust). Care is needed with induction probe instruments to ensure are switched on in a field free region (with the sensing region well earth shielded) and that measurements are made within the known zero or reading drift time.

c) The operation of induction probe instruments is adversely affected by the presence of ionized air. This provides some effective conductivity which will allow currents to flow to the sensing surface and seriously upset observations. However, ionized air has little influence on the operation of field mill type fieldmeters so these should be used if ionized air is or may be present.

d) When searching for possibly charged items resting on an earthed surface it is helpful to lift suspect items clear of the surface. This will reduce the suppression of the voltage on the item by its capacitance to the earthy surface. (An example might be a plastic document cover resting on an earthy work surface). It is also of course helpful to have a fieldmeter with suitably high sensitivity.

e) When trying to identify charged items or charged areas of a surface it may be that observations are strongly affected by some other charge item nearby. Any plastic looking item should be considered suspect! A piece of aluminium kitchen foil (connected to earth) provides a simple way to shield suspect items and so give confidence in identification of items charged.

f) It may be that an item happens to be without charge at the time of examination. If an item or material is suspect then it is useful to see if it easily becomes charged when rubbed and how quickly that charge is able to dissipate. A example is the case of

flooring. It is useful to lay the fieldmeter on the floor surface so the sensing aperture is looking across the surface, the metalwork of the fieldmeter rests in contact with the floor surface and the display can be read from above. The floor is rubbed or scuffed, with the shoe, just in front of the sensing aperture. The fieldmeter will show if the flooring becomes highly charged and how quickly the charge is able to dissipate.

g) The operation of most fieldmeters is susceptible to water, dust and dirt. Fieldmeters can be built to operate without loss of performance in adverse environmental conditions – but this is not easy [1,2] and the instruments are larger and more expensive. One simple way to improve the immunity of normal fieldmeters to their operating environment is to provide a purge of clean dry air over the electronic circuitry and out through the sensing region to keep the sensing surface mounting clean and dry. This same approach, but using an inert gas, may provide a way to make investigative studies acceptable in situations where flammable gases may be present. This, however, needs to be considered carefully and agreed with the plant safety officer.

h) It is usually useful to make direct recordings of observations. This shows the time variation of electric field values and allows cross correlation of electrostatic variations to other events (for example features of plant operation). This can be very useful for interpretation of observations and for clear and persuasive presentation of results. A good example is the variation of body voltage during walking on flooring where individual steps are shown by the increase of voltage as each foot is lifted from the floor and the capacitance is reduced. There are several units available today (for example the Picoscope) that quite economically turn a PC or laptop computer into a 2 channel digital storage oscilloscope or datalogger.

i) Measurements of electric fields can be made with appropriately designed instrumentation immersed in dielectric liquids [3]. Because liquid shear at moving surfaces can cause charge separation it is best to use a fieldmeter geometry and speed of operation that minimizes such effects.

4.3 Measuring surface voltage

If an earthed fieldmeter is near a surface at a voltage then an electric field will be generated at the fieldmeter sensing aperture. The electric field depends in a complex way on the geometry of the fieldmeter and the surface. For operation at a defined separation distance there is a linear relation between voltage and the fieldmeter reading – but <u>not</u> with distance. This is shown below. (Many instrument manufacturers assume a linear relationship - which is not correct!). Fieldmeters may be conveniently set to display the surface voltage directly as the reading to become ‘proximity voltmeters’.

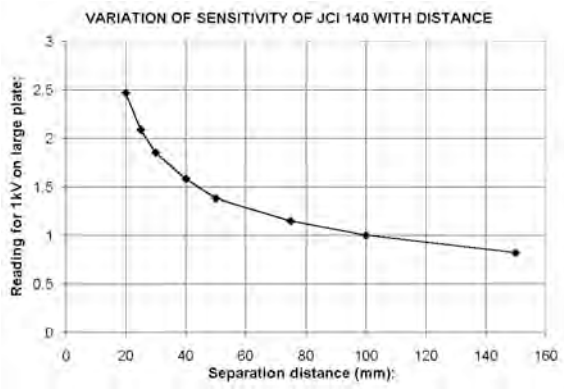


Figure 4.1

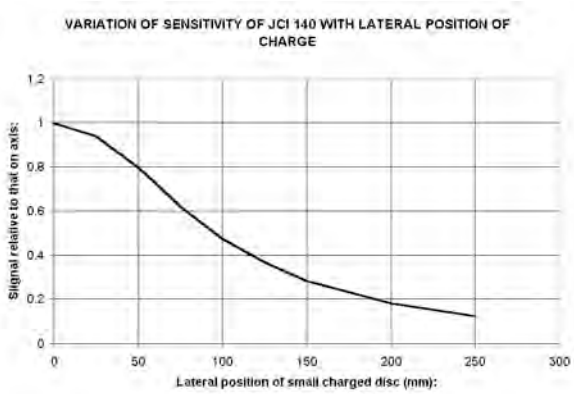


Figure 4.2

Two problems with such measurements: first, the proximity of the fieldmeter to the surface will add capacitance. This may affect the distribution of charge and the effective surface voltage. This is likely to be a particular problem with charged dielectric layers well away from nearby earthy surfaces. Second, while it is generally good to use a large separation distance this means that readings will be quite a bit in error for small surfaces and will easily be affected by other surfaces and charges nearby. Quantitative measurements may require physical or software modelling of the particular practical situation. This is considered later.

An elegant solution for accurate local surface voltage measurement is the 'voltage follower probe' [4]. This is basically a fieldmeter (usually using a tuning fork for signal modulation rather than a rotating chopper) with the voltage of the whole sensing head unit adjusted to give zero electric field at the sensing surface. This needs to be mounted close to the surface to give good immunity to influence from any other sources of static charge. This close spacing gives the opportunity for good spatial resolution of charge/voltage patterns. Because the probe potential follows the surface voltage it does not create any capacitance loading. The limitations of this approach are that it is difficult to make instruments that will make measurements on surfaces at many kilovolts or where the surface voltage is changing very quickly (probably faster than a kHz).

4.4 Electrostatic voltmeter

An ‘electrostatic voltmeter’ provides the ability to measure the voltage of a conducting item without drawing any charge or current. There are two major configuration for electrostatic voltmeter a mechanically stable mounting of a high voltage electrode near the sensing aperture of a fieldmeter with shielding to prevent any influence of other nearby sources of electric field. The second, ‘voltage follower’, arrangement is also a fieldmeter but with the sensing surface mounted close to the surface to be measured and the voltage of the fieldmeter servo-adjusted to achieve zero electric field [4]. This of course can be used with insulating as well as conducting surfaces – but is limited by the maximum feedback controlled voltage achievable and by the rate of change of surface voltage.

One particularly useful application of the electrostatic voltmeter based on the use of an earthed fieldmeter is for the measurement of body voltage. By connecting a person’s body to an electrostatic voltmeter with an well insulated lead it becomes easy to monitor the body voltage during such actions as walking over flooring, getting up from a chair and getting out of a car. All these are actions that can create voltages up to 20kV or more with variations in time relating to specific features of body actions. Examples are the increase in voltage associated with the change in capacitance on lifting a foot from the floor during walking. It needs to be recognized that the electrostatic voltmeter will have some internal capacitance (probably only a few pF) and the high voltage connection lead will also have some capacitance. The connection will be susceptibility to the influence of any other nearby varying charges. It is hence best to keep the lead as short as sensible and to avoid it tribocharging by rubbing against surfaces.

4.5 Measuring potentials in a volume

A fieldmeter at earth potential mounted well away from nearby structures acts as a probe of the local potential. The electric field at the sensing aperture E depends on the local potential V, present at that position before the fieldmeter was introduced, and the effective diameter of the fieldmeter d, as:

$$E = f\,V / d$$

The factor f is near unity [5,6].

This approach is very appropriate for measurement and long term continuous monitoring of atmospheric electric fields and for investigation or potential distributions in industrial risk situations. Notable examples have been studies of electrostatic risks during the high pressure jet

washing of the cargo tanks of large crude oil tankers [7,8] and electrostatic conditions during filling of large food product silos [8].

For operation in wet environments (for example for measurement of atmospheric electric fields) critical gaps need to be at least 6mm to avoid water bridging between plane horizontal surfaces. This requires an appropriately large sensing aperture to achieve sensible coupling of the external electric field to the primary sensing surface. Insulation for the sensing surfaces needs to be provided with suitably long surface tracking paths and, of course, the signal processing circuits need to be well protected from the environment [1,2]. Use of virtual earth charge measurement input circuits minimises the limitation on leakage to the sensing surfaces.

The actual sensitivity of measurement of a fieldmeter acting as a potential probe can be checked in the practical situation by applying a calibration voltage to the whole fieldmeter and its mounting assembly relative to earth under electrostatically stable conditions. This gives the change in fieldmeter reading as a function of applied voltage. If this is checked for linearity the relationship is established to predict the local voltage from fieldmeter readings. Predictions can be checked by raising the fieldmeter assembly to a voltage at which the electric field reading is zero – when the fieldmeter is at the local potential.

The ambient atmospheric electric field E_a can be conveniently measured using an electrostatic fieldmeter at earth potential mounted on a pole a known distance above ground level. In this arrangement the fieldmeter is used as a probe of the local potential at its mounting height. This mounting arrangement is simple to implement, avoids anxieties about ground level dust, debris and insects entering the fieldmeter sensing aperture and also gives useful enhancement to the basic fieldmeter sensitivity.

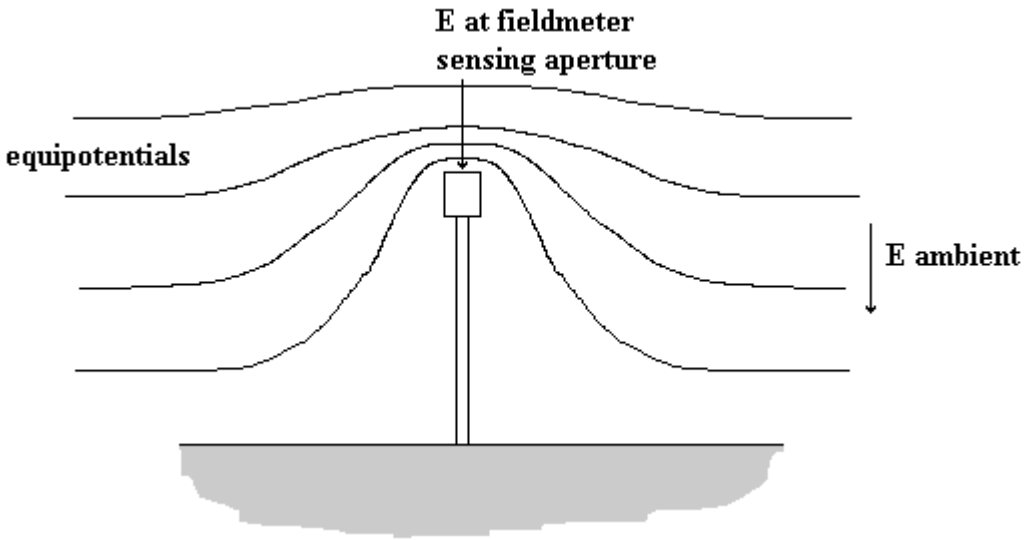


Figure 4.3 Perturbation of potential distribution by earthed projection

The local potential V observed by a fieldmeter measuring an electric field of E_{fm} (V m^{-1}) at the fieldmeter sensing aperture is close to:

$$V = E_{fm}\, d / a$$

where d the effective sensing head diameter (m).

For an ambient atmospheric electric field, E_v (V m^{-1}) the local voltage at a height h (m) is:

$$V = E_v\, h.$$

Hence the ambient electric field is obtained from measurement of the electric field at the fieldmeter sensing aperture as:

$E_v = E_{fm}\, d / h$

There will be a contribution to the electric field measured dependent on the alignment of the sensing aperture relative to the ambient electric field. If for example the two field components are in directions to add, then the atmospheric field can be derived as:

$E_v = E_{fm}\, d / (h\,(1-d/h))$

As d/h is normally small the influence of this effect is small.

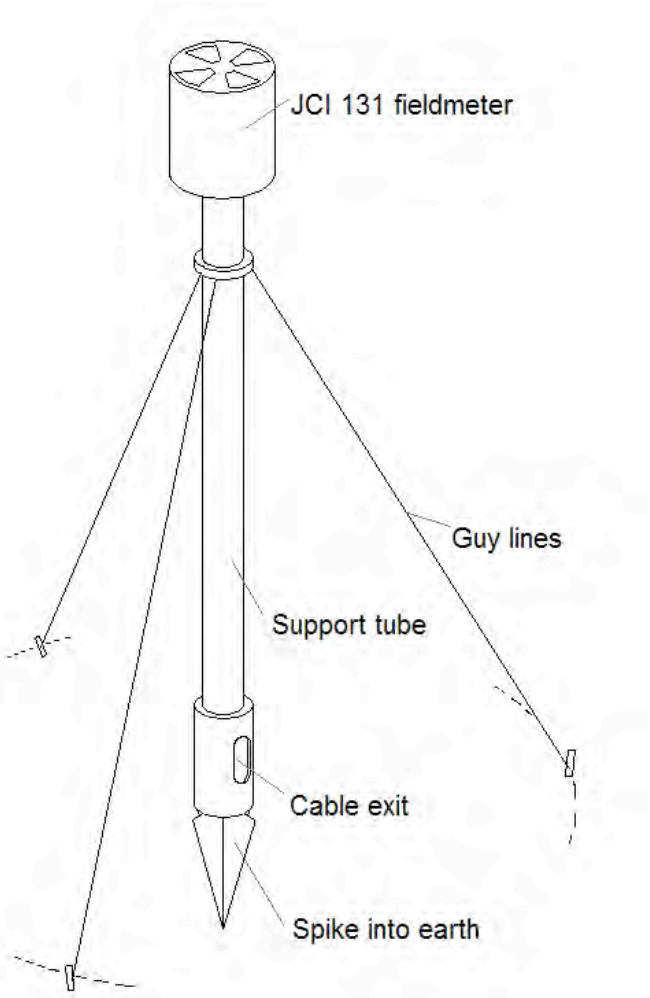


Figure 4.4 Fieldmeter mounting for measurement of atmospheric electric fields

A fieldmeter for long term monitoring of atmospheric electric fields needs to be immune to weather conditions. To avoid the risk of water bridging between sensing surfaces it is necessary for gaps to be greater than about 5mm. Insulation needs to provide long tracking paths. Opportunity needs to be provided in upward looking fieldmeters for rain water drainage. Use of virtual earth charge sensing input circuits minimizes the influence of leakage resistance between the sensing electrodes and earth. The electronic circuits need to be enclosed in a weather-proof casing. The simplest way to overcome risks of problems from ice and snow is probably to provide the option for some additional heating.

Operational health monitoring is important for confidence in long term continuous measurements in adverse environmental conditions. Continuous monitoring of operational health requires creation of an electric field at the fieldmeter sensing aperture that can be reliably separated from the quasi-continuous electric fields being observed [1,2]. This is conveniently achieved by applying an alternating potential either to the fieldmeter assembly or to a nearby

shield electrode that is at an odd sub-multiple and phase locked to the chopping frequency. The operational health signal can thus be arranged to provide no interference to the main electric field signal and its strength can be measured by separate phase sensitive detection at its frequency. The value of operational health monitoring was demonstrated some years ago by noting the influence of a spider's web spun across the sensing aperture of a fieldmeter that was monitoring atmospheric electric fields [2].

It is sometimes necessary to mount the fieldmeter assembly for long term monitoring of atmospheric electric fields in less than electrostatically ideal situations. Examples are the risk of some electrostatic shielding from nearby trees or antenna structures or alternatively the need for the mounting to be near the top of a hill. In such situations it is suggested that observations can be normalized by comparison of observations to simultaneous measurements with a hand held or portable fieldmeter making measurements over a nearby large flat area of ground under clear blue sky conditions.

Space potentials can also be measured using isolated 'water dropper' or radioactive sources. In both cases the potential of the source adjusts itself to the condition that there is no electric field to remove positive or negative charge from the source. At this point the source is at the local potential. The source potential may then be measured by a very high impedance voltmeter. These approaches may be useful for laboratory type experimental studies but are not suited to practical or industrial measurements. The charge balancing currents available are very small - so very high quality insulation is needed and time response will be slow.

4.6 Measurement of charge

The Faraday Pail is an appropriate and a very useful instrument for measurement of charge. However, its use needs to be approached with some care. The following points need to be borne in mind:

1) a Faraday Pail only measures the nett charge introduced. So material that contains large quantities of both positive and negative charge may show only a modest nett charge.
2) the pail and charge within the pail need to be well isolated from the surroundings. This means the pail needs to be fairly deep compared to its diameter and to be well shielded from the external environment (see Chapter 3.3.2).
3) If one wishes to measure the charge on samples of a powder it is important to remember that the very act of sampling by scooping up or sliding down a surface can easily generate additional charge on the powder. The same may well apply if liquid is sampled by flowing along a sampling tube. If the risk is recognized then the influence can be minimized – for example by gentle and careful handling to minimize surface rubbing actions. Where practical it is best for the powder (or liquid) to flow directly from the process into the Faraday Pail without contact to any other surface. Alternatively, it is probably better to take a relatively large sample rather than a small one, and to avoid tapping the last trace of powder into the pail as it is this that will have the strongest bonding, per unit quantity of material, to a triboelectrically different surface.
4) If powder is dispensed into the pail from a spoon or spatula it is best this is of metal and is connected to earth. It is also wise that the operator is bonded to earth and is wearing antistatic clothing. If a plastic surface is used for dispensing then retained charge may create electric fields at the powder separation point and affect the charge carried on the powder. If it is desired to measure charge separation as powder slides down an insulating surface (as a model of a practical problem situation) then it would be wise to start with the insulating surface charge neutralized.
5) If a simple Faraday Pail system is set up using a fieldmeter that happens to be available then it is necessary, of course, to earth the pail to start from a 'zero' reading condition.

In atmospheres that could be flammable this needs to be done with care to avoid any risk of an incendive discharge after the pail has become charged and may be at a significant voltage. A wooden 'earthing' contact is a simple way to avoid this risk.

4.7 Surface charge density

When a fieldmeter mounted in a large plane guard plate is brought up near a uniformly charged dielectric web, nearer than any other earthed surfaces, there is an electric field created:

$$E = (\sigma_1 + \sigma_2)/\varepsilon_o$$

where $(\sigma_1 + \sigma_2)$ is the algebraic sum of the charge densities on the web [10].

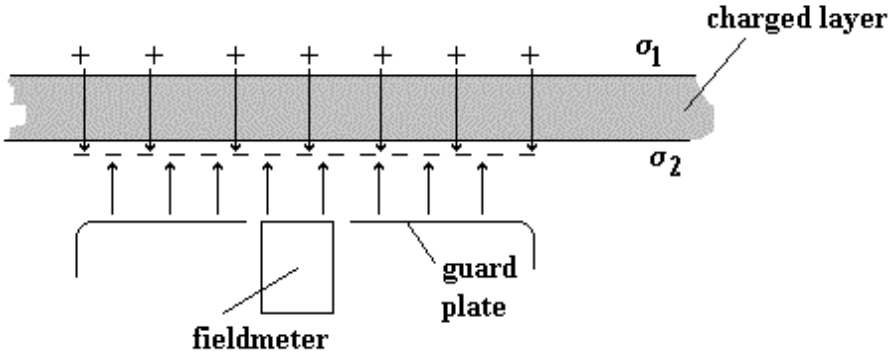


Figure 4.5 Measurement of surface charge density

If a charged dielectric web is rested against and earthed surface then only the charge on the outer surface is available to couple to a nearby fieldmeter. The electric field, at a guard-plated fieldmeter a distance d (m) away is reduced by capacitance effects so that:

$$E = \sigma\, t /(k\, \varepsilon_o\, d)$$

where t is the thickness (m) and k the permittivity of the web. This provides a practical way to measure the charges on each side of web materials.

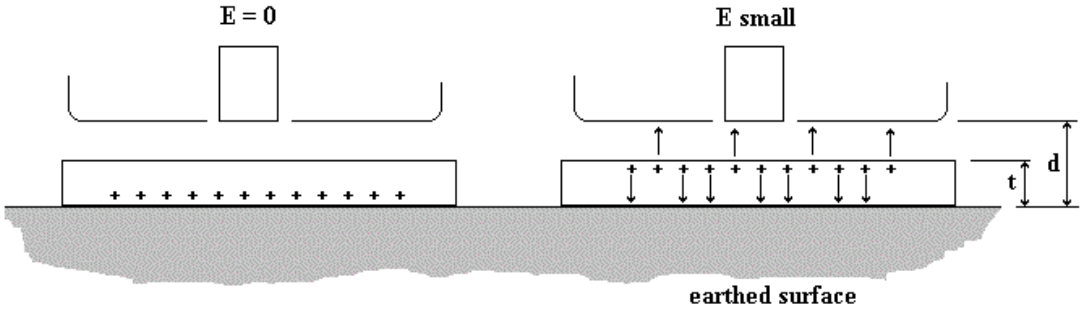


Figure 4.6 Measurements of charge density on a layer against an earthed surface

For example, a dielectric web of 100μ thickness and permittivity 2 with a charge density of say 10^{-6} C m^{-2} would give a field of about 1.2 10^5 V m^{-1} freely supported near a guarded fieldmeter and about 550 V m^{-1} if this web were rested against an earthed backing with the charge on the outer surface and the fieldmeter 10mm away. (In terms of a 'capacitance loading' [9.10,11] this would be equivalent to a loading value around 220).

The same sort of suppression of surface voltage may arise from conductive components

(layers or threads) buried within materials [9,10,11]. The relevance of this 'capacitance loading' effect can be directly checked by measuring the apparent surface voltage created by a known quantity of charge on the material and comparing this with that for a thin layer of a good dielectric material.

4.8 Volume charge density

The density of space charge in a volume can be measured from the maximum space potential (Chapter 3.2.3 above) or from the boundary electric field for simple geometric systems. For a uniformly charged spherical volume:

$$V_{max} = n\,q\,a^2 / (6\,\varepsilon_o)$$

$$E_{boundary} = n\,q\,a / (3\,\varepsilon_o)$$

Charge densities in more complex geometries may be measured using a small scale sampling volume that is transparent to charge movement but electrically opaque. This might conveniently be an earthed wire mesh cube or sphere with a fieldmeter looking inwards from the outer boundary. The electrostatic opacity can be checked by raising the shielded volume and the fieldmeter (operated by battery) to a high potential and checking that the fieldmeter reading is unaffected.

The density of space charge may also be determined in complex geometric structures using a fieldmeter that is bonded to earth to plot the distribution of space potential though the volume and then matching this to computer modelling calculations (see 4.16 below). Examples of such situations have been studies in silos and the cargo tanks of large crude oil tankers [7,8].

4.9 Charge decay for assessing materials

The importance of charge decay measurements for assessing the suitability of materials to avoid risks and problems and for the constructive use of static electricity has been discussed in Chapter 3.4. This emphasised the importance of using a correct test instrumentation and test procedure – that gives demonstrated matching of characteristics to those observed with tribocharging with a variety of sample materials [15]. In particular it noted the suitability of corona charging as a basis for compact and easy to use instrumentation that satisfied this requirement.

Some points that need to be noted in making charge decay measurements:

1) With thin fabric, film and layer materials it is important to stretch the test area to be flat. This avoids the sample surface being rubbed by movement of the air dam used to remove residual corona air ionisation and avoids oscillatory signals due to flapping of the surface.

2) With such thin fabric, film and layer materials it is necessary to make measurements both with an open backing and against an earthed backing surface. These represent the extremes of practical application and the longer of the decay time values observed should be used to judge acceptability of the material.

3) Where an appreciable surface voltage is observed after the sample is mounted into the test position then decisions need to be made as to how best to proceed. If the voltage is falling away moderately quickly then it will be best to wait for this to fall to a suitably low level before carrying out a test. If the observed self-decay is quite slow then it may be useful to start by measuring the self-decay of charge on the surface. With light films and powders it is also wise to make charge decay measurements with a slow plate release to minimise disturbance of the sample surface. Self-decay characteristics may

not match closely to the decay characteristics observed with corona charging because the surface distribution of charge may be very different from the normal localised patch of corona deposited charge. The charge distribution pattern may be more similar to a later time in corona charge decay when the initial local patch of charge has spread out over the surface and the rate of decay slowed up.

4) With long charge decay time materials, that easily become charged in normal handling, it may be quite acceptable to make simple charge decay tests just using a stable support for the samples and a fieldmeter to monitor the self-decay. As well as mechanical stability it is important to provide shielding against any other sources of charge around – including people! With a defined volume of powder, or liquid, the results should be sensible to compare between different materials.

5) Experience with a number of liquids [12] has shown reasonable matching between decay time and volume resistivity according to the textbook relationship, $\tau = e\, e_0\, \rho$. With some liquids the decay follows a nearly exponential form but with others the rate of decay slows up quite a bit duirng the progress of decay – as is observed with most solid material surfaces. While conductivity measurements may be more convenient with liquids it is recomended that matching to decay peformance should not be assumed.

6) Charge decay times with many powders are very long – for instance with many pharmaceutical powders and paint powders. In such cases the comments above need to be noted. Where decay times are likely to be over say 10,000s it is not usually practical to make measurements out to the 1/e level. In such situations it is useful to analyse the voltage decay curve to show the variation of the rate of decay during the progress of decay. This is best done by calculating the local decay time constant for small steps over the voltage decay curve as if the form of the decay curve over these short intervals did follow an exponential. When this is done two opportunities become available:

   a) it will be noted that after an initial period the local decay time constant increases rougly linearly with time. This provides an opportunity to calculate decay time to 1/e, or some other end point, for comparison between materials. For such predictions to be useful the surface voltages of the decay curve need to be measured with a resolution and stability better than 0.1% and with the advantage of ‘stutter timing’.

   b) a simple comparison between materials may be made in terms of the local decay time constant at a time of, say, 1000s

7) when making charge decay studies on film or layer materials it is useful to measure the quantity of charge transferred [13,14]. Calculations can then be made of the ‘capacitance loading’. If this is done over a range of quantities of charge it will be noted that there is a roughly linear variation of capacitance loading with quantity of charge. The intercept of the positive and negative corona measurements at zero charge then provide a basis for calculating the maximum surface voltages that are expected on the material as a function of the quantity of charge placed on the material [15,16].

8) In many situations a high capacitance loading is an adequate alternative to a short charge decay time – but not always. Studies were made on a problem with thin steel sheets for drink cans that were sticking together in a stack during manufacture causing problems with handling. These sheets were coated on one side with a protective plastic film. When many sheets had been collected into a stack it was difficult to separate them. Fieldmeter measurements showed very low surface voltages when the coatings were rubbed, in the range 100-200V. This voltage was stable – so the decay time was

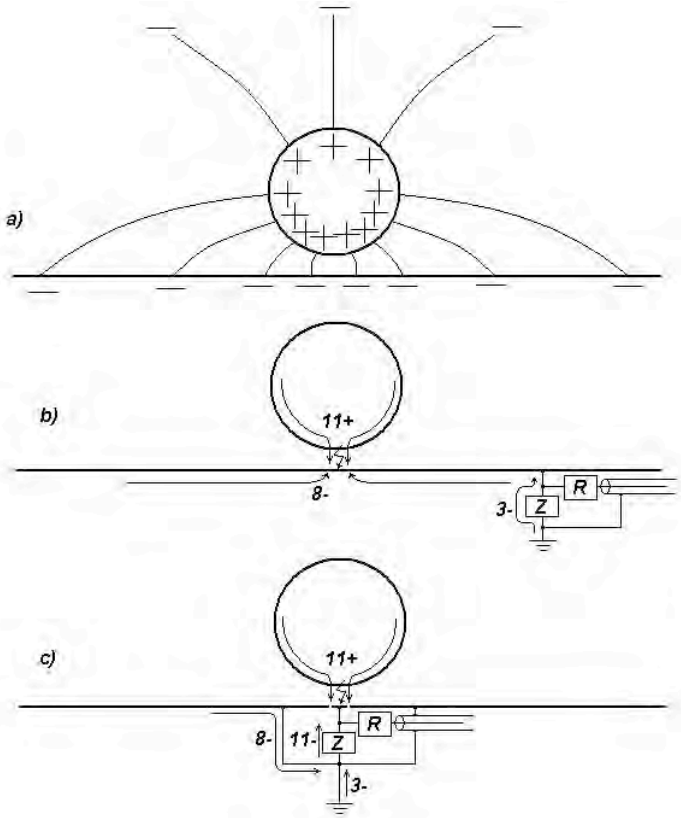
long. Because the protective film was thin and on a metal sheet backing the capacitance loading was obviously very high. On consideration it was realised that the sheets were very smooth and flat so the metal side of one sheet would come closer to charge on the plastic film that the thickness of the film. In this situation large electric fields would arise between the surface charge on the surface of the coating and the overlying metal surface. This was able to exert the high forces observed clamping the sheets together. This situation may also apply for dust settling on surfaces where charge may be retained on a thin surface coating and particles held by short range electrostatic attraction. From these examples one may conclude that high capacitance loading is only useful to control problems arising from the influence of surface charge at some distance from a surface – but not necessarily on a surface. Such problems will be overcome by ensuring the surface can dissipate charge, in the high capacitance loading situation of its application, with a decay time of no more than several seconds.

9) The charge decay time characteristics of many materials varies appreciably with humidity. Standard test conditions, to allow fair comparison between materials, require that measurements be made at the defined levels of 23C and 50%RH and 23C and 15%RH [17,18]. Other defined levels may be more appropriate for particular industries or applications. The surfaces of materials need to be exposed to these conditions for at least 24 hours to ensure full accommodation to the defined conditions. It needs to be recognized that any elevation of temperature within measuring instrumentation will affect the ambient humidity there – and 1C will be responsible for a local charge of about 2% in RH. It is hence useful to measure both temperature and humidity within charge decay measuring instrumentation.

4.10 Measurements on discharges

Care need to be taken in measuring the quantities of charge transferred and currents in electrostatic discharges [19,20]. As illustrated in the following diagrams it is important to use a shielded probe and ensure the discharge takes place to the probe tip. The same approach needs to be adopted for discharges to surfaces of insulating and composite materials [20]. The validity of this has been confirmed experimentally [20].

Figure 4.7 (a) shows a plausible electric field distribution associated with a charge sphere near a large metal plate. Figure 4.7 (b) shows that at discharge only the fraction of the sphere charge that was coupled to the outside world, rather than the plate, is observed by the measurement circuit. Figure 4.7 (c) shows that with a shielded probe all the charge transfer associated with the discharge flows through the probe and into the measurement circuit. Figure 4.8 shows an example of a practical probe design.



4.7 Arrangements for measuring charge transfer and currents in electrostatic discharges

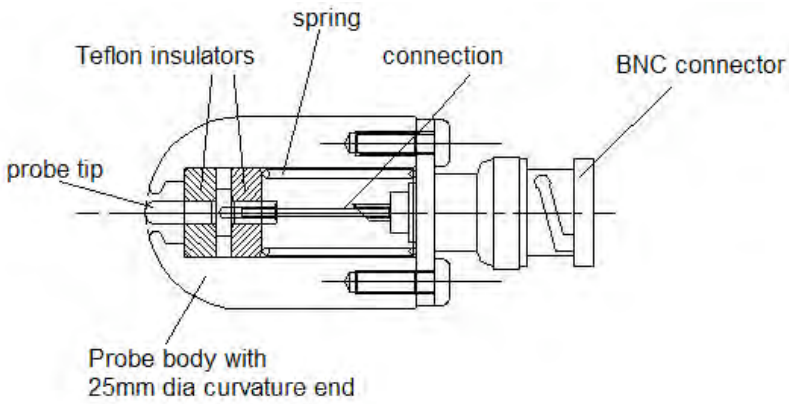


Figure 4.8: Example of design for a shielded probe

Electrostatic discharges can involve current risetimes down to below 1ns [21]. Proper measurements of current hence require the use of very fast response recording oscilloscopes with careful matching of observation signals into the coaxial cable to avoid risk of reflection effects. This means that the resistance Z must have a very low inductance and resistor R needs to be equal to the characteristic impedance of the coaxial cable, which needs to match the input impedance of the oscilloscope.

To avoid risk of the discharge spreading from the probe tip to the surrounding shielding surface the impedance Z needs to be kept low. For current flow measurements, a value of 1R is usually appropriate. This may conveniently be constructed from say ten 10R surface mount resistors in parallel arranged to minimise stray inductance.

If a virtual earth circuit is used for charge measurement then it will be necessary to have an input capacitor suitable to absorb the initial charge inflow with an input resistor to the virtual earth amplifier that limits the charge neutralising current to within the current capability of the amplifier. A similar need would arise if a virtual earth amplifier were used to measure discharge currents.

4.11 Radio detection of sparks – radio spectrum

The occurrence of spark type electrostatic discharges can be monitored fairly easily and at high sensitivity using radio detection circuits. Radio emission depends on the rate of charge of current in a discharge so spark type discharges radiate much more effectively at high frequencies than do corona type discharges. Sparks may be incendive, if the discharged energy is sufficiently high, but corona is generally considered to be unable to cause ignition. Thus radio detection provides a good way to monitor the occurrence of electrostatic events that could cause ignition events and to relate these to relevant operational activities.

Radio detection is effective over a wide range of frequencies - and 38MHz is convenient as it not within broadcast bands [22]. The radio receiver needs to be based on an r.f. amplifier stage followed by signal detection. A superhet configuration is not suitable because differences in phasing between the incoming signal and the local oscillator give wide variations of signal output. The antenna can be quite simple and may be a simple dipole or a tuned loop with coupled pick-up loop to match into coupling coax cable impedance. What is important about the antenna is the shield it in insulation with a sizeable radius of curvature and/or mount it in a region of low electric field to minimize risks of influence by corona or water spray discharges close coupled to the detection circuits. The influence of such discharges close to an antenna can also be minimized by using two separate radio detection units with a coincidence circuit to respond only to events coincident between the two antennae. If observations are to be made within a conducting enclosure than radio observation of the external environment in anti-coincidence will improve confidence in internal measurements. Radio detection observations have been used in a number of studies into the occurrence of electrostatic sparks during the washing of the cargo tanks of very large crude oil tankers with high pressure water jets [5,8].

The radio emission spectrum can provide useful information on the character of spark discharges and help identify the structure and position of sparks [23]. However, as spark events are individual it would be necessary to have a single short spectrum analyzer for such work!

Studies in the microelectronics industry have shown it is feasible to locate the source of sparks in three dimensions by measuring the relative time of arrival of initial signal edges at a number of antennae spaced apart to allow triangulation of observations [24,25].

4.12 Lightning warning

Clouds in the atmosphere contain charged water droplets. In thunderstorm conditions the electric fields within clouds become sufficiently high that long high voltage lightning discharges can be initiated. If the electric field below between the cloud and ground is sufficiently high then lightning discharges can occur to earth. The atmospheric electric field at ground level under a thundercloud will be 5kV m^{-1} or more.

Advance warning of the risk of local occurrence of lightning discharges is important in a variety of industries – e.g. connecting mining explosives, loading military munitions, personnel working in exposed outdoor situations.

A number of lightning warning systems are commercially available – some rely purely on measurement of local atmospheric electric fields, others combine this with assessment of the size of electric field steps associated with the occurrence of more distant lightning events. Other systems use the time of travel of low frequency lightning impulse signals to 3 or more base stations to locate the occurrence of lightning events.

An old Nitro Nobel system assessed the risk of local occurrence of lightning by combination of measured values of local atmospheric electric field with observations of lightning events from radio signals at 2-200kHz and radio noise in a narrow band at 27kHz. An update of this system has been developed (JCI 504) based on use of a JCI 131 electrostatic fieldmeter for measurement of local atmospheric electric fields with the use of the mounting pole as a radio antenna for radio circuits included within the casing of the fieldmeter. Operational health facilities are included on the electric field and on the two channels of radio observations. These operational health facilities provide confidence in long term continuous monitoring in even very adverse weather conditions [2]. The risk of local lightning is assessed via software comparison of values of electric field, the strength of noise signals and the rate of occurrence of lightning impulse signals – both relative to set threshold signal levels.

4.13 Incendivity of electrostatic discharges

The risk of ignition of flammable gases and powders by a capacitive electrostatic discharge relates primarily to the energy dissipated in the discharge [26]. There are influences from the duration of the discharge, from the radius of curvature of the electrodes, from the size of and the electrode gap, the temperature, pressure and oxygen concentration [26].

For discharges between metal electrodes the energy U (J) in the discharge will be:

$$U = \tfrac{1}{2} C V^2$$

- where C is the capacitance (farads) and V is the voltage (V). There is no accepted way (yet) to determine the effective energy released in discharges to insulating and composite materials.

In most practical situations the capacitance on which the discharge energy is stored is associated with some finite conducting body – a person, a drum resting on the ground, etc. In such situations the inductance in the discharge circuit in minimal and the resistance is that associated with the nature of the body involved. In building test equipment to measure minimum ignition energies care must be taken in the selection of capacitors and circuit arrangement to ensure there will be minimum inductance. System resistance should be low as the incendivity of discharges may be affected by the time duration of the discharge in relation to the flame kernel formation time. It is also important to ensure that the breakdown gap is sufficiently large. Powders present their own problems. They are usually dispersed into the discharge gap just before occurrence of the discharge. However it seems that ignition probability may be affected by dust residues from preceding tests and by whether an ignition has just occurred.

Ignition is a statistical occurrence, so measuring the incendivity of electrostatic discharges is difficult. This means that many tests are needed under particular conditions to determine a probability of ignition. Simultaneous observation of other relevant features of discharges should help understanding of ignition probability – for instance from observations of charge transfer, discharge current, low light level photography, sound output and the size of the flame kernel created (via, for example, shadowgraph or Schleiren photography).

Studies have been made on the incendivity of discharges between an earthed probe and charged insulating layers [27,28,29,30], to insulating layers on an earthed backing surface [27], to liquid surfaces [31] and between an earthed probe and charged clouds [32,33].

One problem that needs to be noted with incendivity tests to liquids is that the surface is likely to be unstable in the high electric fields that will arise just before breakdown. With rough surface materials, such as fabrics (particularly those including conductive threads), there can be opportunity for corona discharges before spark breakdown that will dissipate charge and reduce the local electric field values. In both cases these effects need to be counteracted by using an appropriately fast speed of approach between the discharging surfaces [7]. It is wise to try to measure the presence of any pre-spark discharge currents or charge flow.

Where discharge surfaces are dissipative (relatively short charge decay time) charge could migrate towards the high field region before occurrence of a discharge. This should also be

guarded against by choosing a speed of approach appropriate to the decay time characteristics of the surface.

The incendivity of discharges to materials seems likely to be affected by the resistivity accessible to a spark discharge [34]. Materials such as cleanroom garments with embedded conductive threads (surface or core conductive) and packaging materials with inner metallised layers are examples where the resistivity accessible to a static discharge could be very different from that measured as a surface property. The accessible resistivity may be the explanation for the ignitions observed on some materials when they are at high humidities [35].

It would be useful if spark incendivity probes included the facility to measure the quantity of charge transferred in discharges at the same time as testing incendivity. This would be a useful check on the similarity of repeated discharges. For such measurements it is necessary to use a shielded probe.

Testing incendivity with tribo or corona charging has limitations. The surface voltage of sample materials tested may be limited by lack of charge transfer and/or by surface charge migration and by the charge experiencing a high capacitance. The actual surface voltage achieved should hence be measured close to the time of occurrence of the testing discharge.

4.14 Shielding

Shielding against electric field transients is needed to protect sensitive microelectronic devices and assemblies against electrostatic damage while in electrostatically unprotected areas. Body voltages can rise to around 20kV and spark discharges could arise at any voltage up to this when packages contacted earth. Current risetimes may be down to 1ns, or less [21]. As device sensitivities may be down around 100V or less, it can be appreciated that good shielding performance needs to offer attenuations of at least 200:1 over the frequency range from 10Hz to 1GHz. Methods of performance measurement need to be able to cover this range.

Shielding performance depends upon conductivity within the material. The resistivity accessible to spark discharges is also relevant to the opportunity to draw energetic electrostatic sparks from charged surfaces [34]. Studies of shielding performance can hence be expected to have relevance to risks of incendive discharges [36].

From the device protection point of view, the most desirable method to measure shielding performance would be to have a fully isolated discharge source or detector inside the shielded enclosure and the corresponding item outside. This raises many practical difficulties. Probably the nearest approach would be a detector inside the enclosure that modelled the type of device to be protected by the enclosure but included elements that would indicate exposure to electric fields and currents of the level of interest with balanced sensitivity over the frequency range of interest. The nearest approach might be a semiconductor device with a number of breakdown gaps and fusible elements of known failure characteristic.

Present methods for assessing shielding performance use application of a unipolar, short risetime electric field pulse with differential oscilloscope observation of signals on the reverse side of the test sample. A ‘human body model’ type discharge pulse is used with performance assessed in terms of the fractional energy transfer through the sample [37]. A deficiency of present methods is they provide no information on the variation of performance with frequency so no guidance is given on suitability of materials for waveforms other than the test waveform. An approach was developed to provide this information [38] but his has not been developed into commercially available equipment.

The approach developed by STFI for assessing materials [39] seems to provide information on the opportunity for occurrence of incendive sparks from charged material surfaces. It may be that measurement of the variation of shielding performance with frequency up to a few MHz will yield comparable information [36].

4.15 Other measurements

Methods are described in the literature for measurements of low currents and resistance/resistivity [13,14]. Capacitance is another basic parameter often needing measurement in practical situations. Other aspects of measurements are considered in relation to the characteristics of materials in Chapter 3.3.

In making measurements of high values of resistance it is important to recognise the risks of leakage currents. These may arise over the surfaces of connecting leads and mounting jigs. Guard rings are a useful way to protect against stray current flows.

When measuring low values of capacitance with connections made via flexible leads it is important to isolate the measurement lead from capacitance of the tester's body (for example using an insulated handle, such as a screwdriver) and to make measurements as the difference of readings just out of contact and in contact.

4.16 Modelling

With studies on practical plant it is often not feasible to make measurements in the preferred location from the electrostatic point of view. Modelling by physical, analytic [40] or computer modelling [41,42,43] provides a way to relate observations at places which are accessible to values of potential, electric field and charge density at other places in a system.

It is often necessary make measurements of surface voltages on small items and/or in situations where observations are likely to be influenced by nearby surfaces. One practical approach is to substitute the item by an isolated conducting item of the same dimensions with an electrostatically shielded lead to an external voltage supply. Application of defined voltages to the conducting model item will produce a relationship between voltage and fieldmeter reading.

Computer modelling can handle quite complex structural arrangements, and in two and three dimensions. However, it would be very unwise to base interpretation of conditions of a complex situation on electrostatic observations at any single location. Modelling may well involve some assumptions about voltages on surfaces and/or the uniformity of space charge and/or the fraction of volumes filled. It is wise therefore to use multipoint fieldmeter observations and/or to explore the variation of voltage through some part of the volume. This provides a way to check the predictions of modelling against practical experience [7,8]. Figures 4.9 and 4.10 show examples of potential distributions calculated in large crude oil tanker cargo tanks during tank washing –

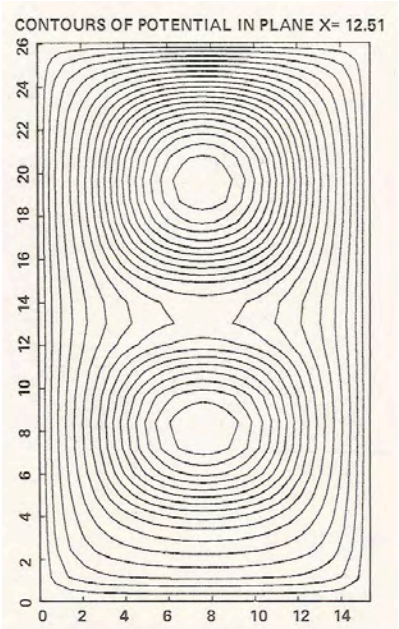


Figure 4.9: Computed potential distribution through the fieldmeter position in tank 4P (for charge density 10nC m^{-3} 9.5kV max 0.5kV per contour)

with Figure 4.10 showing correlation between computed and measured values.

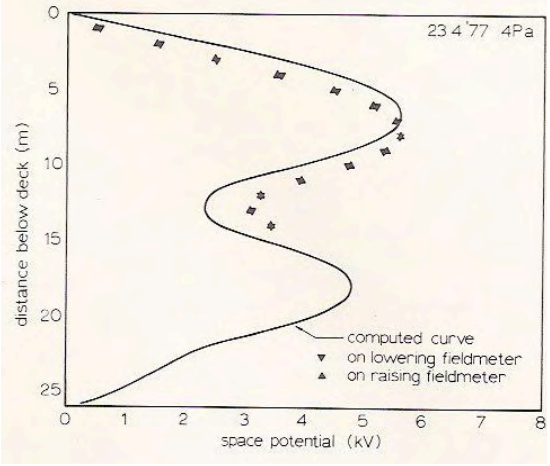


Figure 4.10: Comparison of computed and fieldmeter measured variations of potential

4.17 Calibration

To give confidence in the results of measurements, to satisfy ISO 9000 and to support any contractural or legal requirements, it is necessary that electrostatic measuring instruments are formally calibrated. Suitable methods for a number of basic measurements are described in British Standard BS7506: Part 2: 1996 [17] and in Annex 3. Formal calibration needs to be made using instruments whose measurement accuracy is traceable to National Standards. While it may not necessary that electrostatic measurements are made to high accuracy there is need for confidence in the values obtained to be with known levels of accuracy.

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