3. INSTRUMENTS AND MEASUREMENTS

3.2 BASIC METHODS

3.2.1 INTRODUCTION

The parameter of basic importance for static electricity is ‘charge’. This can, in some practical situations, be measured directly. However, observation of the electric fields created by charges provides a way to easily detect and locate sources of static charge and provide the basis to measure a whole variety of parameters of interest in electrostatics - voltages on surfaces 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. Separately there are needs to measure small currents, the resistance between contacting surfaces and the ability of materials to provide shielding against the electric field transients arising from electrostatic discharges.

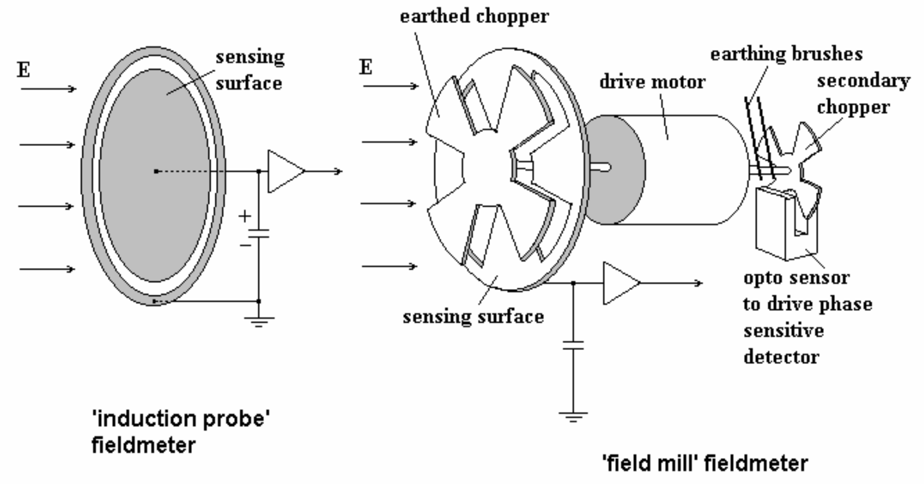
3.2.2 MEASUREMENT OF ELECTRIC FIELD

3.2.2.1 General features of fieldmeter instruments

The presence of 'static electricity' on items and surfaces is detected and measured at a distance and without contact using a 'fieldmeter'. These come in two basic types: 'induction probe' and 'field mill' instruments [1,2].

As shown below, the 'induction probe' fieldmeter 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 an input capacitor and the voltage developed across the capacitor or the charge induced is input to an amplifier (FET or MOSFET) with very high input resistance. The limitations of such instruments are they are not very sensitive and they cannot be used for long term continuous monitoring. It is also important to note that they must be 'zeroed' in a region free of electric field before each instance of measurement.

'Field mill' instruments overcome the limitations of simple induction probe instruments by using an earthed chopper to modulate the electric field at the sensing surface [2,3,4]. The basic arrangement is shown below. This system is mechanically more complex but provide much higher sensitivity, long term zero stability and avoids the need to 'zero' the instrument for each observation. 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 sensitivity is useful because it enables even low levels of static charge to be detected at a good distance and with confidence. High accuracy is often not necessary, but it is important when measurements with small differences are needed.



'induction probe' fieldmeter

'field mill' fieldmeter

Induction and ‘field mill’ type fieldmeters

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 [5]. 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. This is because the sensing aperture is much smaller as it is usually limited by the amplitude of vibratory movement. Internal gaps are also small, so there is also greater susceptibility to surface contamination.

3.2.2.2 New design features for ‘field mill’ fieldmeters

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 [1,2]. 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 thin wire 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. Also it may not be easy to mount and adjust suitable earthing brushes in small scale instruments.

A ‘back to back’ fieldmeter approach was devised in 1990 that overcomes many of the limitations of traditional ‘earthed chopper’ types of instruments [3,4]. 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 signal it is possible to fully compensate for the effect of any nett charge held on the dual rotor assembly.

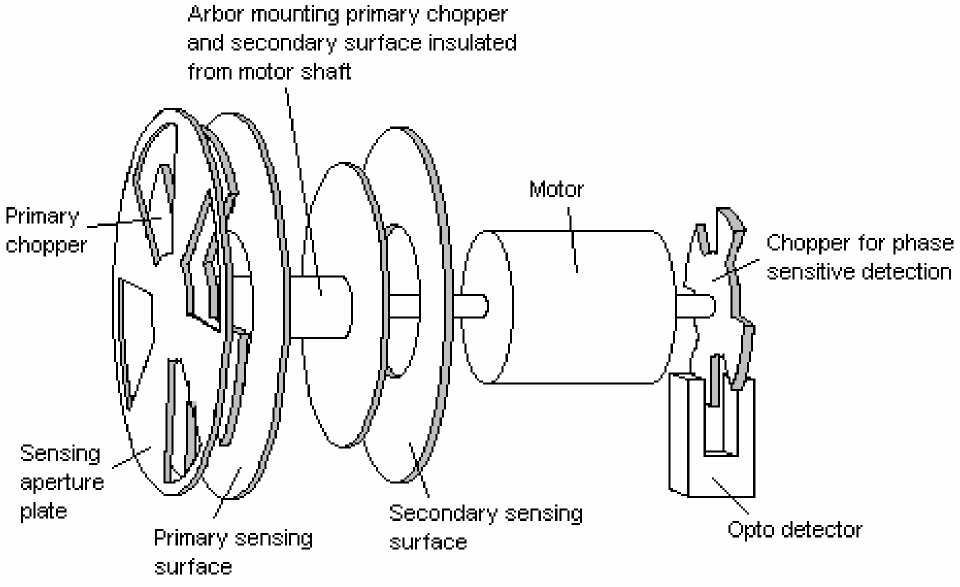


Figure 1: Basic arrangement for 'back to back' fieldmeter

A useful simplification for practical design 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. The diagram above shows the basic arrangement for the rotor assembly, the sensing surfaces, the motor drive and the phase sensitive detection.

Although infra red detectors are often used for phase sensitive detection these can be susceptible to tungsten light and sunlight illumination. Experience [4] has shown that magnetic reluctance is a very practical method for phase sensing. 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. Immunity to charge on the rotor assembly is easily tested in setting up these instruments by adding charge to, and then earthing, the rotor assembly and adjusting for no change of output.

The influence of corrosion and different electrochemical potentials on surfaces is minimised by gold plating all surfaces in and around the sensing region. It is also advantageous to keep gaps between surfaces as large as compatible with other design requirements to minimise the influence of dust and surface contamination and to avoid the risk of bridging by debris, fibres and water droplets.

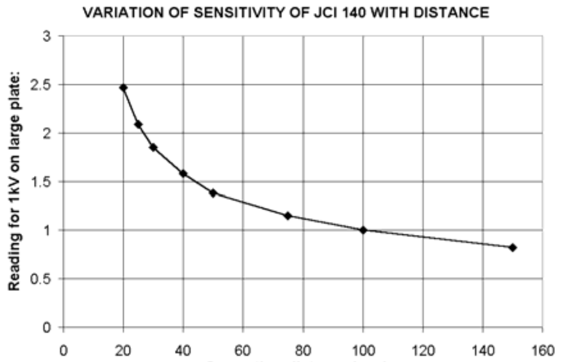
For operation in wet environments (for example for measurement of atmospheric electric fields) critical gaps need to be at least 6mm to avoid water bridging between plane horizontal surfaces. This requires an appropriately large sensing aperture to achieve sensible coupling of the external electric field 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 [4,6].

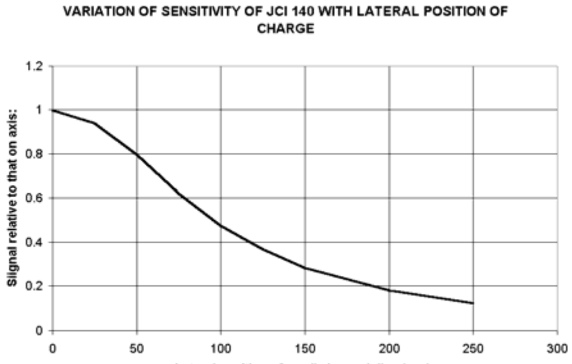
Calibration of electrostatic fieldmeters is carried out in relation to the electric field over the sensing aperture with this flush with a surrounding plane surface. Formal methods of calibration have been developed and documented [7,13].

The measurement of electric fields at the sensing aperture of a fieldmeter is one thing, interpretation of the meaning of observations is another. The use and interpretation of fieldmeter observations is considered in several of the following Sections.

3.2.3 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 not with distance. This shown below. (Many instrument manufacturers assume a linear relationship). Fieldmeters may be conveniently set to display the surface voltage directly as the reading.





Two problems with such measurements: first, the proximity of the fieldmeter to the surface will add capacitance and may affect the distribution of charge and hence 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' [5]. 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 is 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.

3.2.4 SPACE VOLTAGE

The local voltage in a space charge cloud (for example of charged mist or dust) can be conveniently measured with a fieldmeter mounted out on a pole or projection. The field at the sensing aperture of an earthed fieldmeter E depends on the effective diameter of the fieldmeter d and the local potential V, present before the fieldmeter was introduced [6,7], as:

$$E = f V / d$$

The factor f is near unity. The fieldmeter needs to be several diameters away from nearby surfaces.

The actual sensitivity of fieldmeters used as potential probes can be checked in-situ by applying a calibration voltage to the whole fieldmeter assembly. This gives the fieldmeter reading as a function of local voltage [6,7].

Application of a low level, low frequency alternating potential to the fieldmeter assembly can be used for continuous monitoring of the operational health of the observation system [8]. This ensures confidence in observations during long term operation in adverse environmental conditions.

3.2.5 CHARGE

Nett charge is best measured using a Faraday Pail. The nett quantity of charge introduced into the pail 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 necessary to note that the charge on the 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.

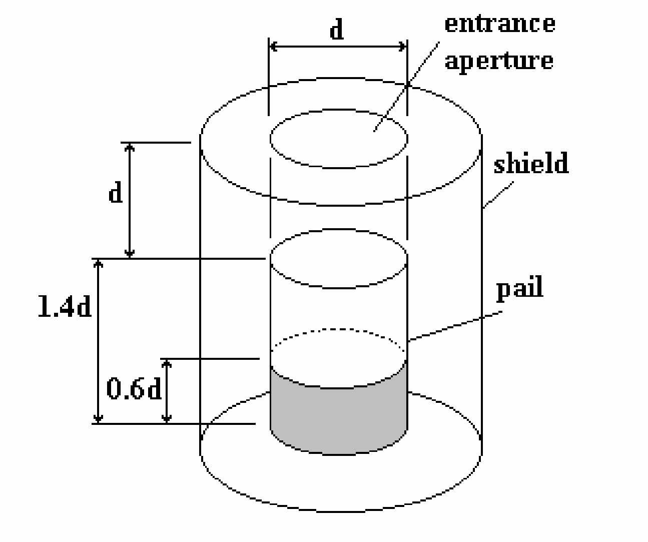
The pail needs to be designed and built with the following basic features [9]:

- 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 the pail needs to be fairly deep (a height to diameter ratio 1.4:1 or more with the charge retained within the lower 40% of the height
- the pail needs to be shielded against the influence of charges in the vicinity.

The charge appearing on the outside of the pail can be measured:

- by having the pail isolated from earth and measuring the increase in pail voltage in

relation to the total capacitance of the pail (for example using a fieldmeter)
- by a direct charge measuring electrometer circuit (operating in a ‘virtual earth’ mode)
- by integration of the current flow to earth



Faraday Pail

The first approach is very simple and has the advantage that it is easy to apply, and its operation checked, in a variety of practical configurations. It has the disadvantage that there is charge sharing between the capacitance of the test item and the capacitance of the pail system, so small errors will arise. The 'virtual earth' charge measurement overcomes this problem as the pail is held at earth potential. However, it is not quite as easy to check reliable operating conditions in practical set-ups.

With the fieldmeter measurement arrangement it is necessary to earth the pail if one wishes to start from a 'zero' reading condition. Note that in flammable atmosphere conditions this needs to be done with care to avoid any risk of an incendive discharge. A wooden earthing contact is a simple way to avoid this risk.

The ‘pail’ may be any convenient container. This can be supported on high quality insulation out of view of a fieldmeter used to measure the change in pail voltage and the whole assembly protected with an earthed shield.

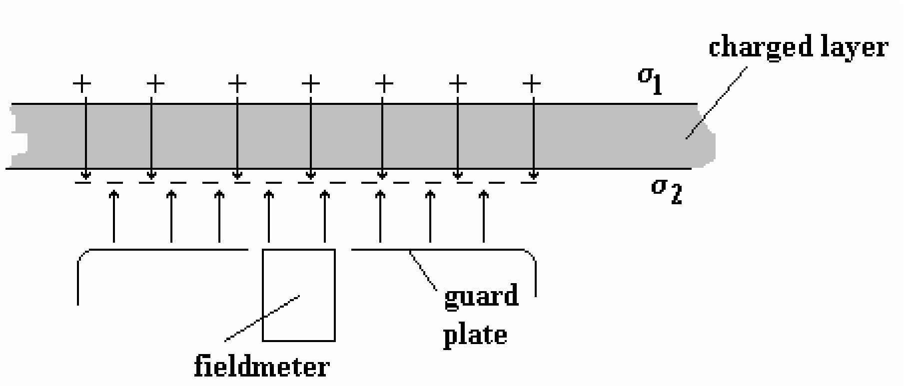
If it is not feasible to fully encompass the charged item or material within a Faraday Pail then a fieldmeter can be used nearby with appropriate attention to determine the relationship between charge and fieldmeter reading.

3.2.6 SURFACE CHARGE DENSITY

When a fieldmeter 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].

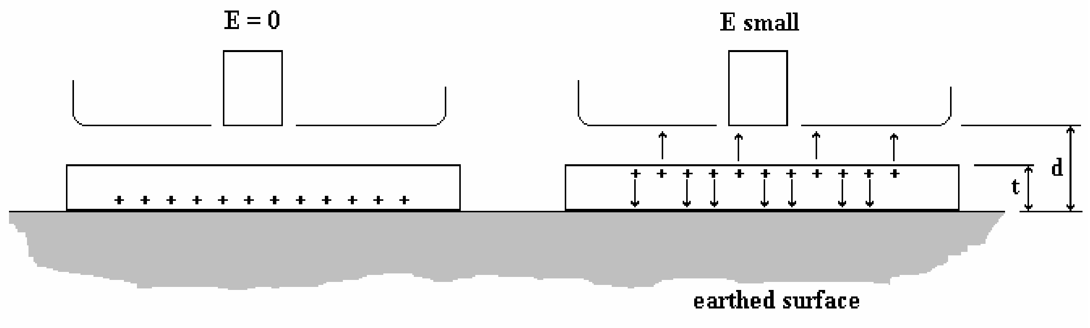


It is to be noted that the above relationship applies for large areas of ideal dielectrics. In practical situations where the areas of layer materials charged may be of limited extent the field observed may be reduced by 'capacitance loading' from within the material [9]. The relevance of this effect 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 [9].

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.



For example, a 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' this would be equivalent to a loading value around 220).

3.2.7 VOLUME CHARGE DENSITY

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

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

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

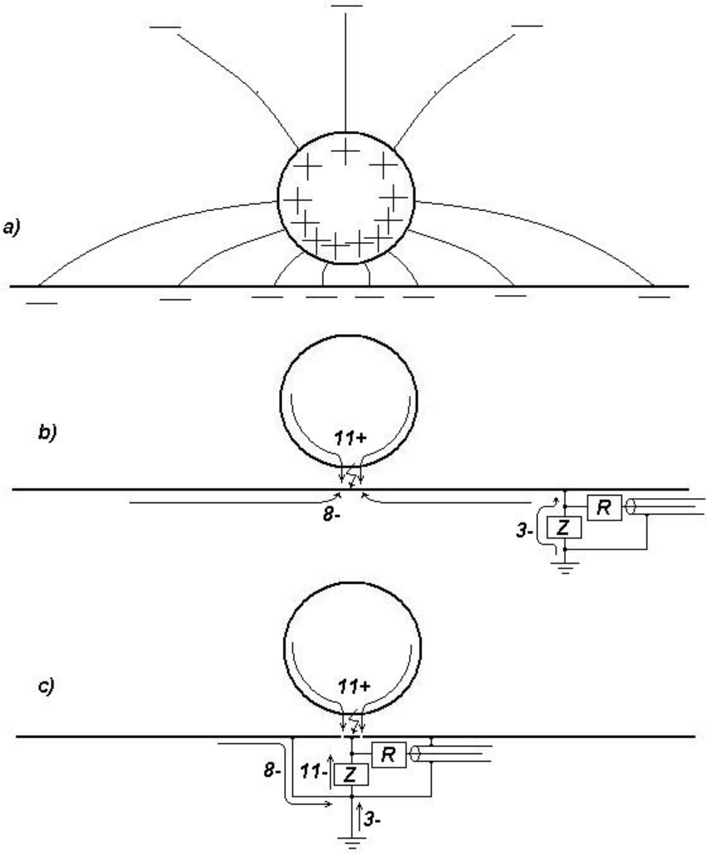
Charge densities in more complex geometries may be measured by a small scale sampling volume (transparent to charge movement and with an electrically opaque earthed conducting boundary) or by observing the distribution of space potential (3.2.3) though the volume in conjunction with modelling calculations (see Section 3.4.4).

3.2.8 CHARGE TRANSFER AND CURRENTS IN DISCHARGES

Care need to be taken in measuring the quantities of charge transferred and currents in electrostatic discharges [10]. 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.

Electrostatic discharges can involve current risetimes down to below 1ns. Proper measurements hence require 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 resistor R needs to be equal to the characteristic impedance of the coaxial cable, which needs to match the input impedance of the oscilloscope [11].

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.



Arrangements for measuring charge transfer and currents in electrostatic discharges

3.2.9 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 [12]. There are influences from the duration of the discharge, from the radius of curvature of the electrodes and the electrode gap, the temperature, pressure and oxygen concentration [12].

For discharges between metal electrodes the energy U (J) in the discharge can be measured as:

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

- 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.

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 may help understanding of ignition probability – for instance, charge transfer, discharge current, light output, sound output and the size of the flame kernel created (via, for example, shadowgraph or Schleiren photography).

3.2.10 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 Section 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 where connections are 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.

3.2.11 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 are described in British Standard BS7506: Part 2: 1996 Annex [13]. Formal calibration needs to be made using instruments whose measurement accuracy is traceable to national standards.

In general it is not necessary that electrostatic measurements are made to high accuracy, but there is need for confidence in the values obtained within known levels of accuracy.

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