



Standard Test Method for Static Electrification¹

This standard is issued under the fixed designation D 4470; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last approval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the generation of electrostatic charge, the measurement of this charge and its associated electric field, and the test conditions which must be controlled in order to obtain reproducible results. This test method is applicable to both solids and liquids. This test method is not applicable to gases, since a transfer of a gas with no solid impurities in it does not generate an electrostatic charge. This test method also does not cover the beneficial uses of static electrification, its associated problems or hazards, or the elimination or reduction of unwanted electrostatic charge.²

1.2 The values stated in SI units are to be regarded as the standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:

D 618 Practice for Conditioning Plastics for Testing³

D 5032 Practice for Maintaining Constant Relative Humidity by Means of Aqueous Glycerin Solutions⁴

E 104 Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions⁵

3. Terminology

3.1 Definitions:

3.1.1 *conducting material (conductor), n*— a material within which an electric current is produced by application of a voltage between points on or within the material.

3.1.1.1 *Discussion*—The term “conducting material” is usually applied only to those materials in which a relatively small potential difference results in a relatively large current since all materials appear to permit some conduction current. Metals and strong electrolytes are examples of conducting materials.

3.1.2 *electric field strength, n*—the magnitude of the vector force on a point charge of unit value and positive polarity.

3.1.3 *excess electrostatic charge, n*—the algebraic sum of all positive and negative electric charges on the surface of, or in, a specific volume.

3.1.4 *insulating material (insulator), n*— a material in which a voltage applied between two points on or within the material produces a small and sometimes negligible current.

3.1.5 *resistivity, surface*—the surface resistance multiplied by that ratio of specimen surface dimensions (width of electrodes defining the current path divided by the distance between electrodes) which transforms the measured resistance to that obtained if the electrodes formed the opposite sides of a square.

3.1.5.1 *Discussion*—Surface resistivity is expressed in ohms. It is popularly expressed also as ohms/square (the size of the square is immaterial). Surface resistivity is the reciprocal of surface conductivity.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *apparent contact area, n*—the area of contact between two flat bodies.

3.2.1.1 *Discussion*—It is the area one would calculate by measuring the length and width of the rectangular macroscopic contact region.

3.2.2 *dissipative material, n*—a material with a volume resistivity greater than 10^5 ohm-cm and less than 10^{12} ohm-cm, a resistivity range between conductive and insulating material as defined in this test method.

3.2.3 *real contact area, n*—the regions of contact between two bodies through which mechanical actions or reactions are transferred.

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² Vosteen, R. E., and Bartnikas, R., Chapter 5, “Electrostatic Charge Measurements,” *Engineering Dielectrics, Vol. IIB, Electrical Properties of Solid Insulating Materials, Measurement Techniques*, R. Bartnikas, Editor, ASTM STP 926, ASTM, Philadelphia, 1987.

³ *Annual Book of ASTM Standards*, Vol 08.01.

⁴ *Annual Book of ASTM Standards*, Vol 10.02.

⁵ *Annual Book of ASTM Standards*, Vol 11.03.

3.2.3.1 *Discussion*—Since real bodies are never perfectly smooth, at least on a microscopic scale, the real contact area of apparently flat materials is always less than the apparent contact area.

3.2.4 *triboelectric charge generation*—the formation, with or without rubbing, of electrostatic charges by separation of contacting materials.⁶

4. Significance and Use

4.1 Whenever two dissimilar materials are contacted and separated, excess electrostatic charge (triboelectric charge) will be found on these materials if at least one of the materials is a good insulator. This excess charge gives rise to electric fields which can exert forces on other objects. If these fields exceed the breakdown strength of the surrounding gas, a disruptive discharge (spark) may occur. The heat from this discharge may ignite explosive atmospheres, the light may fog photosensitized materials, and the current flowing in a static discharge may cause catastrophic failure of solid state devices. Electric forces may be used beneficially, as in electrostatic copying, spray painting and beneficiation of ores. They may be detrimental as when they attract dirt to a surface or when they cause sheets to stick together. Since most plastic materials in use today have very good insulating qualities, it is difficult to avoid generation of static electricity. Since it depends on many parameters, it is difficult to generate static electricity reliably and reproducibly.

5. Apparatus

5.1 *Charging Mechanisms*—The charging mechanisms can be constructed in a variety of ways, and should preferably be made as analagous to the particular application as possible. Some examples of charging mechanisms are described in 5.1.1, 5.1.2, and 5.1.3.

5.1.1 *Powder or Liquids Transported Through Tubes or Down Troughs*—Contact between the specimen and wall of the tube will charge the specimen or the tube, or both. Either the specimen or the tube must be insulating, or partially insulating. When the specimen is separated from the tube, electrostatic charge will be generated. This charge may be measured by catching a known amount of the specimen in a Faraday cage, or the charge remaining on the tube may be measured. A trough may be substituted for the tube and gravity used to effect the movement of the specimen along the trough.

5.1.2 *Webs Transported Over Rollers*— Contact between the web and the roller surface will charge the web if it is an insulator or partial insulator. If the rollers are insulators or partial insulators they will become charged thus lowering, or eliminating, the charge transfer to the web after a period of time. The electric field on the web may be measured with a fieldmeter, or the charge on the web can be measured with a cylindrical Faraday cage if the width of the web is not too large.

5.1.3 *Transport of Insulating or Partially Insulating Sheet Material*—Sheet materials may be transported on air layers, by

sliding down chutes, by vacuum platens, and by pinch rollers. Of these types of transport, pinch rollers and sliding down chutes generate the largest amount of charge. Generally, the better the contact (larger real contact area), the greater will be the charge generated. Pinch rollers are usually a high pressure, small apparent area of contact, leading to a relatively large real area of contact between the sheet and rollers. Sliding serves to multiply the real area of contact over that which would be obtained with a contact without sliding.

5.2 *Electrostatic Charge Measurements*—Fig. 1 shows a block diagram of the typical components necessary for this measurement while Fig. 2 shows a schematic diagram.

5.2.1 *Faraday Cage*—The Faraday cage consists of two conducting enclosures, one enclosed and insulated from the other. The inner enclosure is electrically connected to the shunt capacitors and the electrometer input. It is insulated from the outer enclosure by rigid, very high resistance, insulators which have resistance practically independent of relative humidity (an example is polytetrafluoroethylene (PFTE)). The inner enclosure should be of such construction that the test specimen can be substantially surrounded by it. The outer enclosure is connected to ground and serves to shield the inner enclosure from external fields which could affect the measurement.

5.2.2 *Shunt Capacitors*—Shunt capacitors may be necessary to reduce the measured voltage to a range where it can be read by the electrometer. Such shunt capacitors must have very low leakage insulation relatively unaffected by relative humidity changes (for example, polystyrene). They should be kept short-circuited when not in use and should be protected from high relative humidity.

5.2.3 *Electrometer*—The electrometer voltmeter measures the voltage developed on the Faraday cage and shunt capacitors. The electrometer must have a high impedance (such as 100 TΩ or higher) and a low drift rate concordant with the time of measurement. Electrometers are available with built-in shunt capacitors selected by a range switch. Electrometers are also available with negative feedback circuits which minimize the effect of input capacity. These circuits reduce the input voltage drop to nearly zero minimizing the effects of leakage of charge to ground and polarization of insulators.

5.2.4 *Display Unit*—The display unit indicates the voltage developed on the electrometer. If the input capacitance is known and does not vary, or if negative feedback is used, the display unit may be calibrated to measure the charge on the Faraday cage directly. The unit may be a meter showing the instantaneous value or it may be more complicated equipment, such as a strip chart recorder giving a reading as a function of time. The electrometer and display unit may be combined in one instrument.

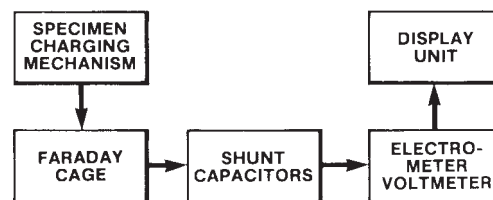


FIG. 1 Block Diagram of Apparatus for Measurement of Electrostatic Charge

⁶ Shashoua, V. E., "Static Electricity in Polymers: Theory and Measurement," *Journal of Polymer Science*, Vol XXXIII, 1958, pp 65–85.

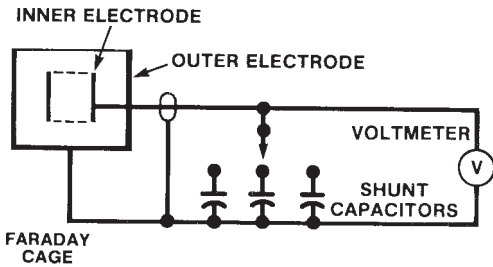


FIG. 2 Schematic Diagram

5.2.5 Electrical Connections:

5.2.5.1 Connections to Faraday Cage—Connections from the inner enclosure of the Faraday cage to the shunt capacitors and the electrometer must be highly insulated and well shielded from external electric fields. They should be stable in time and in the different ambient conditions in which measurements are made. Preferably, they should be rigid, although shielded cable may be used if it is low noise cable where flexing will not lead to the generation of static charge between the shield and the insulation of the cable. When using cable or rigid connections, the capacitance of these must be taken into account when calculating or measuring the capacitance of the input system, unless using an electrometer with negative feedback.

5.2.5.2 Connections to Display Unit—No special connecting wires are normally necessary between the electrometer output and the display unit. Manufacturer’s recommendations should be followed when connecting an external display unit to the electrometer output.

5.3 Electric Field Strength Measurements—The diagram of Fig. 3 illustrates the major parts of a commercially available rotating vane fieldmeter. A commercially available vibrating plate fieldmeter is illustrated in Fig. 4. The setup required for calibration of a fieldmeter is shown in Fig. 5.

5.3.1 Rotating Vane Fieldmeter—In Fig. 1 an electrostatically charged material placed at a known distance from the sensing unit will induce electrostatic charge in the face of the sensing unit, the rotating vane, and the fixed sensor plate. When the rotating vane covers the sensor plate, the induced charge in the sensor is small. When the opening in the rotating vane is opposite the sensor, the induced charge in the sensor is a maximum. Thus the rotating vane produces a periodically varying electrical signal on the sensor plate. This signal is amplified, processed, and read on a suitable display unit. These fieldmeters can be made polarity-sensitive by inducing a charge of known polarity on the sensor with an internal source or by phase detection circuitry. Efforts must be made to

adequately shield the sensor and associated circuits from noise generated by the motor driving the rotating vane.

5.3.2 Vibrating Plate Fieldmeter—In Fig. 2 a vibrating sensor plate is enclosed in a sensing unit. A charged material placed in front of the sensing unit induces a charge in the face plate and in the sensor. As the sensor moves away from the charged material, less charge is induced on the sensor. As it moves toward the charged material, more charge is induced on the sensor. This produces a periodically varying electrical signal on the sensor plate. This signal is amplified, processed, and read on a suitable display unit. Charge polarity is determined by phase detection circuits. Again, the sensor and associated circuits must be adequately shielded from noise generated by the driving mechanism.

5.3.3 Display Unit—The display unit may contain the power switch, circuits to process the signal (amplifiers, rectifiers, phase detectors, and the like), and a meter showing the instantaneous value of the electric field. Alternatively, a strip chart recorder giving a reading as a function of time may be used.

6. Test Conditions

6.1 Static electrification depends upon many parameters. To obtain reproducible results apparatus must be constructed to control all the measurable parameters and to keep all the unmeasurable parameters constant. The known parameters are as follows:

6.1.1 Cleanliness of Material Surfaces—Static electrification of contacting materials is a surface phenomenon. Thus, the surfaces must be kept in an uncontaminated state. Since contamination is very difficult to measure, efforts should be made to keep the surfaces clean. Storing samples under constant ambient conditions, such as temperature and relative humidity, is a must. Introduction of different gases into the air where they can be adsorbed on the surfaces has been known to change the results of an electrification test. Dirt particles settling on one or more surfaces can alter the results. Even contact to another surface during a test can alter a surface and give nonreproducible results in subsequent tests. Sometimes, it is better to use new samples from a sufficiently uniform material than to re-use samples. “Cleaning” of a surface with solvents rarely cleans the surface. It probably produces a uniform, reproducible, state of contamination, however. Thus, cleaning with solvents should be considered as a means of obtaining reproducibility in a test.

6.1.2 Real Area of Contact—Charge is transferred only at the points of real contact. Any test parameter that affects the

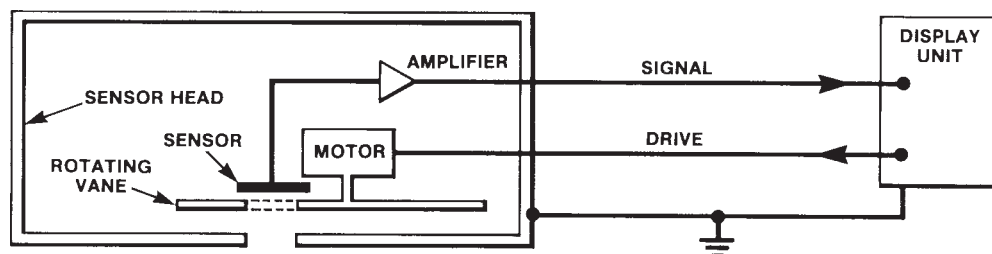


FIG. 3 Rotating Vane Fieldmeter

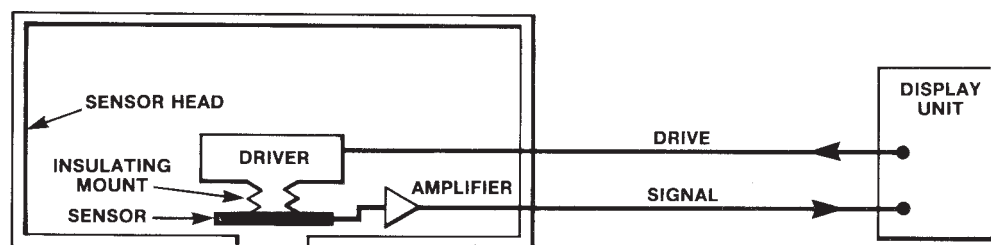


FIG. 4 Vibrating Sensor Fieldmeter

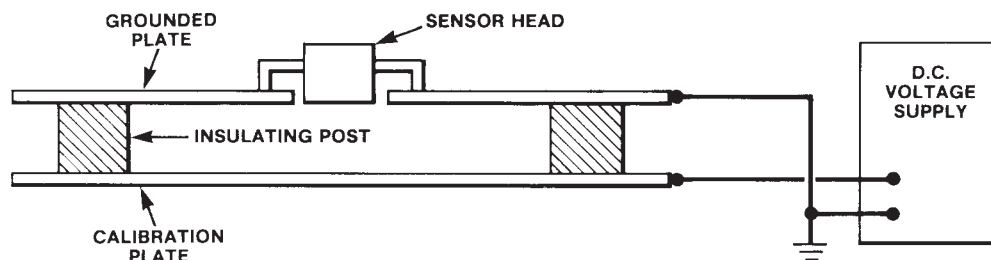


FIG. 5 Calibration Fixture

real area of contact between surfaces, such as pressure, must be controlled. Slip between surfaces during the making or breaking of contact must be minimized or measured so it can be made reproducible. Roughness of surfaces can alter the real contact area and hence the charge transfer, so one must be careful to test surfaces of approximately the same roughness or under conditions (such as high pressure or long time of contact) where surface roughness has less affect.

6.1.3 *Time of Contact*—Electrostatic charge is transferred almost instantaneously at the points of real contact. As time goes on, charge can flow from the contact areas to the noncontact areas and into the bulk of the specimen. Also, some materials undergo plastic deformation under pressure which can produce a time dependent increase in real contact area. Plastic deformation often depends upon temperature and adsorbed water, which is another reason for controlling these parameters.

6.1.4 *Rapidity of Separation*—As two contacting materials are separated, transferred charge can tunnel back to its origin. This process occurs rapidly up until a certain separation distance between two points is achieved. This separation distance is unmeasurable and probably does not change much with speed of separation. However, if the surfaces or volumes are partial insulators, charge can flow from a broken contact point to an unbroken point and hence back to its origin. This means that for partially insulating materials, such as some webs being transported over rollers, the charge on the web will be a function of the web resistivity and the web velocity as it leaves a roller.

6.1.5 *Electric Fields*—Since charge transfer is a movement of charged particles, electric fields can affect the movement. Electric fields can exist because of other charged objects in the vicinity of the test. They also exist by virtue of any excess charge on a contacting surface before a test contact is made. Elimination of external fields can be accomplished by removing all insulators from the region of the test or by shielding the test area from external fields (remember that a person may

become charged and produce external fields). Eliminating the effects of excess charge may not be so easy. Radioactive and corona dischargers can be used to get rid of most of the charge but rarely eliminate all of it. Also, elimination of excess charge on a sheet with these dischargers may not neutralize the charge but instead may lead to “polar” charge. Polar charge exists when one side of the sheet has excess charge of one polarity and the other side has an equal excess charge of the opposite polarity. Very high charge densities can exist in a polar configuration with little measurable external field. Usually polar charges can be detected by placing the sheet on a grounded metal plate and bringing an insulated metal plate connected to an ungrounded electrometer into contact with the other side of the sheet. An electrostatic field measuring or noncontacting voltage measuring instrument of sufficient sensitivity may also be used.

NOTE 1—One must also be aware of contact potential differences between metals that affect charge transfer. If one uses a thin insulating sheet mounted on metal, and uses a different metal to contact the surface of the sheet, the contact-potential difference between the metals may affect the charge transfer between the metal and insulator.

7. Test Specimens

7.1 The form and size of test specimens is largely determined by the end use of the material or other practical considerations. Since this test method has a wide range of applicability (solids in various forms and liquids), specimen preparation guidelines are, of necessity, general. Depending upon the mode of charging, use specimens of equal sizes for comparison. Test five specimens of each composition. Keep the specimens free of contamination. When using specimens for repeated contacts, recognize and take into account the probability of the results being affected by contamination. When cleaned with solvents, recondition the specimens after cleaning and before further testing.

8. Calibration and Standardization

8.1 Calibration of Charge Measuring Apparatus:

8.1.1 Calibrate the electrometer and associated readout equipment to the desired accuracy by applying a precision voltage source to the electrometer input. Accomplish this with the cage and shunt capacitors disconnected, if possible, to avoid polarization of the insulators of these components.

8.1.2 The capacitance, C , of the system consists of the parallel combination of the capacitance of the cage, the shunt, the connecting lines, and the electrometer, in farads, as follows:

$$C = C_c + C_s + C_l + C_e \quad (1)$$

where:

C_e = capacitance of the cage,

C_s = capacitance of the shunt,

C_l = capacitance of the connecting lines, and

C_e = capacitance of the electrometer.

With standard audio frequency bridges, $C_c + C_s + C_l$ can be readily determined. Some electrometers permit a similar measurement of C_e , otherwise, C_e must be taken from the instruction manual or special procedures. For example, a charge decay rate measurement or a charge sharing measurement must be used for determining C_e experimentally. Electrometers having feedback circuits minimize the effects of external capacitance so only the capacitance of the electrometer need be measured. After calibration, or before using the instrument after turning it on, the drift rate should be checked to make certain it is within manufacturer's specifications.

8.2 *Calibration of Fieldmeters*—Calibrate the fieldmeters by placing the sensing unit in a hole in a large grounded plate so that the surface of the sensing unit is flush with the surface of the plate, as shown in Fig. 5. A second plate to which a voltage can be applied is placed parallel with and at a known distance from the first plate. The plates should be large enough to ensure a uniform field in the region of the sensing unit (usually a plate with dimensions five to ten times the dimensions of the sensing unit suffices). Different voltage levels applied to the second plate result in corresponding readings on the display unit. The field strength is determined by dividing the voltage on the plate by the spacing between the plates. The gain of the amplifier should be adjusted to achieve the correct field strength reading on the display unit.

9. Conditioning

9.1 Condition test specimens at constant relative humidity and temperature, in accordance with Practice D 618, because charge generation varies widely with the moisture content of a material. The conditioning time required depends on the rate of adsorption of moisture and the thickness (or mass) of the specimen. Since there is a hysteresis effect on conditioning of many materials, the moisture content of a specimen also depends on whether the material was wetter or dryer than the conditions of the test. Specimens should be dryer than the specified test condition before conditioning. Equally condition specimens for at least 24 h at the specified relative humidity before testing. Make the measurements at the end of the conditioning time in the conditioning environment.

10. Procedure

10.1 *Electrostatic Charging*—Because of the wide variety of material shapes and charging mechanisms, the procedure shall be determined by the experimenter. Careful notes of the procedure should be maintained and included in the report.

10.2 Measurement of Electrostatic Charge:

10.2.1 *Small Specimens*—Measure electrostatic charge on small specimens by dropping them into a Faraday cage in the form of two cups with a small opening on top of the inner cup, and a lid which can be closed on the top of the outer cup. The inner cup should be of sufficient depth so that the depth is large when compared with the opening in the cup and with the height of the specimen (or specimens) from the bottom of the cup.

10.2.2 *Large Specimens*—Measure electrostatic charge on portions of large specimens which cannot be totally enclosed by a Faraday cage (such as long webs) by using two concentric cylinders enclosing the portion of the specimen to be measured. The outer cylinder should be longer than the inner cylinder, and guard cylinders of the same size as the inner cylinder should be placed at each end of the inner cylinder to shield it from electrostatic charge on portions of the specimen outside the inner cylinder.

10.2.3 *Liquids*—Liquids can be caught in a cage similar to the one used for small specimens. The inner cup should have a larger depth than the depth of the liquid in order to substantially capture all the field due to the charged liquid.

10.3 *Electric Field Measurement*—Measure the electric field by positioning the sensor head at a location where a measurement is desired, then slightly orient the head for maximum response and read the display unit. The value of field strength read is that at the front plate of the sensor head and its dominant direction is perpendicular to the plane of the front plate.

11. Interpretation of Results

11.1 Electrostatic Charging:

11.1.1 *Large Solid Samples*—The real area of contact between two surfaces usually is not known. Thus, the true charge density at the points of contact cannot be determined. Where the real contact area is an appreciable fraction of the apparent contact area, and where there is reason to believe that this fraction does not appreciably vary from one test to another (under constant pressure, for example), charge density averaged over the whole contact area may be used for comparison purposes.

11.1.2 *Powders and Liquids*—Charges on powders and liquids separating from a wall are usually measured relative to their volumes or mass. A given mass of the specimen is caught in a Faraday cage and the charge measured. Charge density can be reported in terms of mass. If the density of the material is known, charge density can be converted to charge per unit volume. In some cases where the ratio of surface area to volume is known and constant, the charge per unit area can be reported. Liquid charge density is always reported in terms of mass or volume.

11.2 *Electric Field Measurements*—Since the fieldmeter disturbs the field it is measuring by its presence in that field, the reading is usually not the field strength which is present when

the fieldmeter is removed, nor is it the field strength at the location if the position of other nearby grounded objects is altered. Thus, although the measurement is accurate and can be made with high precision, the quantitative interpretation in terms of other quantities, such as excess electrostatic charge density, may be extremely difficult. Various cases should be distinguished.

11.2.1 Large Conducting Sheets—The field for this case is uniform inside the gap and perpendicular to the surfaces if the sheets are parallel. If the front face of the sensor is one of the parallel surfaces, and if the face is large compared to the sensor opening in the face, the field will be nearly uniform at the hole and the reading will vary with the reciprocal of the spacing between the plates. This is similar to the method of calibration and can be used to check the calibration if a calibration setup is not readily available.

11.2.2 Large Insulating Sheets—If the sensor face is large compared to the sensor opening, the field will be nearly uniform at the hole. In this case, however, the field varies very little with spacing, provided that the dimensions of the sheet are large compared to the spacing between the sensor and the sheet, and as long as there are no other grounded objects in the vicinity to affect the field. Quantitative interpretation of the data can be fairly accurate in this case.

11.2.3 Large Partially Insulating Sheets— If the sheets are not moving, charge will redistribute on the sheet in the vicinity of the grounded sensor head. This will cause the reading to vary both in time and spacing. If the sheet is moving at a constant speed there will be an equilibrium distribution of charge on the sheet which will take some time to establish. The reading in this case can vary with distance and with time until the equilibrium distribution is established. Quantitative interpretation of the data can be highly *inaccurate* in this case.

11.2.4 Arbitrarily Shaped Conductors— Quantitative interpretation of the data requires computation of the field distribution. This is possible in many cases: one example is a charged conducting sphere and a ground plane. In this case, the field strength depends on the spacing between the sphere and the plane. Other regular shaped conductors are possible but irregular shapes can only be approximated at best.

11.2.5 Arbitrarily Shaped Insulators— By superposition of their coulomb fields, the field at the sensor can, in principle, be calculated. Thus, by going backwards, a measurement of the field can lead to the (assumed) distribution of charges on the insulator. However, if the distribution is not uniform or if field distortion due to the sensor or other nearby grounded conducting objects is not taken into account, or both, fairly large errors may be encountered. The change of field reading with spacing can often help in minimizing these errors. Field and charge calculations cannot be generalized since geometry of the measuring situation is very important.

11.2.6 Qualitative measurements of the field strength can be made without need to calculate the field distribution. These measurements are then highly reliable for comparison purposes. For example, measurements of the field on a moving web can be compared from day to day, under different charging conditions, and for different materials under the same charging conditions.

12. Report

12.1 Report the following:

12.1.1 Identification of composition and size of the specimen,

12.1.2 Sample preparation procedures indicating the conditioning times and any cleaning procedures used (include sample resistivity, if known),

12.1.3 Description of apparatus or method of test, including geometry of measurement situation(s) and a model of commercial equipment used if pertinent to the test. Also include calibration procedure and elapsed time between calibration and measurement,

12.1.4 Range of parameters used in test, including the ambient conditions of the test along with their variability. For instance, temperature may be $20 \pm 1^\circ\text{C}$ and relative humidity may be $50 \pm 2\%$. If any known parameters were uncontrolled or their variation was unknown this should be stated. Parameters include pressure between contacting surfaces, time of contact, rapidity of separation, amount of rubbing (length of rubbed surface) if any, length of tubing, velocity of flow of a liquid or powder, and the like, and

12.1.5 Magnitude and polarity of the average charge density or electric field on five or more identical specimens with standard deviation, or with the range of charging on the specimens in absolute values or as a percentage variation of the average.

13. Precision and Bias

13.1 The overall precision of the measurement is determined by (1) inherent instrument errors, (2) calibration errors, and (3) technique related errors.

13.1.1 The precision and bias of the measuring instruments is usually 5 % or better and is usually specified by the manufacturer for commercial instruments.

13.1.2 Calibration errors are dependent on the stability of the calibrating voltage source, bias of the associated voltage and capacitance measuring equipment, and bias of spacing and related geometry of the test setup. Overall precisions of $\pm 2\%$ or better are possible.

13.1.3 Technique related errors are difficult to assess and can greatly exceed instrument and calibration errors. Careful attention to details of geometry and other relevant variables is essential to minimize this error. The precision and bias of the test method is largely determined by the method employed and the skill of the investigator. Many investigators have claimed reproducibility of the tests in their laboratory of 20 % or better. There is insufficient data to determine if this reproducibility can be obtained from one laboratory to another in a wide variety of tests.

14. Keywords

14.1 apparent contact area; charge generation; charge measurement; charging mechanism; conducting material; conductor; contact area; electric charge; electric field; electric field strength; electrometer; electrostatic charge; electrostatic charge generation; excess electrostatic charge; Faraday cage; field meter; insulating material; insulator; partial conductor; partial insulator; real contact area; resistance; surface; rotating vane