
ELECTROSTATICS

SECOND EDITION

**THE KLUWER INTERNATIONAL SERIES
IN ENGINEERING AND COMPUTER SCIENCE**

ELECTROSTATICS

SECOND EDITION

by

Niels Jonassen

*Retired
Associate Professor
Department of Physics
Technical University of Denmark*

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Chapter 1

INTRODUCTION

If you ask an average group of people “Do you know anything about electromagnetic induction ?” or dielectric relaxation, Gauss’ law, the photoelectric effect or any other arbitrary selection of important physical phenomena or concepts, the chances are that quite a large fraction of your group has never heard of them.

But if you ask the same group of people if they ever heard of Static Electricity, probably more than eighty per cent will have a personal, although probably rather vague and inaccurate, notion of the topic.

Of course if your group is selected among the inhabitants of the humid marshes along the lower Mekong or Mississippi River, maybe only, say, thirty per cent will nod at the mentioning of static electricity.

But what is it that comes to people’s mind when you ask about SE ?

About fifty years ago it would most likely be electric shocks and explosions. The farmers of Nebraska and Kansas were quite familiar with explosions in grain silos. There are numerous examples of fatal accidents in hospitals, where anesthetics like diethyl ether or cyclopropane were used, and in the 1950es a number of oil tankers blew up during tank washing. All due to static electricity.

And then there was, and still is, the well-known minor shock you get when touching a doorknob after having walked across a dry carpet.

Of cause such types of accidents may still occur, but the most important type of static electric phenomena today is no doubt what is colloquially known as *ESD*.

Although the acronym just means *ElectroStaticDischarge* it has become common to use the abbreviation for any kind of static electricity in the electronic industry.

The main difference between an old-fashioned static accident and an ESD-event lies primarily in the magnitude of the parameters involved.

While it will take a discharge (spark) from an insulated conductor of several hundred pF (picofarads), charged to 1-2 kV, to ignite a gas/air mixture (and then only if the mixture is exactly right), it may only require a voltage difference of, say, 50 V to cause breakdown in a sensitive semiconductor component.

But static electricity may show itself in many other ways.

When you have problems separating the pages of your *Playboy* magazine (assuming the mailman hasn't read it before you), it's a case of *static cling*, as is the sticking of one layer of clothes to another. In the same group of mechanical effects we find the mutual repulsion of fibers in a yarn, making processing of the filaments difficult.

All the above examples have the character of hazards, risks or at least nuisances, but it would be unfair to static electricity to leave it at that.

When you can operate coal-fired power plants, cement factories and a lot of other industrial operations without producing unacceptable levels of particulate air pollution it is because of the *electrofilter*, the first and one of the most important electrostatic inventions.

A score of surfaces in our surroundings have been coated by an electrostatic process. This is true for the chassis of your car and the body of your refrigerator. And even the plastic on the shelves of the fridge has been applied by the help of an electrostatic field

Flocking is a special process where you shoot nylon fibers into an adhesive layer, and by a similar method you can make sandpaper better and more uniformly than by any other method.

And finally we have to mention *xerography*, the principle for making photocopies. The importance for and impact on society of this invention is beyond discussion. But it should also be mentioned for another reason.

Where *Cottrell's* electrofilter is based on a simple and straightforward idea of charging airborne particles and move them out of the air by an electric field, then this is not the case with *Chester Coulson's* xerography.

Based on a mixture of electrostatics and photoconductivity (some materials are insulative in the dark and conductive when illuminated), both fields covering a range of unreliable processes, the idea was almost doomed from the beginning.

But as we all know, persistence and ingenuity prevailed.

Chapter 2

FUNDAMENTAL CONCEPTS

2.1 CHARGE

In order to understand basic static electric phenomena it is necessary to be familiar with some fundamental concepts.

The most fundamental of these concepts is the *charge*.

The closest we can get a definition of what a charge is, is to say that it is a property of some fundamental atomic particles, primarily the *proton* and the *electron*.

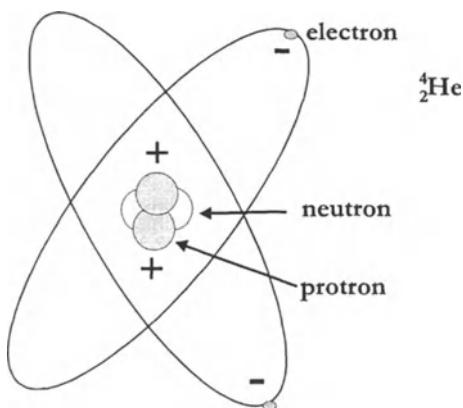


Fig. 2.1

Protons are located in the nucleus of any atom and electrons are outside the nucleus, but still tied to the atom.

In Fig. 2.1 is shown a (very primitive) sketch of a helium atom.

The nucleus contains two protons (and two neutrons) and in the neighborhood of the nucleus are two electrons.

It now appears that two protons will repel each other as will two electrons, but a proton and an electron will attract each other.

We consider these forces as caused by a special property, which is what we call the charge.

Apparently the nature of the charge of a proton is different from that of an electron, and we call the charge of a proton positive and that of an electron negative.*

Charges are today always measured in the unit of coulomb, C, where 1 coulomb is defined as 1 ampere·second, and the electron charge, e, is

$$e = -1.608 \cdot 10^{-19} \text{ C}$$

The proton charge has the same numerical value as that of an electron

* The designation positive and negative in relation to static charges was used long before the concepts of protons and electrons was known. It was Benjamin Franklin who suggested the names positive and negative instead of the older glass- and amber-electricity.

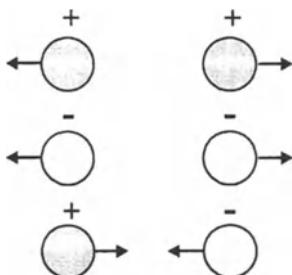


Fig. 2.2

If a body has an excess of electrons it is negatively charged. If it has a deficit of electrons it is positively charged. Charged bodies interact as shown in Fig. 2.2

All electrostatic charging processes consist of electrons being transferred from one body or surface (which will be positive) to another (which will be negative).

The number of electrons transferred in any charging process is enormous.

Let us look at some examples.

If a powder, like sugar or flour, slides down a tube and sticks to the wall the charge on each tiny particle may be 10^{-14} - 10^{-13} C, i.e. 100,000 to 1 million electrons have been transferred per particle.

If a person, who has walked across a carpeted floor, receives a shock when touching a doorknob, she would typically have had a charge of about 10^{-7} C.

If we collect the powder sliding down the tube we will often find a specific charge of about 10^{-7} C·kg⁻¹.

If we rub a plastic chartreuse with a piece of fur we typically find a charge of 10^{-7} C/sheet.

2.2 ELECTRIC FIELD

All electric effects are caused by forces between electric charges, the attraction between opposite charges and the repulsion between charges of the same polarity.

Two charges q_1 and q_2 at a distance r will either attract or repel each other with a force F given by

$$F = \frac{q_1 q_2}{4\pi\epsilon r^2} \quad (2.1)$$

Eq. (2.1) is called *Coulomb's law*.

ϵ is the absolute permittivity of the space between the charges.

ϵ can be written as

$$\epsilon = \epsilon_r \epsilon_0$$

where ϵ_r is the relative permittivity or dielectric constant of the space (see polarization) and ϵ_0 is the permittivity of vacuum (or in practice of air) defined by

$$\epsilon_0 = 1/(\mu_0 c)$$

where μ_0 is the (magnetic) vacuum permeability and c is the vacuum speed of light.

Coulomb's law, eq. (2.1), is not very useful in practical cases. The law is only valid if the charges involved are so-called *point charges*, i.e. the charges are located on bodies with dimensions small compared with the distance between the charges.

The most practical parameter when dealing with electrical phenomena is the *electric field*.

The definition of an electric field is very simple

An electric field is a region where a charge feels a force.

This force is caused by other charges, so a charge or charge distributions creates an electric field in its environment.

The magnitude of the field is characterized by the *field strength*. If a charge q experiences a force F (i.e. the charge is in an electric field) then the field strength E is given by

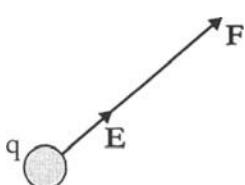


Fig. 2.3

$$F = qE \quad (2.2)$$

For a positive charge the force has the same direction as the field strength, Fig. 2.3. For a negative charge the opposite direction.

It appears from eq. (2.2) that the dimension of field strength is force over charge, and hence the unit is $N \cdot C^{-1}$ (newton per coulomb).

As we shall see later this is identical to $V \cdot m^{-1}$ (volt per meter), which is the commonly used name for the unit of field strength.

For simple charge distributions it is possible to calculate the field strength as a function of distance from the charge.

In Fig. 2.4 is shown the field from a positive point charge, i.e. a charge located within a region, which is small compared to the distance to such places where you want to see the effect of the charge.

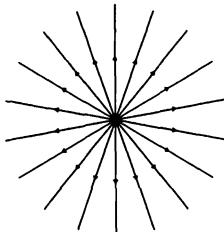


Fig. 2.4

If the charge is q the field strength at a distance r can be written

$$E = \frac{q}{4\pi\epsilon r^2} \quad (2.3)$$

The lines shown are so-called *field-lines*.

The direction of the field lines is the direction of the field strength and their density indicates the magnitude of the field strength.

Field lines make up a very useful tool for getting a feeling of how a field varies around a charge distribution.

It should, however, be remembered that fields are three-dimensional and that a flat representation can never tell the full story of the field.

2.3 ELECTRIC FLUX AND GAUSS' LAW

The field from any charge distribution can in principle be calculated from eq. (2.3) by considering the distribution made up of individual point charges and adding the field strengths from each of these charges. However, the field strengths to be added are vectors, varying in size and directions and normally the summing, or rather integration, would at best be rather tedious. If on the other hand the charge distribution to be considered shows some degree of symmetry, the resulting field strength can often be easily calculated by use of the concept of electric flux.

The flux of the electric field E through a surface S , fig. 2.5, is defined by

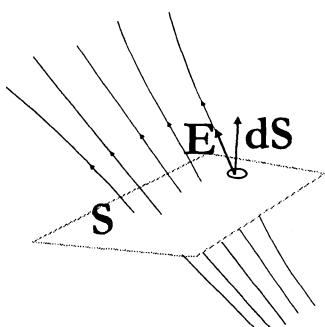


Fig. 2.5

$$\Phi_E = \int E \cdot dS \quad (2.4)$$

Here dS is an area segment of S chosen so small that it can be considered being plane and the field strength E is constant over dS . The vector dS is perpendicular to the area. It can now be shown, from eq. (2.3), that if

S is a closed surface, fig. 2.6, eq. (2.4) can be written

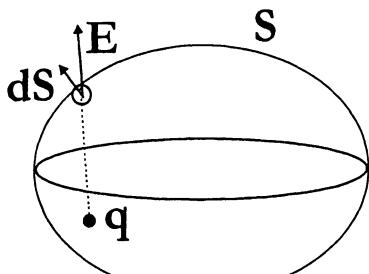


Fig. 2.6

$$\int_{cS} \mathbf{E} \cdot d\mathbf{S} = \frac{q}{\epsilon} \quad (2.5)$$

Here q is the sum of the charges surrounded by the closed surface, independent of the distribution of the charges.

Eq. (2.5) is called **Gauss's law** (or theorem) in integral form.

2.3.1 APPLICATIONS OF GAUSS' LAW

Gauss' law is very convenient for calculating the field from symmetrical charge distributions.

Below are given some typical examples

Spherical charge distribution

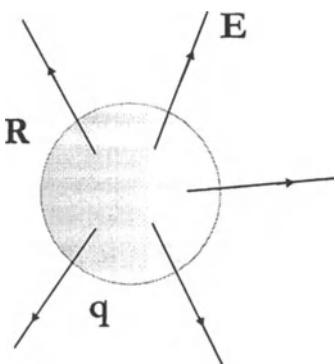


Fig. 2.7

$$\mathbf{E} = 0 \text{ for } r < R$$

$$\mathbf{E} = \frac{q}{4\pi\epsilon_0 r^2} \text{ for } r \geq R \quad (2.6)$$

The field strength (outside the sphere) is inversely proportional to the square of the distance from the center.

Cylindrical charge distribution

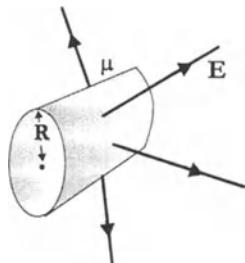


Fig. 2.8

$$E = 0 \text{ for } r < R$$

$$E = \frac{\mu}{2\pi\epsilon r} \text{ for } r \geq R \quad (2.7)$$

The field strength (outside the cylinder) is proportional to the linear charge density μ and inversely proportional to the distance from the

axis.

Plane charge distribution (for instance plastic sheet)

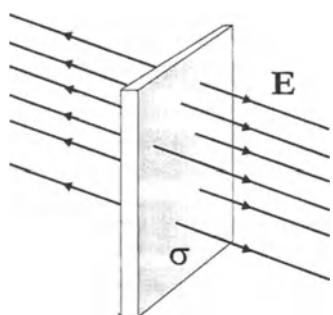
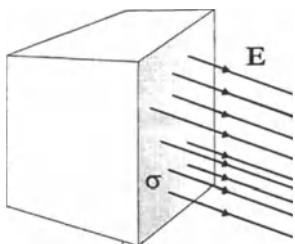


Fig. 2.9

$$E = \frac{\sigma}{2\epsilon} \quad (2.8)$$

The field strength is proportional to the charge density σ and independent of the distance.

Field in front of charged conductor



$$E = \frac{\sigma}{\epsilon} \quad (2.9)$$

Fig. 2.10

The field strength is proportional to the charge density and independent of the distance.

It should be emphasized that the above formula are valid only when the charged objects are far removed from conductive elements.

In Fig. 2.11 is shown two metal plates with the area S, placed parallel to each other. The right plate is grounded, the left one is insulated.

If we give the insulated plate a charge q , this charge will by induction (see later) bind a charge $-q$ on the grounded plate, and establish an electric field E in the space between the two plates.

This field is rather unusual. It has the same value in each point. It is homogeneous.

In practice fields are seldom, if ever, homogeneous.

Even in the simple case shown in Fig. 2.11 there is a little cheating involved. We have omitted the field at the edge of the plates, the so-called *stray field*.

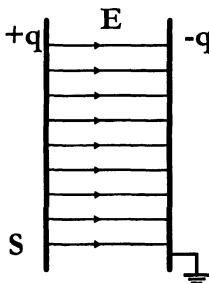


Fig. 2.11

You can not go discontinuously from a field strength $E \neq 0$ to a field free region. You have to pass through all value from E down to zero.

Still the field in Fig. 2.11 is the closest we ever come to a homogeneous field.

The value of E in the breadpart of the field is (eq. (2.9)) given by

$$E = \frac{\sigma}{\epsilon} = \frac{q}{2\epsilon}$$

As mentioned fields are hardly ever homogeneous.

Fig. 2.12 shows the field from a positively charged body or surface D. We see that the field is divergent and decreases with the distance from the surface (the field lines spread out).

This is often the case, and it is also more or less what you would expect, the further you get away from the charge the smaller is the effect on other charges.

But it is not always so..

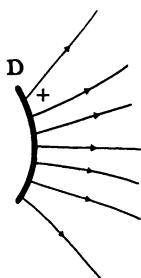


Fig. 2.12

If there are conductive items in the field, be they grounded or not, the situation gets much more complicated.

Fig. 2.13 shows the same charged surface D, but now a grounded object (conductor) G has been introduced in the field.

The field lines now converge on G, and the highest field strength is found in front of the grounded object.

We express this by saying that the field has been *distorted* by the introduction of the grounded object.

What the reading of the field meter will give us, is the distorted field strength in front of the meter, which could be very different from the field strength in the same place, when the meter is absent.

The conductor G could for instance be a field meter placed in the position shown in order to measure the field from the charged object. In the example discussed above we notice that the introduction of G into the field did not affect the charge distribution on D. This means that D is an insulator.

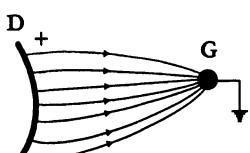


Fig. 2.13

If D had been a conductor the introduction of G could possibly have changed the charge distribution, making the distortion even more pronounced.

In the example discussed above we notice that the introduction of G into the field did not affect the charge distribution on D. This means that D is an insulator.

2.4 FIELD STRENGTH AND VOLTAGE

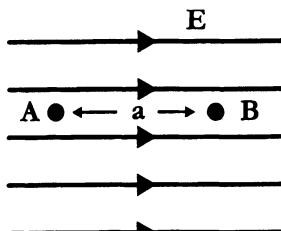


Fig. 2.14

Let us again look at a homogeneous field E , Fig. 2.14.

Consider two points A and B at a distance a in the direction of the field.

We now define the *voltage difference* or *potential difference* between A and B

$$V(A) - V(B) = E \cdot a \quad (2.10)$$

It appears from eq. (2.10) that the unit for voltage difference is

$$\text{N} \cdot \text{C}^{-1} \cdot \text{m} = \text{J} \cdot \text{C}^{-1}$$

which we call volt (V), so

$$1 \text{ V} = 1 \text{ J} \cdot \text{C}^{-1}$$

If the field is not homogeneous, Fig. 2.15, we can not use the simple definition of eq. (2.10).

In this general case the *voltage difference* or *potential difference* between A and B is defined by

$$V(A) - V(B) = \int_A^B E \cdot da \quad (2.11)$$

The voltage difference between A and B is independent of the path from A to B along which the integral is calculated.

Eq. (2.11) only defines voltage differences. In order to define the *voltage* or *potential* of a point we have to choose a point of zero potential, and by tradition and for many practical reasons we choose any

point in ground or connected to ground, i.e.

$$V(G) = 0 \quad (2.12)$$

We thus get the definition of *voltage* or *potential* of a point A in an electric field

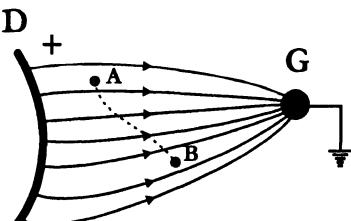


Fig. 2.15

$$V(A) = \int_A^G E \cdot da \quad (2.13)$$

Voltage and voltage difference are properties of an electric field.
You don't have a voltage unless you have a field

So let us summarize:

The voltage- or potential difference between points A and B is the integral of the field strength from A to B

The voltage or potential of a point A is the integral of the field strength from A to ground.

Some readers may wonder: Has this anything to do with the voltage of a battery ?

And the answer is: Absolutely. It is one and the same thing.

If you buy a 1.5 V battery, what you get is a gadget with an *electromotive force* of 1,5 V.

And if you don't load your battery too heavily it will have a voltage difference between the two terminals of 1.5 V, which as explained above means that the integral of the electric field strength from the positive to the negative terminal is 1.5 V.

So what about the field if the terminals are connected with a wire and you have a current ? Well then you have field in the wire, and that field is the reason for the current.

So, without an electric field, no voltage and no currents.

But let's get back to electrostatics.

2.5 CHARGED INSULATOR

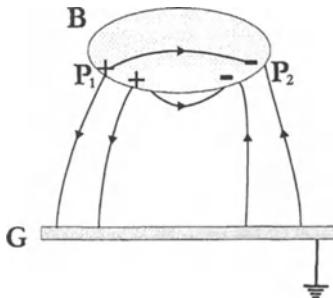


Fig. 2.16

Fig. 2.16 shows a charged insulative body, in the neighborhood of a grounded plane G.

The body has spots of positive as well as negative charge.

If we consider a point P_1 , surrounded by positive charge we find that the potential of P_1

$$V_{P_1} = \int_{P_1}^G E \cdot da \text{ is } > 0$$

while the potential of a point P_2 in a negative region V_{P_2} is < 0

The potentials V_{P_1} and V_{P_2} are surface potentials and will usually vary from point to point along the surface of the insulator.

Further we have no knowledge of the potential of a point of the interior.

It is therefore not possible to characterize a charged insulator with a voltage or potential-figure characterizing the insulator as a whole.

An insulator does not have a voltage !

Pointing a meter toward a charged plastic box and pronouncing it to have a voltage of 3 kV is nonsense !

2.6 SURFACE POTENTIAL OF UNIFORMLY CHARGED INSULATOR DISK

In Fig. 2.17 is shown an insulator disk with the thickness t resting on a grounded plane. The disk is charged uniformly with a positive charge with the surface density σ ($C \cdot m^{-2}$). The permittivity of the material is ϵ ($= \epsilon_r \epsilon_0$), where ϵ_r is the relative permittivity (see later under polarization)

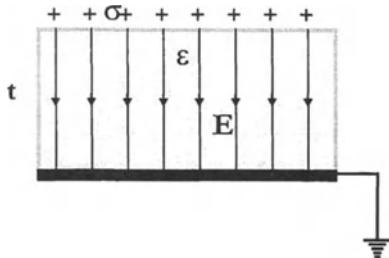


Fig. 2.17

If the distance from the free surface of the disk to other grounded surroundings than the plane is much larger than the thickness d , then the field strength inside the material is given by

$$E = \frac{\sigma}{\epsilon} \quad (2.14)$$

According to eqs. (2.11) or (2.13) the surface potential of the disk is then

$$V_s = E \cdot t = \frac{\sigma}{\epsilon} \cdot t \quad (2.15)$$

This is the potential of any point on the surface of the insulator disk. But it is not the potential of the insulator.

Any point inside the disk has a potential different from that given by eq. (2.15).

A point, say, in the middle has only half the potential as that of a point on the surface.

The surface potential, as given by eq. (2.15), is a convenient measure for the charged state of for instance a photodrum or a charged electret.

But V_s is not the voltage or potential of the disk.

An insulator does not have a voltage.

2.7 INSULATED CHARGED CONDUCTOR

If you place a charge on an insulated conductor the charge will create a field around but also inside the conductor. the “interior” field will make charges (electrons) move until we have such a charge distribution that the field in any point inside the conductor is zero. if the field wasn’t zero, we would have further charge displacement, Fig. 2.18

When this situation is reached, which, in broad terms, happens instantly, all the charge is located on the surface.

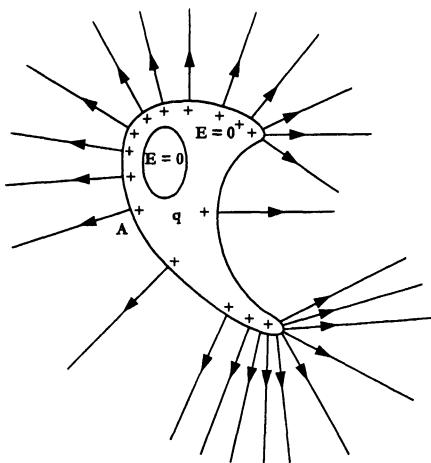


Fig. 2.18

The field from the charge will be perpendicular to the surface. If it weren't, you would have charge displacement along the surface until the perpendicular situation was reached.

The charge will accumulate, and therefore the field will be strongest, around sharp point and protrusions of the conductor.

If there are cavities in the conductor the field will be zero here as well as in the body part of the conductor.

Provided of course, that you do not place a charge in the cavity.
The actual charge distribution over the surface of the conductor depends upon the placing of the body relative to other conductors especially ground

We will discuss this question when talking about voltage and conductors.

2.8 FARADAY SCREENING

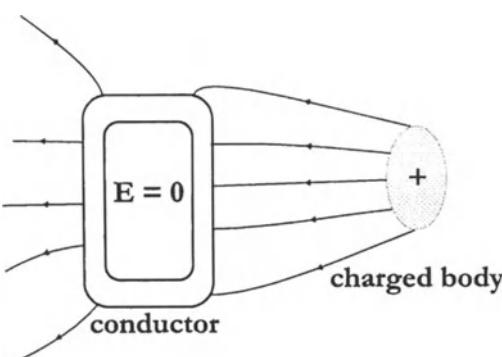


Fig. 2.19

As explained above the field inside a conductor is zero even in cavities.

This is true not only when the external field is caused by a net charge on the conductor, as in Fig. 2.18, but also when the conductor is placed in the field from another charged body, Fig. 2.19. If therefore an item is placed in the cavity, it is

safe, screened, from external fields.

It does not matter if the “hollow” conductor is grounded or not.

This phenomenon is known as Faraday screening.

It is used in very open lightning conductor nets wrapping a building and screening the interior somewhat from the fields from nearby lightning discharges.

But much more importantly is the application of the principle by the use of conductive bags for screening semiconductor components from the fields from charged bodies in the neighborhood.

2.9 POTENTIAL OF CONDUCTOR, CAPACITANCE

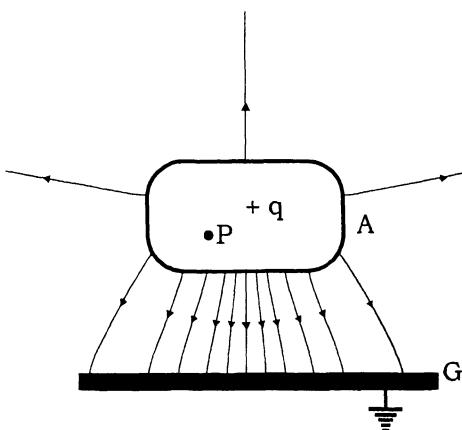


Fig. 2.20

A conductor A is placed in the neighborhood of a grounded plane G, Fig. 2.20. When a (positive) charge q is placed on A the charge will distribute itself on the surface.

Since the field inside the conductor is zero and the field at the surface is perpendicular to the surface, the potential difference between any points in an on the conductor is zero.

Hence the potential V (relative to ground) is the same for any point P in or on the conductor.

The value of V is proportional to the charge q for a given placement of A relative to ground.

This relation is usually written

$$q = C \cdot V \quad (2.16)$$

The factor C is called the capacitance of the conductor with respect to ground.

It appears that the dimension of capacitance is charge/voltage with the unit $C \cdot V^{-1}$, which is called farad (F), i.e.

$$1 F = 1 C \cdot V^{-1}$$

Only insulated conductors can have a capacitance. The concept of capacitance can not be meaningfully applied to insulators.

A farad is a very large unit. The capacitance of most static electric systems is in the range $10 - 1000 \text{ pF}$ ($1 \text{ pF} = 10^{-12} \text{ F}$)

2.9.1 PARALLEL PLATE CAPACITOR

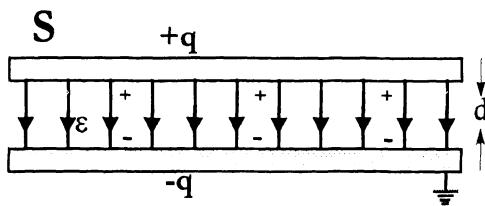


Fig 2.21

If the geometry of an insulated conductor system is sufficiently well-defined and simple, it is possible to calculate its capacitance.

The best known example of this is the parallel plate capacitor, Fig. 2.21.

Two metal plates with the area S are placed parallel to each other at a distance d , the interspace being filled with an insulator (dielectric) with the (absolute) permittivity ϵ . One plate is insulated, the other grounded. If a charge $+q$ is placed on the insulated plate it will bind a charge $-q$ on the grounded plate. Both charges are located on the sides facing each other.

This will create a field E in the interspace
And thus a voltage V of the insulated plate

$$E = \frac{\sigma}{\epsilon} = \frac{q}{\epsilon S} \quad (2.17)$$

According to eq. (2.16) the capacitance of the system is thus

$$C = \epsilon \frac{S}{d} = \epsilon_r \epsilon_0 \frac{S}{d} \quad (2.19)$$

Example 2.1

If we put $S = 100 \text{ cm}^2$, $d = 1.00 \text{ mm}$ and $\epsilon_r = 4$ ($\epsilon_0 = 8.85 \cdot 10^{-12} \text{ F} \cdot \text{m}^{-1}$) we find
 $C = 354 \text{ pF}$

We notice that eqs. (2.17) and (2.18) are similar to eqs. (2.14) and (2.15) for the field strength inside and surface potential of a charged insulator disk.

There is, however, an important difference. The voltage V of eq. (2.18) is the voltage or potential of the insulated metal plate of the capacitor, characterizing the plate as a whole.

The voltage V_s of eq. (2.15) only relates to the surface of the charged insulator disk.

2.9.2 CAPACITANCE OF STANDING PERSON

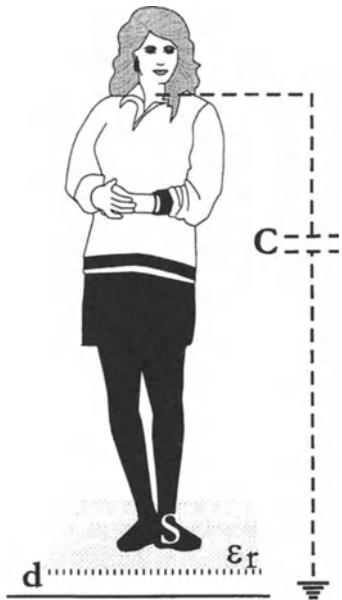


Fig. 2.22

A person is a conductor and if the person is insulated from ground she has a capacitance. The capacitance of a standing person can be reasonably estimated by eq. (2.19), where A is the area of the shoe soles, d the thickness of the insulating layer from the underside of the feet to a (somewhat) conductive layer in the floor, and ϵ_r the relative permittivity of the same layer.

Representative values may be: $S = 300 \text{ cm}^2$, $d = 5-10 \text{ mm}$ and $\epsilon_r = 4-10$, leading to a range of the capacitance of

$$C_{\text{estimate}} = 100-300 \text{ pF}$$

If we now for a given person find the actual values of S , d and ϵ_r and

calculate the capacitance C_{calc} according to eq. (2.19) and compare this with the capacitance C_{meas} measured by some electrical method (preferably electrostatic) we find that

$$C_{\text{calc}} \approx 60 - 70 \% \text{ of } C_{\text{meas}}$$

This means that the capacitance of the feet makes up 60-70 % of the total capacitance, which again means that when a standing person is charged, 60-70 % of the charge is located on the underside of the feet.

This fact is important for understanding why the effect of a discharge from a charged person is different from the discharge from an ordinary charged conductor. We shall treat this in more details when dealing with the various ESD damage models.

2.10 INDUCTION

Induction (or more correctly electrostatic induction) describes the static effect of an electric field on a conductor.

Fig. 2.23 shows an insulated, uncharged conductor B in the field from a positively charged insulator A.

The field from A will make electrons in B move to the side of B facing A. These electrons make up the so-called bound induced charge. This charge can not be removed as long as B is in the field from A.

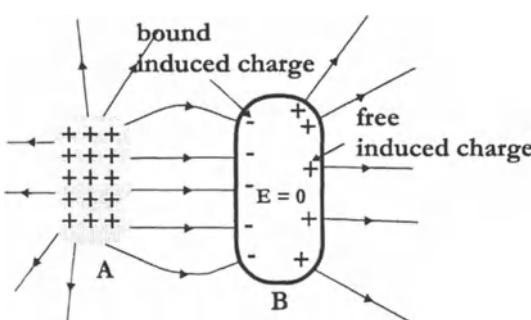


Fig. 2.23

The corresponding excess positive charge, the free induced charge is located on the opposite side of B. But the total charge on B is still zero as is the field inside B.

The free induced charge (positive) creates an electric field in the surroundings of B,

with the field lines eventually terminating on some grounded object.

If this field is integrated from B to a ground point, we will get a positive figure, which per definition is the voltage of B.

We thus have an uncharged conductor with a positive voltage.

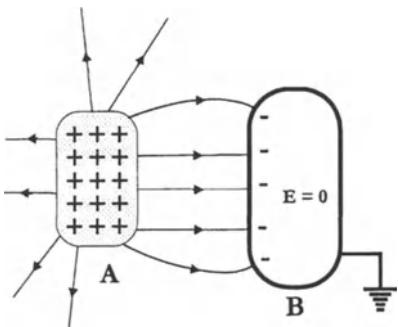


Fig. 2.24

Fig. 2.24 shows the same situation as Fig. 2.23, except now the conductor is grounded. Consequently the voltage of B is zero. But B still has the negative, bound induced charge. We thus have a negatively charged conductor with zero voltage.

If finally the ground connection is broken, and B is moved away from the neighborhood of A (in an insulated way), B will still

have its negative charge, which now will give B a negative voltage.

We express this as B has been charged by induction.

We shall return to the possible risks of this situation when dealing with static discharges.

2.11 POLARIZATION

If a conductor is placed in an electric field, induction will make charges move in the conductor until the interior field is zero.

If the material placed in the electric field is an insulator the above processes can not take place because of the absence of mobile charge carriers.

But the field may disturb the otherwise symmetrical distribution of positive and negative charges in the molecular structure of the insulator. Fig. 2.25a shows an atom in a field-free region. The time-mean distribution of the charges of the atom is symmetrical, so that there is

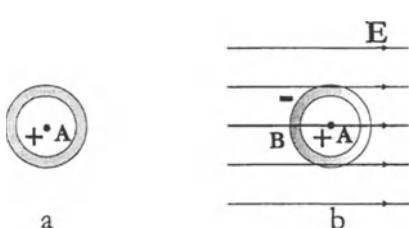


Fig. 2.25

no external field. The atom is neutral.

If an electric field E is applied, Fig. 2.25b, the symmetry will be disturbed. The (center of distribution of the) electrons will be displaced in the opposite direction of the field, and for some materials the nucleus may shift in the direction of the field.

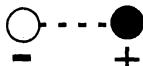


Fig. 2.26

The situation in Fig. 2.25b may be represented by a negative and a positive charge separated a distance depending on the field strength, Fig. 2.26.

This is called an electrical dipole, and such dipoles are formed throughout the insulator, hence the name polarization.

And an insulator in which dipoles may be formed is often called a *dielectric*.

The dipoles will line up end-to-end as a dipole-string along the field lines. If the field is rectilinear we can imagine a situation as shown in Fig. 2.27

The (field from the) internal +/- charges will cancel each other, and the string will act like one long dipole, a simplified dipole-string Fig. 2.28.

So what will these polarization dipoles do to the field inside the dielectric?

Let's answer this question in two steps.



Fig. 2.27

Fig. 2.29 shows a conductor A placed in an electric field with the strength E_0 . As explained in the previous section the field will bind (in

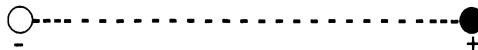


Fig. 2.28

this case) a negative charge on the left side (bound induced charge) and free an equally large positive charge on the right side (free induced charge). The total field inside the conductor will be zero. The free charge may be removed if the conductor is grounded.

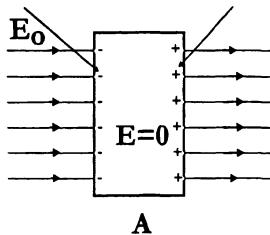
bound induced charge

Fig. 2.29

free induced charge

If, however, the body A is a dielectric the situation is different, Fig. 2.30. The external field E_o will cause polarization, i.e. form dipole-strings. The strings

will be “stacked” on top of each other and create a dipole field E_p in the opposite direction of and superimposed on E_o .

The resulting field

$$E = E_o - E_p$$

is smaller than E_o and it turns out that is a constant, characteristic for the dielectric in question.

$$\frac{E_o}{E} = \epsilon_r$$

ϵ_r is called the **relative permittivity** or **dielectric constant**. Many commonly used dielectrics have ϵ_r -values from 2 to 7.

The charges of the dipoles are called **polarized charges**. In contrast to induced charges they can not be removed from the dielectric.

The situation in Fig. 2.30 is the simplest possible, with the external field being homogeneous and the field lines being perpendicular to the sides of the dielectric.

If the latter is not the case, E_o and E will not be parallel. A “refraction” will happen at the interface, and we have a parallel to Snell's law of optical refraction, where the optical refractive indices are substituted by the relative permittivities.

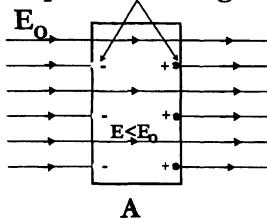
polarized charges

Fig. 2.30

2.11.1 EFFECT ON CAPACITANCE

Under the section on the parallel plate capacitor (page 16) it was shown that the capacitance could be written

$$C = \epsilon_r \epsilon_0 \frac{S}{d} \quad (2.19)$$

This means that the capacitance is increased by a factor of ϵ_r when the electrode interspace is filled by a dielectric with the relative permittivity ϵ_r . The explanation for this is that the field strength for a given charge is ϵ_r times smaller than would have been the case in vacuum (or air) and hence the voltage difference across the capacitor plates is also ϵ_r times smaller. And when the voltage difference V for a given charge q becomes ϵ_r smaller, the capacitance C becomes ϵ_r times larger (eq. (2.16), page 15)

Other aspects of polarization will be treated under *static electric effects*.

2.12 MOBILITY

All materials contain to a certain extent mobile charge carriers. In some materials only one polarity of charge carriers are mobile, like the electrons in metals.

In other materials, like many liquids, the charge carriers are electrolytic ions and both polarities are mobile.

But in both of the above cases the charge carriers are always present in the materials and have well-defined properties.

This is not the case in gases. If we want a gas to contain mobile charge carriers we have to create them by an ionization process, and the resulting *gas ions* are unstable structures with badly defined and varying properties.

We shall deal with this problem in a special section.

If an electric field is established in a material containing mobile charge carriers the positive carriers will move in the direction of the field, the negative in the opposite direction, Fig. 2.31.

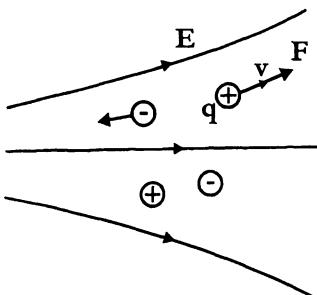


Fig. 2.31

The force F on a carrier with the charge q exposed to a field with the strength E is

$$F = qE \quad (2.2)$$

One might now expect the carrier to move on an accelerated motion, but it appears that the mean acceleration is for most materials zero, and the numerical value of the velocity v of the charge carriers is (at constant temperature)

proportional to the field strength E

$$v = kE \quad (2.20)$$

The factor k is called the *mobility* of the charge carriers, with the unit $\text{m}^2\text{V}^{-1}\text{s}^{-1}$.

2.13 CONDUCTIVITY AND RESISTIVITY

A transport of charge induced by an electric field is called an electric current. We define the *current density* j as the current passing through a unit area, perpendicular to the field strength, per unit time.

j is a vector in the direction of the flow of positive charges.

If the concentration of mobile charge carriers is n , their charge q and their velocity v , j can be written

$$j = nqv = nqkE \quad (2.21)$$

The unit for current is the ampere (A) which is a fundamental unit in the International System of Units (SI). The unit for current density is thus $\text{A}\cdot\text{m}^{-2}$.

The quantity

$$\gamma = nqk \quad (2.22)$$

is called the (volume or bulk) conductivity of the material considered, and eq. (2.21) may thus be formulated

$$j = \gamma E \quad (2.23)$$

As E is measured in $\text{V}\cdot\text{m}^{-1}$ and j in $\text{A}\cdot\text{m}^{-2}$ the unit for γ is $\text{A}\cdot\text{V}^{-1}\cdot\text{m}^{-1} = \Omega^{-1}\cdot\text{m}^{-1}$.

Eq. (2.23) is often written

$$E = \rho j \quad (2.24)$$

The quantity $\rho = 1/\gamma$ is called the (volume or bulk) resistivity of the material.

The unit for ρ is $\Omega \cdot m$.

Since the mobility k and the concentration n of the charge carriers are constant for most materials, γ (and ρ) are also constant (for constant temperature) for a range of values of E and eq. (2.23) can thus be expressed

the current density is proportional to the electrical field strength

Both relations expressed in eqs. (2.23) and (2.24) are called

Ohm's law (on differential form)

In table 2.1 is shown the bulk resistivity at room temperatures of some commonly used materials

material	bulk resistivity $\Omega \cdot m$
silver	$1.6 \cdot 10^{-8}$
copper	$1.7 \cdot 10^{-8}$
aluminum	$2.9 \cdot 10^{-7}$
iron	$1.0 \cdot 10^{-8}$
1N HCl	$1.0 \cdot 10^{-2}$
distilled water	10^4
celluloid	$2 \cdot 10^8$
dry wood	$3 \cdot 10^8$
glass (dry)	$2 \cdot 10^{11}$
plexiglas	$1 \cdot 10^{13}$
rubber	$3 \cdot 10^{14}$
quartz	$5 \cdot 10^{16}$
polystyrene	$1 \cdot 10^{17}$

Table 2.1.

Bulk resistivity (at room temperature) of some commonly used materials

2.14 CONDUCTANCE AND RESISTANCE

The material properties, conductivity and resistivity, refer to the region around a point in a material. They are thus differential quantities and as

such not accessible to direct measurements but have to be deduced from the determination of other quantities of integral nature. This is probably best explained by a simple example.

Fig. 2.32 shows a cylindrical conductor of cross section S , length L and bulk conductivity γ . If an electric field E is established in the material along the axis a current I will flow in the direction of the field. The density of the current is given by

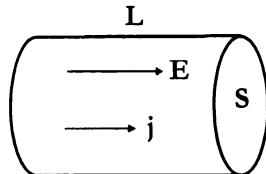


Fig. 2.32

$$j = \gamma E \quad (2.23)$$

And the current I can be written

$$I = jS = \gamma SE \quad (2.24)$$

or

$$I = \gamma \frac{S}{L} LE \quad (2.25)$$

If the material is homogeneous the field strength is constant along the conductor and the quantity LE is, eq. (2.11), equal to the voltage difference between the ends of the conductor, and eq. (2.25) may be reformulated

$$I = GV \quad (2.26)$$

where

$$G = \gamma \frac{S}{L} \quad (2.27)$$

is the **conductance** of the conductor.

According to eq. (2.26) the unit for conductance is ampere/volt, or siemens, S. i.e.

$$1 \text{ S} = 1 \text{ A} \cdot \text{V}^{-1}$$

Eq. 2.26 may also be written

$$V = \frac{1}{G} V = RI \quad (2.28)$$

where

$$R = \rho \frac{L}{S} \quad (2.29)$$

is the **resistance** of the conductor.

The resistance is thus the reciprocal of the conductance. The unit of resistance is volt/ampere, which is called ohm (Ω), i.e.

$$1 \Omega = 1 \text{V}\cdot\text{A}^{-1}$$

Eqs. 2.26) and (2.28) are **Ohm's law** (on integral form).

By measuring V and I the resistance R characteristic for the particular conductor is determined from eq. (2.28) and the resistivity ρ , characteristic for the material, from eq. (2.29).

Although eq. (2.28) had been derived for a special simple case, it expresses a general relation for all current paths which can be stated as follows: *The ratio between the voltage difference between two points and the current flowing between the same two points is equal to a constant, the resistance, characteristic for the current path. The resistance can, for isotropic, homogeneous media be written as the product of the resistivity and a geometrical factor with the dimension of reciprocal length.*

This is the integral version of **Ohm's law**.

2.15 SURFACE CONDUCTIVITY AND RESISTIVITY

In the previous section the transport of charge through the bulk of a material was discussed. However in static electric contexts charge transport often takes place along the surface or in a shallow layer on the surface of an insulative material.

This process is usually characterized by the **surface conductivity**, γ_s , and corresponding **surface resistivity**, ρ_s . If an electric field is applied with a component E_s along the surface, a current with the **linear current density**, j_s , will flow in the direction of E_s .

The surface conductivity γ_s is then defined by

$$j_s = \gamma_s E_s \quad (2.30)$$

And correspondingly for the surface resistivity ρ_s ,

$$E_s = \rho_s j_s \quad (2.31)$$

because

$$\rho_s = \frac{1}{\gamma_s}$$

As j_s is a linear current density the unit is $A \cdot m^{-1}$, and not $A \cdot m^{-2}$ as is the case for a conventional current density. The unit for E_s is $V \cdot m^{-1}$; consequently the unit for γ_s is $A \cdot V^{-1} = \Omega^{-1}$ and for ρ_s the unit is $V \cdot A^{-1} = \Omega$.

2.16 SURFACE CONDUCTANCE AND RESISTANCE

If a voltage difference V_s applied between two electrodes placed on the surface of a material releases a current I_s between the electrodes, a surface conductance G_s and surface resistance R_s are defined respectively by

$$I_s = G_s V_s \quad (2.32)$$

and

$$V_s = R_s I_s \quad (2.33)$$

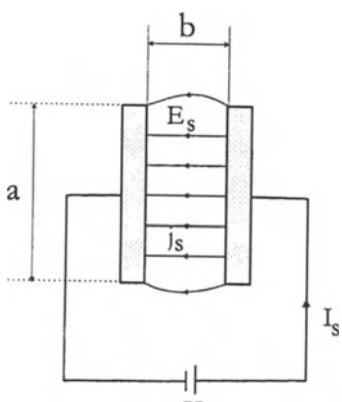


Fig. 2.33

With suitable electrode geometry, eq. (2.33) may be derived from eq. (2.31) and thus the differential property ρ_s can be deduced from the measurable integral quantity R_s .

Fig. 2.33 shows two electrodes of length a placed parallel to each other at a distance b on the surface of a material. A voltage source V_s makes a current I_s flow between the

electrodes. The field E_s and the linear current density j_s between the electrodes are approximately given by

$$E_s = \frac{V_s}{b} \quad \text{and} \quad j_s = \frac{I_s}{a}$$

Eq. (2.31) may thus be written

$$\frac{V_s}{b} = \rho_s \frac{I_s}{a}$$

or according to eq. (2.31)

$$\rho_s = \frac{V_s}{I_s} \cdot \frac{a}{b} = R_s \frac{a}{b} \quad (2.34)$$

Why Not Ohms per Square ?

It appears from eq. (2.34) that if the electrode spacing b is chosen equal to the electrode length a , i.e. if the electrodes are forming a square, the surface resistivity ρ_s will be equal to the surface resistance R_s across the square, both quantities obviously measured in ohms.

This geometrical fact has given rise (in some parts of the world) to the confusing and completely unnecessary habit of stating surface resistivities as being measured in *ohms per square*.

It's metrologically evident that there can be no such unit. No system has a square among the fundamental units.

It may be practical, for instance in the thin film industry, to calculate the resistance of a strip of a film by the number of times the width enters the length, i.e. use eq. (2.35), but in general electrostatics nobody needs the square. Quite the contrary, it may lead to even more absurd statements like *ohms per square inch* etc.

A way to get around this problem and at the same time apply a better measuring procedure is to use cylindrical geometry when determining the surface resistivity.

Let the cylindrical electrodes A and B be placed on a surface, Fig. 2.34. The radii of the inner and outer electrodes are a and b respectively. If a voltage difference V_s is applied between the electrodes, the field strength E_s in a point at a distance r ($a < r < b$) from the axis is given by.

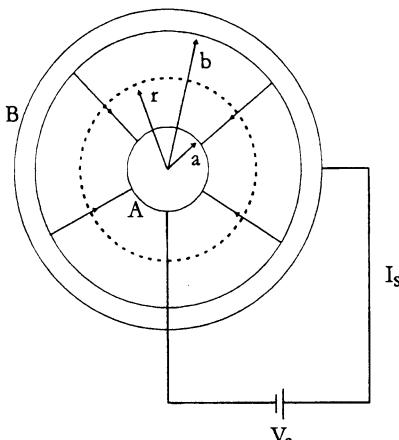


Fig. 2.34

$$E_s = \frac{V_s}{r \ln \frac{b}{a}} \quad (2.34)$$

The voltage difference V_s will cause a current I_s to flow between the electrodes. The current has a density j_s at a distance r

$$j_s = \frac{I_s}{2\pi r} \quad (2.35)$$

Combining eqs. (2.32), (2.33), (2.34) and (2.35) we find

$$\rho_s = \frac{V_s}{I_s} \cdot \frac{2\pi}{\ln \frac{b}{a}} = R_s \cdot \frac{2\pi}{\ln \frac{b}{a}} \quad (2.36)$$

The advantage of using cylindrical electrodes is primarily that the fields and current densities between the electrodes are better defined than they are with linear electrodes. And obviously eq. (2.36) also shows, like the definition in eq. (2.32), that surface resistivity is measured in ohms, *nothing more, nothing less*.

The practical execution of resistivity measurements will be dealt with in Chapter 8: ELECTROSTATIC MEASUREMENTS

Chapter 3

STATIC ELECTRIFICATION

As already mentioned two bodies interacting with electrical forces are said to be charged. The main question is then: how do the bodies obtain the charges?

First of all let's stress that charges are never generated. They exist all the time as positive charges of the protons of the nuclei of the atoms and negative charges of the electrons around the nuclei. But only when electrons are removed from some of the atoms in one material and transferred to atoms in another or maybe even the same material do we see an electric effect. This effect is usually most conveniently described by the electric field, which we will discuss later.

And we are normally only aware of this effect if the electron-exchanging materials are separated in such a way that the charges do not reunite during the separation process.

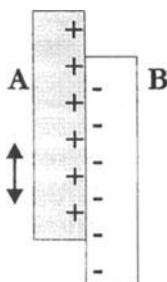
The transfer of electrons between atoms or molecules may occur when two solids, identical or different, contact each other, with electrons crossing the interface in a preferential direction, giving one material a positive and the other a negative excess charge.

The exchange of electrons may also occur when an insulative liquid is flowing through a tube, or when a liquid of almost any type is breaking up into droplets of non-uniform magnitude, or when droplets are falling through an inhomogeneous field, like in a thundercloud.

3.1 CHARGING OF SOLIDS TRIBOELECTRIFICATION

The most important type of charge separation involves the contact and friction between solids known as *triboelectrification*.

When two solid materials A and B, Fig. 3.1, are brought into contact with and possibly rubbed against each other, electrons may move across the interface.



3.1.1 METALS

It may be surprising that this also happens when the two materials are metals. And even

more surprising that this is the only case where the result of the charge transfer can be accurately predicted.

When two metals contact, a voltage difference is established across the interface, the so-called *contact potential difference*, with a magnitude from a couple of tenths to a few volts.

If the metals are “well-defined” the contact potential difference can be calculated from the work functions, i.e. the energy it takes to remove a (loosely bound) electron from the metal.

It should be stressed, however, that this charge exchange between metals only gives rise to what we normally understand with static electricity in case the two metals are separated extremely fast, for instance if a metal powder is blown against a metal surface.

3.1.2 INSULATORS

It is likely that processes similar to the ones described above for metals may take place during contact between materials of which one or both are insulators.

It is, however, difficult completely to characterize an insulative surface. In many materials, especially non-crystalline ones, the energy levels are badly defined and the contact processes are therefore not known in details.

It is conceivable that only electrons located close to the surface can participate in the charging of highly insulative materials. For some of these materials it is possible, similar to metals, to measure the work function for loosely bound electrons.

The practical implication of this, however, is not great mostly because the measured values only hold true for materials with well-defined surface states. As soon as a surface that may have been prepared in vacuum is exposed to “ordinary” air, the state, including the energy levels of surface electrons may change considerably.

Consequently charging experiments with insulators can only be expected to yield quantitatively predictable results if the surfaces are carefully prepared and the experiments performed in vacuum.

And such experiments may disclose very little about what one can expect to find under more practical conditions.

3.1.2.1 Contact Electrification

3.1.2.1.1 Triboelectric Series

One of the material parameters influencing the course of a charging process between two solid materials is the *permittivity*. Scientifically speaking the permittivity is defined as the ratio between corresponding values of the dielectric displacement and the electric field strength. However, in this context it is of more importance that the permittivity

positive end

Plexiglas

Bakelite

Cellulose acetate

Glass

Quartz

Nylon

Wool

Silk

Cotton

Paper

Amber

Resins (natural and man-made)

Metals

Rubber

Acetate rayon

Dacron

Orlon

Polystyrene

Teflon

Cellulose nitrate

Polyvinyl chloride

negative end

Table 3.1

Triboelectric series

is also a measure of the ability of the material to become polarized (see *Polarization*, p. 20)

If an ion or other charged small atomic or molecular cluster lands on an insulative surface it will be bound to the surface by polarization forces, the stronger the forces the higher the permittivity of the material.

This is the background for *Coehn's law*, which states that when two materials are in contact the one with the highest permittivity becomes positive.

This law was originally based on a comparison of known values of permittivities and published *triboelectric series*, i.e. a list of materials arranged in such an order that any material will become positively charged when rubbed against another material that is nearer the negative end of the series.

There is no doubt that such a

correlation exists, but with quite a few exemptions, and certain groups of materials may even be arranged in closed series.

Table 3.1 shows an example of a triboelectric series.

Such series should be used with a certain caution, as the order of the materials may vary from series to series.

It is possible, from the relative position in a series to predict the sharing of polarity, but the magnitude of the charges separated by contact and friction between two given materials can only be predicted with a high degree of uncertainty.

However, the magnitude of the charges often increases with the degree of friction between the surfaces.

The reason for this could be that the rubbing increases the area of contact between the surfaces and that the charging process itself is only governed by the energy state of the surfaces and charged particles will cross the interface at points of sufficient proximity. This, however, is hardly a satisfactory interpretation, because then it wouldn't be possible to explain the fact that two identical surfaces may get charged by being rubbed against each other, although it could be argued that no two surfaces are ever identical, and that incidental and uncontrollable differences might cause different affinities to charged particles.

3.1.2.2 Asymmetric Friction

As mentioned above the degree of friction during contact between two materials will influence the contact area and thus the exchange of charges. But the process of friction may have a specific influence of its own.

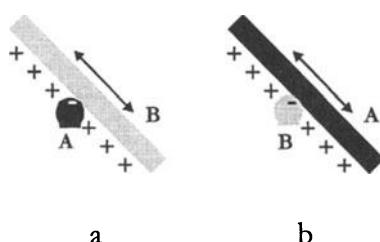


Fig. 3.2

is illustrated in Fig. 3.2.

It can be demonstrated that if two, macroscopically speaking, identical surfaces are rubbed against each other in such a way that the contact takes place between a small area of one surface and a larger area of the other, the polarities of the surfaces are likely to change if the roles of the surfaces are interchanged. This

Two pieces, A and B, are rubbed against each other. In situation a, A is stationary and B is being used as the bow on a string. If now in this case the “bow”, B, becomes positive, then, when the roles of A and B are reversed, situation b, the “bow”, in this case A, will again be positive.

This is a case of *asymmetrical friction*.

A possible explanation of this phenomenon is that the asymmetry may cause a thermal gradient to develop between the surfaces and thus induce already existing charge carriers to move in a certain direction, or the charge carriers may even be produced by a thermal dissociation of the material in charged components.

Other conditions than those mentioned above may play a role in charge exchange between contacting solid materials, such as the existence of (external) electric fields across interfaces. This effect may be utilized in electrostatic separation.

3.1.2.3 Post-contact Processes

Although contact between metals may produce charge transfer, no net charge will remain on the metals after separation, unless at least one of the metals is insulated and the separation happens very quickly.

If, on the other hand, at least one of the materials is an insulator, both surfaces will be charged immediately after separation, and if they are both insulative or one of them is an insulated conductor, the charges may remain on the materials, even when they are far removed from each other.

During the initial part of separation a series of processes may take place reducing the magnitude of the charges remaining on the surfaces.

Although the course of a charging process is difficult, if at all possible, to predict from the knowledge of characteristic parameters of the materials involved, certain rules may be formulated concerning the likelihood of encountering major charges under given circumstances.

The level of a static charging is governed by two competing processes: the rate of charge separation and the rate of charge neutralization or decay. We can give general rules for the rate of charge separation only to a very limited degree. The problem of charge decay will be treated in details in Chapter 4: CHARGE DECAY. In that chapter it will be shown that the decay rate in bulk decay, i.e. processes where the charge carriers move through the charged material, is inversely proportional to

the product $\rho\epsilon$, where ρ is the (volume) resistivity and ϵ the permittivity of the material. Although geometrical factors may also influence the decay rate it seems natural to use the product $\rho\epsilon$ as a measure for the ability of a material to get charged. And since the permittivity for most common materials fall within a rather narrow range, see Table 5.1, the bulk resistivity alone would also give a usable criterion for chargeability. But bulk resistivity is difficult to measure especially on manufactured items. On the other hand it is often possible and sometimes easy to determine the surface resistivity of materials, samples, and manufactured items. It should be stressed, however, that it is, for a given sample of a material, not possible to predict the decay rate from a measurement of the surface resistivity. All that can be concluded is that the lower the surface resistivity the higher is the decay rate for fixed geometrical conditions.

And this “relation” has over the years led to different electrostatic characterizations of materials by the surface resistivity.

An old (European) classification is shown in Table 3.2

<i>Material type</i>	<i>Surface resistivity</i>
<i>Static</i>	$>10^{14} \Omega$
<i>Astatic</i>	$10^{14} - 10^{10} \Omega$
<i>Antistatic</i>	$<10^{10} \Omega$

Table 3.2 Old surface resistivity classification

<i>Material type</i>	<i>Surface resistivity</i>
<i>Insulative</i>	$>10^{12} \Omega$
<i>Static dissipative</i>	$10^{12}-10^5 \Omega$
<i>Conductive</i>	$<10^5 \Omega$

Table 3.3 Modern surface resistivity classification

The division of materials into these groups should be taken only as a rule of thumb. It is true that most measurements of charging of solid

materials show that the level of charges separated do increase with the resistivity, but definitely not in an unambiguous way. Although materials of low resistivity never charge unless the surfaces are separated extremely fast, there are many examples of highly resistive materials being brought into contact without showing any significant charges after separation. Undoubtedly the nature of the contact play a role in the charging process. Normally the charges separated will be greater the more intimate the contact and friction is, and therefore smooth surfaces will often charge more than rough ones. When it is stated that materials of low resistivity do not charge this is generally true only when both materials have low resistivity. If for instance an insulative sheet of plastic is guided by a metal roller, the sheet as well as the roller may be charged, and if the roller is not grounded, both polarities of charge may be retained after separation.

3.2 CHARGING OF LIQUIDS

The charging of solid materials by contact and friction as described in the previous section is the best known type of static electrification, but it is not the only one.

Liquids may also get charged, for instance by flowing through tubes or by spraying.

The mechanism involved in the charging of liquids is somewhat different from the processes active in solids charging.

It has been demonstrated that phenomena like *electrophoresis* and *capillary electricity* in aqueous solutions can be explained if it is assumed that on the interface between a liquid and a solid or between a liquid and a gas an electrical double layer exists in the liquid with a layer of charge close to the surface and a layer of the opposite polarity a short distance deeper inside the liquid.

3.2.1 FLOW AND SPRAYING

If the surface of a liquid is changed, the electric double layer has to be formed or destroyed.

These processes are supposed to have a certain inertia, which implies that it is possible to separate the charges of the double layer by mechanical action on the liquid.

If a liquid is flowing through a tube there is a tendency for the outer charge of the double layer to be given off to the tube and the inner charge to be carried along with the flow, Fig. 3.3.

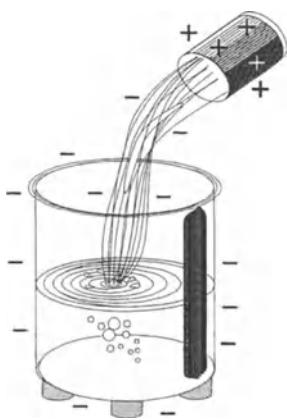


Fig. 3.3

Because the specific charge (charge per unit volume) of the liquid depends often very little on the linear velocity, the charging current is more or less proportional to the flow rate of the liquid. The specific charge generally increases with decreasing tube diameter and flow through a filter, which can be considered as a large number of (parallel) narrow tubes, often cause chargings.

The effect of the charging increases with the resistivity of the fluid (and depends on several other parameters) and as a consequence only highly insulative liquids ($\rho > \text{ca. } 10^7 \Omega \cdot \text{m}$) will show charging by flow. Water will thus not charge by flow.

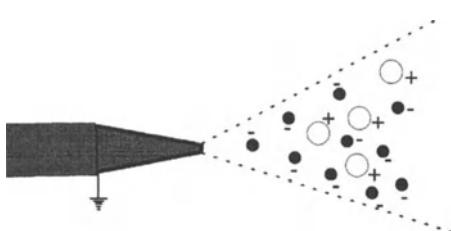


Fig. 3.4

It is an old experience that the breaking up of a liquid into droplets may cause charge separation.

This is what happens with “waterfall” electricity, or whenever water is broken into droplets, Fig. 3.4, where the fine mist consisting

mainly of very small droplets is predominantly negative, and the larger water drops precipitating more easily, are positive.

While charging of liquids by flow can only occur with highly insulative liquids, charging by spraying may happen with almost any kind of liquid.

3.3 CHARGING OF POWDERS

Dust and powders may get charged by contact and friction between the particles, especially if the individual particles have different properties, for instance regarding size and/or material. A charging of this type may result in the particles sticking together. More common, however, are

the processes where a powder is being transported through a system of tubes and the powder as a whole is being charged by the friction with the walls of the tube system. This kind of charging may take place if either the powder, the tubes or both are insulative.

3.4 CHARGING OF GASES

This section could actually be abbreviated to a single phrase:
GASES DO NOT CHARGE !

But it is not uncommon to find large static charges where gases are used in connection with transport of liquids and solids such as powders. And this phenomenon is often interpreted as a charging of the gas itself.

This, however, is not the case.

The kinetic energy you may impart on a gas molecule in an air flow, even at high velocities, is first of all much lower than the thermal kinetic energies at normal temperatures and again both much lower than what is required to knock off an electron from either the gas molecule itself or for instance container walls.

And this theoretical prediction is backed by experiments where filtered air is blown against a solid surface. No charging occurs.

The charging observed with ordinary compressed air is caused by liquid or solid impurities of the gas impinging on the target and is thus rather a case of dust charging.

The polarity of the target charge may thus be positive or negative, depending on the nature of the target as well as of the impurities.

Placing air at the top of a triboelectric list, as it is sometimes seen, makes thus no sense. I can add that almost all the charging experiments I have done with non-filtered air impinging on a variety of solid materials have always shown a positive charge on the target, which apparently should place air at the negative end of the list. But that's wrong. All experiments with carefully filtered air show no charging demonstrating that **GASES DO NOT CHARGE.**

Chapter 4

DECAY OF CHARGE

Static electricity is often defined as the behavior of electric charges at rest on insulators or insulated conductors. Nevertheless, an important part of this science deals with the movement of charges under the action of the fields they create themselves, spreading or neutralizing the charges and making the fields decay. As a matter of fact it is usually incorrect to talk about decay of a charge accumulation. If we have a certain amount of a radioactive substance the number of atoms will decrease with time, turning into other nuclides. And that process is a real decay. But in the case of a static electric charge there is only one situation, where the charge literally disappears. That of a negatively charged metallic object being connected to ground through a metallic connection. In that situation the excess electrons will flow to ground. In all other situations the apparent decay consists of oppositely charged carriers, electrons or ions, being attracted to the charge where the field from the carriers will superimpose the original field making the total field decrease, i.e. decay.

So what we actually observe is a decay of a field.

Although the decay is always governed by Ohm's law, eqs. (2.23) or (2.24), it is convenient to distinguish between three different types of decay schemes:

- Charge decay of a capacitive system, i.e. an insulated conductor characterized by its capacitance C and resistance to ground R .
- Charge decay of a non-conducting system, where the charge is located on a semi-insulative material with a given resistivity ρ and permittivity ϵ , and where the charge transport takes place exclusively through the material or along its surface.
- Charge decay through the air.

4.1 CHARGE DECAY OF CAPACITIVE SYSTEM

An insulated conductor may be characterized electrically by its capacitance C and resistance to ground R . Such an arrangement is called a capacitive system. The resistance R may be the well-defined resistance

of a resistor or the odd and rather uncertain (insulation) resistance of the support of the conductor. It is characteristic for the decay of charge of a capacitive system that the contact between the conductor and the resistive path to ground only needs to be established at a single point. If the only resistive way from the conductor to ground is through the surrounding air, special conditions may prevail, as will be explained later. The capacitance C is an integral measure of the distribution of the electric flux from a given charge on the conductor between the conductor and ground.

The capacitance will thus depend upon the location of the conductor and may change somewhat if the conductor itself or other neighboring conductors are moved. However, both the resistance and the capacitance are accessible for direct measurement.

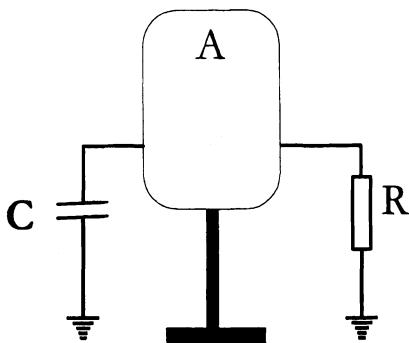


Fig. 4.1

Let the conductor A, Fig. 4.1, with the capacitance C and the resistance to ground R be initially charged with the charge q_0 , giving rise to an initial voltage

$$V_0 = \frac{q_0}{C} \quad (4.1)$$

The conductor will be surrounded by an electric field E which at any time and in any point is proportional to the charge q and the voltage V . A current I will flow to ground

$$I = \frac{V}{R} = \frac{q}{RC} \quad (4.2)$$

The current will make the charge decay with the rate

$$-\frac{dq}{dt} = I \quad (4.3)$$

Combining eqs. (4.2) and (4.3) we find

$$-\frac{dq}{dt} = \frac{q}{RC} \quad (4.4)$$

with the solution

$$q = q_0 \cdot e^{-\frac{t}{\tau}} \quad (4.5)$$

where the **time constant** $\tau = RC$.

The time constant indicates the time it takes the decaying quantity to decrease to $\frac{1}{e} \approx 37\%$ of the initial value.

As the voltage V and the field strength E around the conductor are proportional to the charge q , these quantities will decrease, or decay, with the same rate.

Example 4.1

A conductor is insulated by a material giving it a resistance to ground of $R = 10^{11} \Omega$. The capacitance of the conductor is $C = 200 \text{ pF}$. A charge $q_0 = 10^6 \text{ C}$ is placed on the conductor.

The initial voltage of the conductor is

$$V_0 = \frac{q_0}{C} = \frac{10^{-6}}{200 \cdot 10^{-12}} = 5000 \text{ V}$$

And the initial current is

$$I_0 = \frac{V_0}{R} = \frac{5000}{10^{11}} = 5 \cdot 10^{-8} \text{ A}$$

The field strength around the conductor will be proportional to the voltage but the exact value in a given point cannot be calculated unless the geometry and dielectric conditions are known in details.

If the distance from the conductor to ground is $d = 1 \text{ m}$ along some arbitrarily chosen path, the initial mean field strength $E_{m,0}$ along this path is

$$E_{m,0} = \frac{V_0}{d} = \frac{5000}{1} = 5000 \text{ V} \cdot \text{m}^{-1}$$

The time constant for the system is

$$\tau = RC = 10^{11} \cdot 200 \cdot 10^{-12} = 20 \text{ s}$$

4.1.1 INCIDENTAL DECAY OF CAPACITIVE SYSTEM

If a charged capacitive system is suddenly connected to ground through a low resistance the charge will decay like a fast current pulse, which may be destructive if it happens to pass through a sensitive component or circuit. The characteristics and effect of the pulse depend upon the capacitive and resistive properties of the charged system. The problem of dealing with various discharge situations, like the *machine model (MM)*, the *charged device model (CDM)* and the *human body model (HBM)* will be dealt with in Chapter 6: ELECTROSTATIC EFFECTS.

4.2 CHARGE DECAY OF NON-CONDUCTORS

As suggested for charged (insulated) conductors it is, at least in principle, possible directly to measure the resistive and capacitive parameters determining the rate of decay of the charge and voltage and thus of the field around the conductor.

However, in many situations we have to deal with charged insulators or semi-insulators for which the charge decay may depend in a rather complex, and in practice unmeasurable, way on the geometrical, dielectric and resistive properties of the environment.

Let us first look at the case where the charge transport takes place through the bulk of the material.

4.2.1 BULK OR VOLUME DECAY

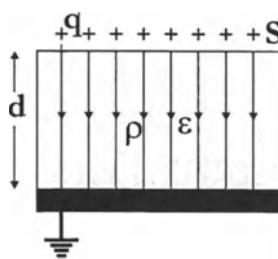


Fig. 4.2

Fig. 4.2 shows a sample of a material with the resistivity ρ and permittivity ϵ resting on a grounded plane. A charge q_0 is distributed uniformly over the area S , giving a surface charge density with an initial value of

$$\sigma_0 = \frac{q_0}{S} \quad (4.6)$$

If we assume the distance to other conductors in the surroundings to be much larger than the thickness d of the sample, the flux from the charge will be directed towards the ground plane and the value of the field strength E will, for a surface charge density σ , be

$$E = \frac{\sigma}{\epsilon} \quad (4.7)$$

neglecting the stray field at the edge of the charge distribution. The field E will cause a current to flow through the material with a density j given by

$$E = \rho j = \frac{\sigma}{\epsilon} \quad (2.24)$$

The current density is also the rate of decay of the surface density, i.e.

$$j = -\frac{d\sigma}{dt} \quad (4.8)$$

Combining eqs. (2.24) and (4.8) we find

$$-\frac{d\sigma}{dt} = \frac{\sigma}{\rho\epsilon}$$

with the solution

$$\sigma = \sigma_0 \cdot e^{-\frac{t}{\tau_0}} \quad (4.10)$$

and the time constant

$$\tau_0 = \rho\epsilon$$

This result is valid only if the flux from the charge extends exclusively through a medium with the parameters ρ and ϵ .

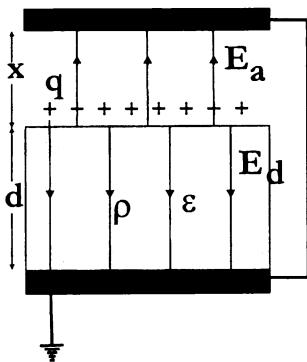


Fig. 4.3

In Fig. 4.3 a grounded plate is placed parallel with the charged semi-insulator at a distance x in vacuum (or air).

Here we have a field E_d in the insulator (the dielectric) as well as a field E_a in the air.

The relationship between the two fields can be found by expressing that the (surface) potential of the surface of the charged disk is the same whether it is calculated by use of E_d or E_a , i.e.

$$E_d \cdot d = E_a \cdot x \quad (4.12)$$

Also the charge density σ is shared between the dielectric, σ_d , and the air, σ_a , in such a way that

$$\sigma_d + \sigma_a = \sigma \quad (4.13)$$

and according to (4.12)

$$\frac{\sigma_d}{\epsilon} \cdot d = \frac{\sigma_a}{\epsilon_0} \cdot x \quad (4.14)$$

Combining (4.13) and (4.14) we find

$$\sigma_d = \frac{1}{1 + \frac{d}{\epsilon_r x}} \cdot \sigma \quad (4.15)$$

It is now important to note that only the field E_d contribute to the neutralization of the charge, i.e.

$$\frac{\sigma_d}{\epsilon} = \rho j = -\rho \frac{d\sigma}{dt} \quad (4.16)$$

From (4.15) and (4.16) we find

$$\sigma = \sigma_0 \cdot e^{-\frac{t}{\rho\epsilon + \rho\epsilon_0 \frac{d}{x}}} \quad (4.17)$$

Eq. (4.17) shows that the charge is being neutralized with a time constant

$$\tau = \rho\epsilon + \rho\epsilon_0 \frac{d}{x} = \tau_0 \left(1 + \frac{d}{\epsilon_r x}\right) \quad (4.18)$$

where ϵ_r is the relative permittivity of the charged material.

Eq. (4.18) expresses, for a special case, that the decay of a charge located on a semi-insulative material is not only determined by the properties of the material but also by the geometry and dielectric properties of the surroundings. The course of the decay can only be predicted in very special cases like the one described above.

Example 4.2

A sample of Plexiglas with a thickness $d = 0.01 \text{ m}$ is resting on a grounded plane, Fig. 4.2. The distance to other conductors is much larger than the thickness of the sample. A positive charge is distributed uniformly over the surface of the sample with a density of $\sigma = 10^7 \cdot \text{m}^{-2}$. The relative permittivity of the plexiglas is $\epsilon_r = 3.4$ ($\epsilon = \epsilon_0 \epsilon_r = 3 \cdot 10^{11} \text{ F} \cdot \text{m}^{-1}$). The resistivity is $\rho = 10^{13} \Omega \cdot \text{m}$.

The initial field strength in the sample is, eq. (4.7)

$$E_o = \frac{\sigma_0}{\epsilon} = \frac{10^{-7}}{3 \cdot 10} = 3300 \text{ V} \cdot \text{m}^{-1}$$

The initial current density is, eq. (2.24)

$$j_o = \frac{E_o}{\rho} = \frac{3300}{10^{13}} = 3.3 \cdot 10^{-10} \text{ A} \cdot \text{m}^{-2}$$

The time constant τ_o for the system is, eq. (4.11)

$$\tau_o = \epsilon \rho \cdot 3 \cdot 10^{11} \cdot 10^3 = 300 \text{ s}$$

If a grounded plate is placed above the plexiglass sample, Fig. 4.3, at a distance $x = 0.003 \text{ m}$, the time constant is now

$$\tau = \tau_o \left(1 + \frac{d}{\epsilon_r x}\right) = 300 \cdot \left(1 + \frac{0.01}{3.4 \cdot 0.003}\right) = 594 \text{ s}$$

It thus takes about twice as long for the charge to decay in this situation, because the field strength and consequently the decay current are only about half the values of those in the situation corresponding to Fig. 4.2.

4.2.2 SURFACE DECAY

As discussed above, it is sometimes possible to predict the neutralization rate of a charge when the neutralizing charge carriers move through the bulk of the charged material. However, in many cases the neutralization happens in a shallow layer on the surface of the material. This could be an antistatic agent or an insulative substrate onto which a conductive material is evaporated. If the conductivity of the layer is much higher than that of the base material, the neutralizing current will run only in this layer, while a part, and maybe even a major part, of the flux will go through the insulative regions and thus not contribute to the neutralization current.

Fig. 4.4 shows a piece of material which has a spot of negative charge at one end. The top layer of the material is conductive or semi-conductive, while the rest of the material is insulative. A grounded electrode is placed on the semi-conductive surface. The negative charge will produce an electric field with the field lines starting at the electrode and terminating at the negative charge.

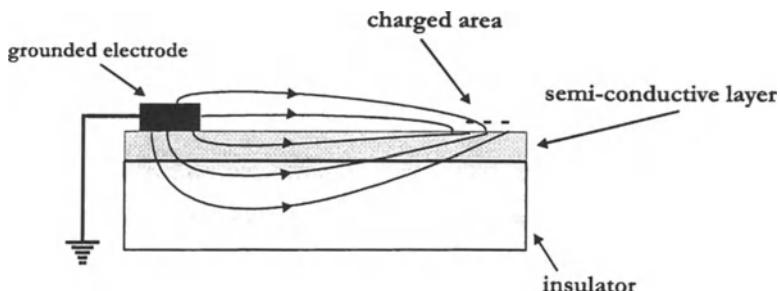


Fig. 4.4

For the part of the flux running through the semi-conductive layer, Ohm's law for surface conduction

$$E_s = \rho_s j_s \quad (2.32)$$

is valid.

But we have no way of knowing what the field strength in the semi-conductive layer is.

There is no doubt that if the charge is, say, doubled the field strength will be doubled in every point but the field distribution will be the same. And if the surface resistivity were doubled the decay rate would be halved.

So in this situation, i.e. with this geometry, it seems likely that we would have a time constant, proportional to the surface resistivity.

But in contrast to the simple situation for bulk decay, Fig. 4.2, we can not (even if we measure the (surface) resistivity and know the permittivity of the conductive layer) theoretically predict the time constant for surface decay.

The reason is, we do not know how the flux is distributed between the conductive layer and the environment.

In Fig. 4.5 is shown a situation, similar to Fig. 4.3 for bulk decay.

We have another grounded conductor in the neighborhood of the charged sample, but not in direct contact, so no neutralizing current will flow to this electrode.

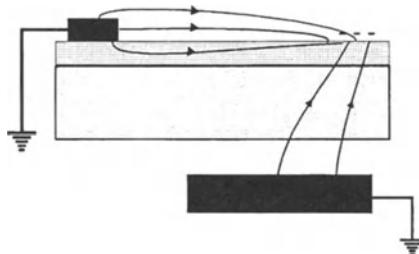


Fig. 4.5

And since the flux to the electrode on top of the material is now lower, so is the neutralizing current, and the time constant will have increased, even if the sample, the charge and the grounding electrode arrangement is the same.

During the above discussion we have tacitly assumed that there is only one value for the resistivity (be it bulk or surface) independently of the field applied. But it is often found that the resistivity increases with decreasing field strength. Nevertheless resistivities are usually determined at only one field strength (one voltage difference between a set of electrodes on the sample) and we have no way of knowing if this particular field strength is typical for the physical conditions during a decay process.

4.3 CHARGE DECAY THROUGH THE AIR

If a charge is located on an insulator there is in principle no way by which the charge may ever be removed. However, if the charged insulator is completely surrounded by a conductive fluid in contact with all points of the surface, the charge, or rather the field from the charge, may be neutralized by oppositely charged ions being attracted to the insulator. Although this scenario in principle could be established by using a conductive liquid, the only practical solution is to surround the charged body by ionized air. In order to describe such a situation it is necessary to give an overview of the electrical properties of ionized air.

4.3.1 ELECTRICAL PROPERTIES OF IONIZED AIR.

In any solid or liquid material the charge, mobility and concentration of possible charge carriers are constant (at constant temperature) as long as Electrical breakdown does not take place. In a metallic conductor the charge carriers are (valence) electrons, in a semiconductor the carriers

may be (positive) holes. But the carriers are always there to yield a current when a field is applied. They do not have to be produced somewhere else and brought to the site where they are needed, and their characteristics like mobility and concentration, do not change during the process. As a consequence the conductivity

$$\gamma = nqk \quad (2.22)$$

can be ascribed a constant value during the decay.

But the situation is not this simple when a gas is the current-carrying medium. Gases inherently contain very few nonpaired charges, which can be moved independently by an electric field to cause a net current. But gases in general and more specifically in the present context, atmospheric air can be ionized, i.e. made to contain mobile charge carriers, atmospheric ions or just air ions.

Air ions differ from electrolytic ions in several ways. They are small molecular clusters consisting mostly of water molecules grouped around a nitrogen or oxygen molecule, which has lost or gained an electron. In the case of positive ions the number of water molecules may be some 10-15, in the case of negative ions 8-12. In the latter case the (negatively) charged molecule is always oxygen.

Air ions have only a limited lifetime, in undisturbed air in the order of minutes. They disappear by positive and negative ions recombining, by combining with airborne particles and by plateout on surfaces, either by diffusion or aided by an electric field. And it's the latter process that is utilized in charge neutralization.

It should be mentioned that when an ion combine with a neutral particle, like an aerosol nucleus, the result is in principle also an ion, a so-called large ion. These large ions, however, do not play any significant role in charge neutralization.

The charge of an atmospheric ion is the electronic charge e , positive or negative. The mobilities are $k^+ \approx 1.3\text{-}1.4 \cdot 10^{-4} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ for positive ions and $k^- \approx 1.8 \cdot 10^{-4} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ for negative ions.

While a solid or liquid material may be characterized by a single conductivity, eq. (2.22), it is necessary to define polar conductivities in order to characterize ionized air.

An atmosphere with the concentrations n^+ and n^- of the positive and negative ions, respectively, may be characterized by the polar conductivities λ^+ and λ^- given by

$$\lambda^+ = n^+ k^+ e \quad (4.19)$$

and

$$\lambda^- = n^- k^- e \quad (4.20)$$

Often it is more convenient to use the corresponding polar resistivities

$$\rho^+ = \frac{1}{\lambda^+} = \frac{1}{n^+ k^+ e} \quad (4.21)$$

and

$$\rho^- = \frac{1}{\lambda^-} = \frac{1}{n^- k^- e} \quad (4.22)$$

4.3.2 CHARGE NEUTRALIZATION

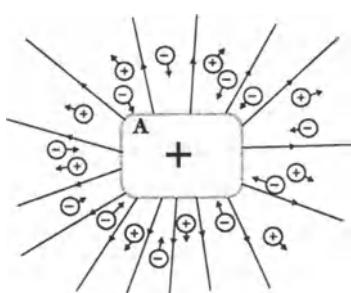


Fig. 4.6

Fig. 4.6 shows a positively charged body A surrounded by an atmosphere containing positive and negative ions. The ions will move in the field. The positive ions will be repelled from the body and move away. The negative ions will be attracted and eventually plate out on the charged body, and the field from the plated out ions will superimpose the original field from the positive charge and thus make it appear like the charge on A has been reduced.

Let's consider a part of the surface of A where the charge

density is σ^+ ($C \cdot m^{-2}$). The charge will create a field perpendicular to the surface with the strength

$$E = \frac{\sigma^+}{\epsilon_0} \quad (4.23)$$

This field will, according to Ohm's law, cause a current towards A with the density j^- ($A \cdot m^{-2}$) given by

$$j^- = \frac{E}{\rho^-} = \frac{\sigma^+}{\epsilon_0 \rho^-} \quad (4.24)$$

The current density is the rate with which the charge density is being neutralized ("decays"), i.e.

$$j^- = -\frac{d\sigma^+}{dt} = \frac{\sigma^+}{\epsilon_0 \rho^-} \quad (4.25)$$

with the solution

$$\sigma^+ = \sigma_0^+ \cdot e^{-\frac{t}{\tau_o^+}} \quad (4.26)$$

where σ_0^+ is the initial charge density and

$$\tau_o^+ = \epsilon_0 \rho^- \quad (4.27)$$

is the time constant for positive charges

If the charge density is integrated over the whole surface of A we find for the total charge

$$q^+ = q_0^+ \cdot e^{-\frac{t}{\tau_0^+}} \quad (4.28)$$

where q_0^+ is the initial total positive charge, and similarly for a negative charge.

$$q^- = q_0^- \cdot e^{-\frac{t}{\tau_0^-}} \quad (4.29)$$

where

$$\tau_0^- = \epsilon_0 \rho^+ \quad (4.30)$$

Equations (4.28) and (4.29)) express that a charge on a conductor decreases exponentially with a time constant $\epsilon_0 \rho$ where ρ is the relevant ("opposite") resistivity of the air.

However, this simple rule is only valid provided the field from the charge extends exclusively through air with a given resistivity. But in many, and probably most, practical cases the electric flux from the charge will be distributed over several regions of different permittivities and resistivities.

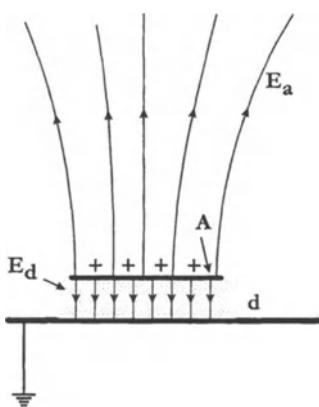


Fig. 4.7.

Fig. 4.7 shows a relatively simple example of this situation. A metal disk with the area A is placed on a slab of insulative material (a dielectric) with the thickness d and permittivity ϵ resting on a grounded plane. The disk has a (positive) charge q , which will create a field E_d in the dielectric and a field E_a in the ambient air. If we assume the dielectric to be perfectly insulative, only the field E_a will contribute to the neutralization of q . The relationship between E_d , E_a and q can be estimated by considering

the capacitance of A with respect to ground, C_d , and with respect to the surrounding air, C_a .

The total capacitance of A is

$$C = C_a + C_d \quad (4.31)$$

The charge q will be distributed on C with the amounts

$$q_a = \frac{C_a}{C_a + C_d} \cdot q \quad (4.32)$$

on the topside and

$$q_d = \frac{C_d}{C_a + C_d} \cdot q \quad (4.33)$$

on the underside.

The field in the surrounding air from the charge q_a will cause a neutralizing current I^- to flow to the disk A.

Using equations (4.31), (4.32) and (4.33) we find

$$I^- = A \cdot j^- = \frac{A \cdot \sigma^+}{\epsilon_0 \rho^-} = \frac{q_a}{\epsilon_0 \rho^-} \quad (4.34)$$

However, I^- is also the rate with which the total charge decays, or rather is being neutralized, i.e.

$$I^- = \frac{q_a}{\epsilon_0 \rho^-} = \frac{\frac{C_a}{C_a + C_d} \cdot q}{\epsilon_0 \rho^-} = -\frac{dq}{dt} \quad (4.35)$$

Equation (4.35) has the solution

$$q = q_0 \cdot e^{-\frac{t}{\tau^+}} \quad (4.36)$$

where the time constant τ^+ is given by

$$\tau^+ = \frac{C_a + C_d}{C_a} \cdot \epsilon_0 \rho^- \quad (4.37)$$

or

$$\tau^+ = \frac{C_a + C_d}{C_a} \cdot \tau_o^+ \quad (4.37)$$

where τ_o^+ is the time constant for a positively charged body freely suspended in air.

As was to be expected, the decay becomes slower (the time constant larger) when a part of the flux runs in an insulative region.

In order to evaluate the influence of the capacitance C_d on the decay time we have to estimate C_d and C_a .

If we assume that the thickness d of the dielectric is much smaller than the linear dimensions of A the capacitance C_d can be written

$$C_d = \epsilon \frac{A}{d} \quad (4.39)$$

C_a depends upon the shape of A and the distance (above A) to grounded surroundings. An appropriate approximation of C_a seems to be that of a semispherical capacitor, Fig. 4.8, with the capacitance

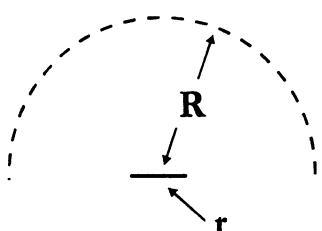


Fig. 4.8

$$C_a = 2\pi\epsilon_0 \frac{R \cdot r}{R - r} \quad (4.40)$$

where r is the (equivalent) radius of A ($= \sqrt{\frac{A}{\pi}}$) and R is the average distance to grounded surroundings.

As we can usually assume $r \ll R$ equation (4.40) can be written

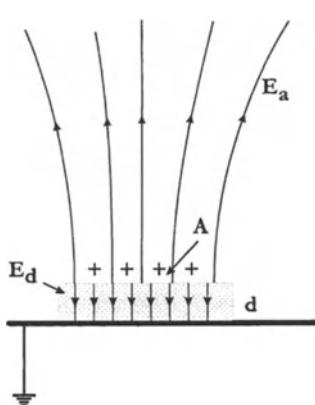


Fig. 4.9

$$C_a \approx 2\pi\epsilon_0 r \quad (4.41)$$

Using (4.39) and (4.41) and setting $A = \pi r^2$ and $\epsilon = \epsilon_r \epsilon_0$, where ϵ_r is the relative permittivity of the insulative slab, equation (4.38) can be written

$$\tau^+ \approx \left(1 + \frac{\epsilon_r r}{2d}\right) \tau_o^+ \quad (4.42)$$

Using eqs. (4.19) and (4.27), eq. (4.42) may also be written

$$\tau^+ = \left(1 + \frac{\epsilon_r r}{2d}\right) \frac{\epsilon_0}{n^- k^- e} = \left(1 + \frac{\epsilon_r r}{2d}\right) \epsilon_0 \rho^+ \quad (4.43)$$

The equations (4.42) and (4.43) give for a given ion environment the rate of neutralization by air ions of a positive charge, as a function of the geometrical and dielectric location of the charge. Similar, symmetrical equations hold true for the neutralization of negative charges.

The equations were developed for a charge located on a conductor, i.e. in a situation where the concept of capacitance can be applied.

However, the same formulas are also, with some approximations, valid in the case of charged insulators.

Fig. 4.9 shows the distribution of the electric flux from a charged insulator disk. It's the same situation as the one shown in Fig 4.7, except that in Fig. 4.9 the metal disk has been removed and the charge is uniformly distributed on an area A of the surface of the insulator.

The fields E_a and E_d are therefore the same in the two situations and consequently the neutralization processes will also be identical.

Equations (4.42) and (4.43) will therefore still express the rate of neutralization of the charge.

Here some readers may ask *When everything seem to be the same for the conductor and the insulator, why can one not use the same concepts, especially the concept of capacitance in the two cases?* The short version of the answer is

the following. If a conductor with the capacitance C and a charge q is grounded, an energy $W_C = \frac{q^2}{2C}$ will be released in a discharge, most likely a spark. In the situation of Fig 4.7 the energy W_C would amount to

$$W_C = \frac{q^2}{4\pi\epsilon_0 r + \frac{2\epsilon A}{d}}$$

the surface of the metal disk by a grounded wire. In the situation of Fig. 4.9 exactly the same energy is stored in the field, as the flux distribution is the same in the two cases. However, if you touch the surface of the charged insulator with a grounded wire you may at best (or worst) provoke a brush discharge releasing a fraction of the total energy stored in the field. And as capacitance is intimately related not only to the energy stored in the field, but also to the energy which may be dissipated in a discharge from the charged item, capacitance has no place when describing charged insulators.

The question of discharges from conductors and insulators is treated in more details in Chapter 5: BREAKDOWN and Chapter 6: ELECTROSTATIC EFFECTS.

Example 4.3

We consider a situation as shown in Fig. 4.7 with $A = 10 \text{ cm} \times 10 \text{ cm} = 10^2 \text{ m}^2$ and $d = 1 \text{ cm} = 10^{-2} \text{ m}$. The insulative plate is plexiglas with $\epsilon_r = 3.3$, i.e. $\epsilon \approx 3 \cdot 10^{11} \text{ F} \cdot \text{m}^{-1}$.

The metal plate is charged by a positive charge.

The surrounding air has a concentration of negative ions $n^- = 10,000 \text{ ions} \cdot \text{cm}^{-3} = 10^{10} \text{ ions} \cdot \text{m}^{-3}$. The mobility is $k^- = 1.8 \cdot 10^4 \text{ m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$.

From eq. (4.22) we find

$$\rho^- = \frac{1}{10^{10} \cdot 1.8 \cdot 10^{-4} \cdot 1.6 \cdot 10^{-19}} \approx 3.5 \cdot 10^{12} \Omega \cdot \text{m}$$

and from eq. (4.30)

$$\tau_o^- \approx 31 \text{ s}$$

From (4.39)

$$C_d \approx 3 \cdot 10^{-11} \cdot \frac{10^{-2}}{10^{-2}} \approx 30 \text{ pF}$$

and, as $r \approx 5.6 \cdot 10^{-2} \text{ m}$,

$$C_a = 2\pi \cdot 8.85 \cdot 10^{-11} \cdot 5.6 \cdot 10^{-2} \approx 3 \text{ pF}$$

From the symmetric formula of eq. (4.38)

$$\tau^- \approx \frac{3 \cdot 10^{-12} + 30 \cdot 10^{-12}}{3 \cdot 10^{-12}} \cdot 31 \approx 340 \text{ s}$$

It appears that the expected time constant is more than ten times higher than the theoretical value for the atmosphere.

Chapter 5

ELECTRICAL BREAKDOWN

5.1 BREAKDOWN IN AIR

Under normal circumstances atmospheric air is considered a good insulator, and a charged insulator or insulated body will lose its charge slowly when surrounded by air. The reason for this is that air, as a rule, contain very few mobile charge carriers, atmospheric ions.

In Chapter 4: DECAY OF CHARGE it was explained how ions in the surrounding air may eventually neutralize the charge on a body. For this to happen in a reasonable time, usually the ion level in the whole atmosphere around the charged item has to be raised by the use of some ionizing device.

But sometimes a charged body may interact with grounded surroundings in such a way that the ion concentration is substantially increased locally. Such an event is called an **electrical breakdown**.

The breakdown is usually caused by the effect of an electrical field on the already existing mobile charge carriers in the air, atmospheric ions and a few free electrons both originating from natural radioactive decay.

The ions as well as the free electrons participate in the random, thermal movement of the molecules. It should be stressed that the thermal energy of ions as well as of electrons is far too low to make a thermal collision result in an electron being knocked off an air molecule, i.e. causing ionization. However, if an electric field exists in the gas, the charged particles will be accelerated in the field and gain an extra kinetic energy. If a particle with the charge q is moved a distance Δx by a field with the strength E the particle gains an increase in its kinetic energy

$$\Delta W_{\text{kin}} = q \cdot E \cdot \Delta x \quad (5.1)$$

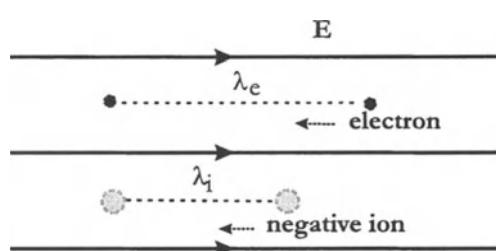


Fig. 5.1

provided the particle doesn't collide with other particles over the distance Δx .

Since an electron and a (negative) air ion both carry an elementary charge (e) they will gain the same increase in energy if they travel the same distance.

However, because of the difference in size the electron is able to travel much longer between collisions with other particles than is the ion. The (mean) distance to be traveled between collisions is called the *mean free path*.

5.1.1 BREADOWN FIELD STRENGTH

Figure 5.1 shows an electron with the mean free path λ_e and a negative ion with the mean free path λ_i in a (homogeneous) electric field E.

The maximum energy $\Delta W_{\max,e}$ to be reached by an electron is thus

$$\Delta W_{\max,e} = e \cdot E \cdot \lambda_e \quad (5.2)$$

and correspondingly for an ion

$$\Delta W_{\max,i} = e \cdot E \cdot \lambda_i \quad (5.3)$$

It takes an energy W_{ion} to ionize an air molecule (i.e. to knock off an electron and eventually create a pair of positive and negative air ions).

Since the mean free paths (in atmospheric air and at atmospheric pressure) of an electron and an ion are $\lambda_e \approx 10^{-5} \text{ m}$ and $\lambda_i \approx 10^{-7} \text{ m}$ respectively (not shown to scale in the figure) an electron is able to reach this energy at a field strength, the *breakdown field strength*, E_b , which is approximately a hundred times lower than would be the case for an ion.

E_b is thus given by the equation

$$W_{\text{ion}} = e \cdot E_b \cdot \lambda_e \quad (5.4)$$

Since $W_{\text{ion}} \approx 5 \cdot 10^{-18} \text{ J}$ (or $\approx 30 \text{ eV}$) for atmospheric air we find from equation (5.4)

$$E_b = \frac{W_{\text{ion}}}{e \cdot \lambda_e} = \frac{5 \cdot 10^{-18}}{1.6 \cdot 10^{-19} \cdot 10^{-5}} \approx 3 \cdot 10^6 \text{ V} \cdot \text{m}^{-1} \quad (5.5)$$

5.1.2 BREAKDOWN VOLTAGE (BETWEEN CONDUCTORS)

The above calculations are valid only for a homogeneous field, such as may be established between two parallel electrodes, Fig. 5.2.

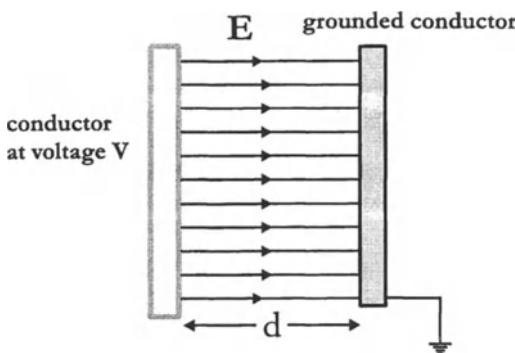


Fig. 5.2

The field strength E in the interspace between the electrodes is

$$E = \frac{V}{d} \quad (5.6)$$

where V is the voltage difference and d the distance between the electrodes.

We then define the *breakdown voltage*, V_b by

$$V_b = E_b \cdot d \quad (5.7)$$

as the voltage difference it takes to establish the breakdown field strength between the electrodes and cause a discharge, in this case a spark.

Let's assume $d = 3 \text{ cm} = 3 \cdot 10^{-2} \text{ m}$. The breakdown voltage is then

$$V_b = E_b \cdot d = 3 \cdot 10^6 \cdot 3 \cdot 10^{-2} = 90,000 \text{ V}$$

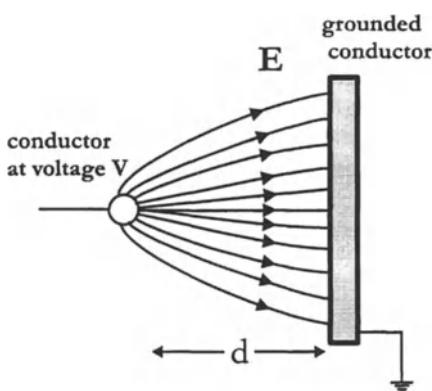


Fig. 5.3

If the field is not homogeneous the conditions become more complicated. Fig. 5.3 shows a situation similar to the one in Fig. 5.2 except here the one electrode is not plane but a small sphere or more generally a sharp point.

The different geometry results in *higher breakdown field strength* and *lower breakdown voltage*.

It appears from the figure that the field strength has its

maximum at the front of the small electrode, and this is consequently the site where a discharge may start.

Let us now assume that we have established a field strength of

$3 \cdot 10^6 \text{ V} \cdot \text{m}^{-1}$ at the tip of the electrode. This field strength would start a discharge in a homogeneous field, Fig. 5.2, because an electron would gain the critical energy W_{ion} over its mean free path, eq. (5.4).

However, the field in Fig. 5.3 decreases rapidly as one moves away from the electrode even over a short distance as the mean free path, and an electron will thus never gain enough energy to ionize.

Therefore $E_{b,\text{sphere}} > 3 \cdot 10^6 \text{ V} \cdot \text{m}^{-1}$. The actual value of E_b depends upon the radius of curvature and shape of the electrode, but not in a simple way.

Although the breakdown field strength is higher in an inhomogeneous field the actual maximum field strength caused by a given voltage is also higher.

If we assume that the linear dimensions of the grounded conductor, Fig. 5.3, are much larger than the distance d and the radius r of the sphere, the maximum field strength at the front of the sphere, E_{\max} , can be approximated by

$$E_{\max} = \frac{2d}{r(2d-r)} \cdot V \quad (5.8)$$

If we let E_{\max} be the breakdown field strength E_b , the breakdown voltage V_b can be written

$$V_b = \left(1 - \frac{r}{2d}\right) \cdot r \cdot E_b \quad (5.9)$$

Equation (5.9) suggests that the breakdown voltage for a spherical electrode approaches a maximum value of

$$V_{b,\max} = r \cdot E_b \quad (5.10)$$

for increasing distances d , and that 95 % of this value has been reached for a distance $d = 10 \cdot r$.

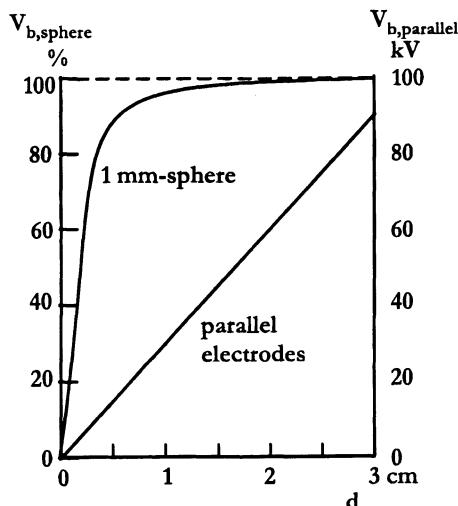


Fig. 5.4

some readers probably will recognize as the relationship between potential and surface field strength of a (conductive) sphere far away from other conductors.

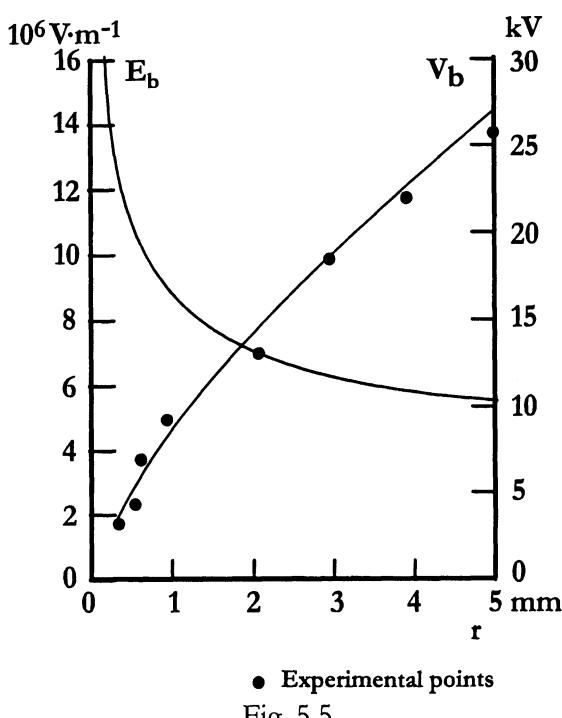
The absolute values for the breakdown field strength as a function of electrode dimensions can be estimated from the formula

$$E_b = \left(300 + \frac{18}{\sqrt{r}}\right) \cdot 10^4 \text{ V} \cdot \text{m}^{-1} \quad (5.11)$$

(*Handbuch der Physik, 1923*), which gives the breakdown field strength at a sphere with the radius r measured in meters. We recognize that as r approaches infinity, E_b will approach $3 \cdot 10^6 \text{ V} \cdot \text{m}^{-1}$, the breakdown field strength for plane electrodes.

Fig 5.5 shows the breakdown field strength E_b as calculated from eq. 5.11, and the corresponding break-down voltage, V_b , calculated from eq. 5.10.

Fig. 5.4 shows the breakdown voltage V_b for parallel electrodes, eq. (5.7), and for a 1mm-sphere, eq. (5.9), in the latter case normalized relative to the maximum value of $r \cdot E_b$. It should be stressed that in developing eq. (5.8) the influence on the field of the connections to a voltage supply has not been included. This necessary approximation can also be deduced from eq. (5.10), which



In order to investigate the validity of eqs. (5.10) and (5.11) the breakdown voltage was determined experimentally for a series of electrodes with radii varying from 0.25 mm to 5 mm. The results are shown in Fig. 5.5 as the experimental points.

It appears that for a 0.5 mm electrode the breakdown voltage is about 5.5 kV at a distance of say 1 cm as compared to the 30 kV breakdown voltage for plane elec-

trodes at the same distance.

The much lower breakdown voltage at a spherical electrode than at parallel electrodes is not the only difference between the two situations. In Chapter 6: ELECTROSTATIC EFFECTS, Discharges this matter will be treated in more details.

5.1.3 PASCHEN'S LAW

According to eq. (5.7) we should expect to get a spark discharge between plane electrodes at a distance d as long as the voltage difference V fulfills the condition

$$V \geq E_b \cdot d$$

where d is the distance between the electrodes and E_b is the breakdown field strength for plane electrodes (in atmospheric air at one atmosphere) $3 \cdot 10^6 \text{ V} \cdot \text{m}^{-1}$. So at a distance of $0.1 \text{ mm} = 10^{-4} \text{ m}$ breakdown should happen at $V = 3 \cdot 10^6 \cdot 10^{-4} = 300 \text{ volts}$. However, this is not so, which is shown in Fig. 5.6.

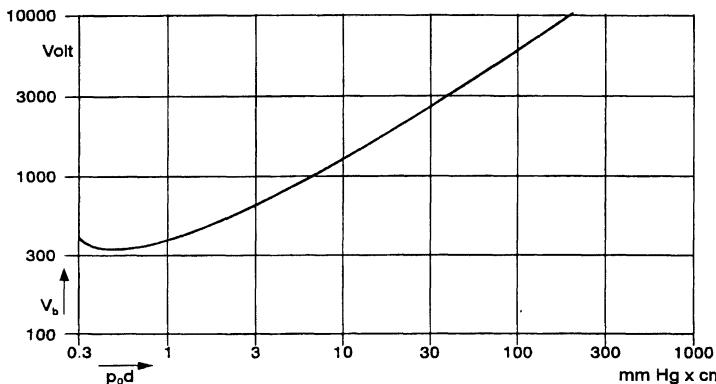


Fig. 5.6

The curve, known as Paschen's curve, shows the breakdown voltage for plane electrodes in atmospheric air (at room temperature) as a function of the product of the atmospheric pressure and the electrode distance. The product is given in the unit of mmHg times cm. If we assume a pressure of 1 atm (760 mmHg) and an electrode distance of 0.1 cm, we find at an abscissa of 76 mmHg·cm a breakdown voltage of 3000 volts, corresponding to the breakdown field strength of $3 \cdot 10^6 \text{ V} \cdot \text{m}^{-1}$ for plane electrodes.

However, the curve also shows that there is a minimum breakdown voltage at about 330-340 volts (corresponding at 1 atm to a distance of 5-6 μm and a field strength of approximately $6 \cdot 10^7 \text{ V} \cdot \text{m}^{-1}$). It means that it is not possible to get a discharge between parallel electrodes at a voltage lower than approximately 300 volts.

One could now ask what happens if the electrodes are not plane? Is it possible to get a corona discharge at, say, 300 volts?

Using eqs. (5.10) and (5.11) we find that a breakdown voltage of 300 volts would correspond to an electrode radius of 3 μm . However, the relationship in eq. (5.11) is at best semi-empirical and was definitely never tested at such small dimensions. It is therefore still unknown whether or not a version of Paschen's law applies to non-parallel electrodes.

5.1.4 INSULATORS

In most, at least unwanted, discharges, insulative materials are involved. And certainly breakdown may happen in fields from charged insulators. However, most of the rules and concepts outlined above for conductors can not be applied to insulators.

Although discharges in the field between oppositely charged insulators are possible there's no simple way in which such events may be predicted.

The most common discharge where insulators are involved happens in the field between a charged insulator and a grounded conductor.

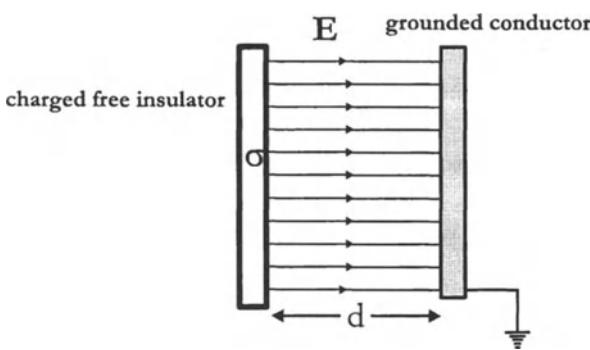


Fig. 5.7

Fig. 5.7 shows a uniformly charged free insulative disc. At a distance d is a grounded conductor parallel to the insulator. If the charge density on the disc is σ the field strength is

$$E = \frac{\sigma}{\epsilon_0} \quad (5.12)$$

Let's assume $\sigma = 2 \cdot 10^5 \text{ C} \cdot \text{m}^{-2}$. The field strength is then approximately $2.3 \cdot 10^6 \text{ V} \cdot \text{m}^{-1}$, i.e. not very far from the breakdown field strength for a homogeneous field. And thus there's a risk of a discharge of some kind. Not a spark, mind you, but probably a brush discharge, which will quench itself as the charge on the insulator is being (partly) neutralized. The possibility or risk of getting a discharge can be evaluated by measuring the field strength at the site of the grounded conductor.

Some readers might wonder: "Why not just measure the (surface) potential of the insulator?"

Let's try to analyze the situation.

If the distance $d = 1 \text{ cm} = 10^{-2} \text{ m}$, the surface potential of the insulator is

$$V_s = 10^{-2} \cdot 2.3 \cdot 10^6 = 23,000 \text{ volts}$$

If you think this sounds like a dangerously high voltage, just decrease the distance to 1 mm and the voltage goes down to 2,300 volts. Mind

you, the risk for a discharge has not changed since the field strength is the same.

The surface potential only tells you something of the risk if you use it to calculate the field strength.

And for that same reason the lower value of 300 volts of the Paschen curve can in no way be applied to insulators.

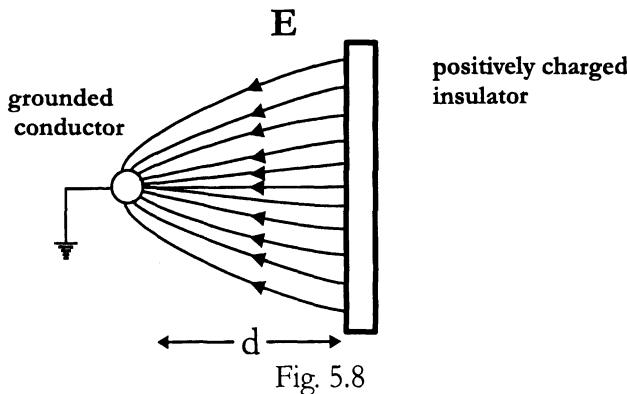


Fig. 5.8 shows a common situation where discharges are caused by a charged insulator. A grounded conductor, in this case a small sphere, is brought near to a charged insulator.

lator, which may or may not be uniformly charged. In all cases the field will be strongly inhomogeneous. The situation looks at first sight very similar to the one in Fig. 5.3 showing a sphere at a positive voltage near a grounded plane conductor. But, quite apart from the reversal of polarities, the conditions are very different in the two cases.

In the case of Fig. 5.3 with two conductors facing each other the distribution of the field is given when the geometry is given and you may be able to define a breakdown field strength and a breakdown voltage which can be compared to the voltage of the electrode, as discussed above. In the situation in Fig. 5.8, on the other hand, you may again be able to calculate the breakdown field strength (eq. (5.11), in case of a sphere) at the face of the electrode, and you can compare this to the field measured at the site of the grounded electrode. The magnitude of this field, however, can be achieved by an infinity of charge distributions on the insulator, and it can not be related to or deduced from any surface potential measured in front of the insulator.

5.2 BREAKDOWN IN DIELECTRICS

Also in dielectrics breakdown may occur when the field strength exceeds a certain critical value, characteristic for the material in question. The process of ionization is somewhat similar to that in air. However, one difference is that a dielectric in which breakdown has occurred normally is ruined, whereas the air almost momentarily regains its initial insulative properties.

5.2.1 BREAKDOWN FIELD STRENGTH

The breakdown field strengths of dielectrics are higher than that of air. Table 5.1 shows the breakdown field strengths and relative permittivities for some commonly used materials.

<i>material</i>	E_b $V \cdot m^{-1}$	ϵ_r
<i>air</i>	$3.0 \cdot 10^6$	1.000536
<i>mica</i>	$1.0 \cdot 10^8$	5.4
<i>mylar</i>	$1.5 \cdot 10^8$	3.0
<i>plexiglas</i>	$4.0 \cdot 10^7$	3.4
<i>polystyrene</i>	$2.4 \cdot 10^7$	2.5
<i>porcelain</i>	$6.0 \cdot 10^6$	7.0
<i>teflon</i>	$1.0 \cdot 10^7$	2.1
<i>Barium titanate</i>	$5.0 \cdot 10^6$	1200

*Table. 5.1
Breakdown field strength and relative permittivity
of commonly used materials*

5.2.2 BREAKDOWN VOLTAGE

As explained above it is the field strength that determines whether or not a discharge takes place in a material. When the breakdown field strengths for the material used are known, it is thus possible to calculate

the maximum voltage differences, which can be maintained in a given setup before a discharge sets in.

Fig. 5.9 shows a simple example. Two parallel metal plates are placed a distance d from each other.

The interspace is filled with a dielectric with the breakdown field strength E_b .

A voltage difference V is applied between the plates creating a field strength

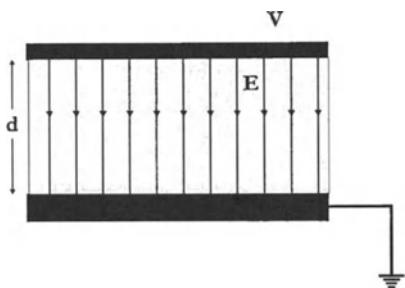


Fig. 5.9

$$E = \frac{V}{d} \quad (5.6)$$

between the plates.

The breakdown voltage between the plates is then

$$V_b = E_b d \quad (5.12)$$

Example 5.1

With $d = 0.1 \text{ m}$ (Fig. 5.9) and air between the plates the breakdown voltage is

$$V_{b,a} = 3 \cdot 10^6 \cdot 0.1 = 3 \cdot 10^5 \text{ V}$$

With plexiglas between the plates the breakdown voltage is

$$V_{b,p} = 4 \cdot 10^7 \cdot 0.1 = 4 \cdot 10^6 \text{ V}$$

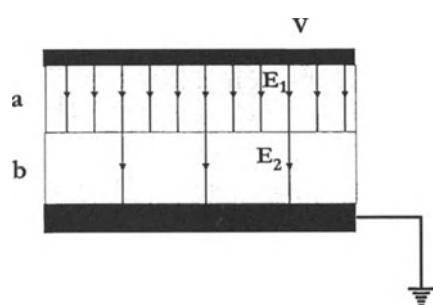


Fig. 5.10

Equation (5.12) is valid only when the entire volume between the plates is filled by the same dielectric.

Fig. 5.10 shows again two parallel plates separated by a distance d . The interspace is filled by two dielectrics of relative permittivities $\epsilon_{r,1}$ and $\epsilon_{r,2}$, breakdown field strengths $E_{b,1}$ and $E_{b,2}$ and

thicknesses a and b , where $d = a + b$.

If the field strengths in the two materials are E_1 and E_2 , respectively, the voltage difference V between the plates is given by

$$V = E_1 a + E_2 b \quad (5.13)$$

If the (common) surface charge density on the plates is σ , we have according to (2.14)

$$E_1 = \frac{\sigma}{\epsilon_{r,1}} \quad \text{and} \quad E_2 = \frac{\sigma}{\epsilon_{r,2}}$$

or $E_2 = \frac{\epsilon_{r,1}}{\epsilon_{r,2}} \cdot E_1$ (5.14)

Equation (5.13) may now be written

$$V = E_1 a + \frac{\epsilon_{r,1}}{\epsilon_{r,2}} E_1 b \quad (5.15)$$

The field strength in either material has to be smaller the breakdown field strength for that material, i.e. $E_1 < E_{b,1}$ and $E_2 < E_{b,2}$. The maximum voltage between the plates will be determined by $E_{b,1}$ if $E_{b,2} > \epsilon_{r,1}/\epsilon_{r,2} E_{b,1}$.

In this case we have

$$V_b = E_{b,1} a + \frac{\epsilon_{r,1}}{\epsilon_{r,2}} E_{b,1} b \quad (5.16)$$

Example 5.2

Let material # 1, Fig. 5.12, be air and material # 2 plexiglas, and let $a = b = 0.05$ m. The maximum voltage between the plates is then according to eq. (5.16)

$$V_b = 3 \cdot 10^6 \cdot 0.05 + \frac{l}{3.4} \cdot 3 \cdot 10^6 \cdot 0.05 \approx 2 \cdot 10^5 \text{ V}$$

Comparing examples 5.1 and 5.2 it appears that when a dielectric in the region between two plates is partly replaced by a dielectric with a higher permittivity, the breakdown voltage will be lower, even if the new dielectric has a higher breakdown field strength.

5.2.3 Maximum charge density

According to eq. (2.9) the field in front of a charged conductor is

$$E = \frac{\sigma}{\epsilon}$$

where $\epsilon = \epsilon_0$. Consequently, the **maximum surface charge density**, σ_m , on a conductor (in air at atmospheric pressure) is

$$\begin{aligned} \sigma_m &= \epsilon_0 E_b \\ &= 8.85 \cdot 10^{-12} \cdot 3 \cdot 10^6 \approx 2.7 \cdot 10^{-5} \text{ C} \cdot \text{m}^{-2} \end{aligned} \quad (5.17)$$

If we have a dielectric like an insulator plate resting on a grounded conductor, Fig. 4.2, and if we assume the distance to other grounded conductors is much larger than the thickness of the insulator plate

The maximum surface charge density is given by

$$\sigma_m = \epsilon_i \epsilon_0 E_b \quad (5.18)$$

Is the dielectric for instance plexiglas we find

$$\sigma_m = 3.4 \cdot 8.85 \cdot 10^{-12} \cdot 4 \cdot 10^7 \approx 1.2 \cdot 10^{-3} \text{ C} \cdot \text{m}^{-2}$$

The fact that the surface of an insulator may hold a much higher charge density than a conductor, plays a role for the so-called stemmed branch or propagating discharges, see Chapter 6: ELECTROSTATIC EFFECTS.

CHAPTER 6

ELECTROSTATIC EFFECTS

In Chapter 3: STATIC ELECTRIFICATION the principal ways in which electrical charges can be separated was discussed. After separation the charges may be located on insulators or insulated conductors. All effects of such static charge distributions are caused by the forces upon and between themselves or induced charges on grounded and ungrounded conductors, or from forces on the charge distributions on airborne charge carriers, i.e. ions and electrons.

Although all static electrical effects are thus related to forces between charges, it is practical to divide the description of the effects into the following two groups.

- *Mechanical effects* involving situations where bodies or particles, charged or polarized, are exposed to electrical forces comparable to or greater than their own weight.
- *Electrical effects* involving the field-induced intermedium motion of already existing charge carriers, either producing ionization and discharge phenomena or just causing non-carrierproducing decay phenomena.

6.1 MECHANICAL EFFECTS

Mechanical effects appear mainly where light materials are involved. Some examples of such effects are:

Repulsion between like charges. If fibers or threads in a bundle or plastic or paper sheets in a stack are being charged with the same polarity, they will repel each other and can be extremely difficult to handle.

Attraction between opposite charges. When a charged length of paper, plastic, cloth etc. is getting close to a conductor, an opposite charge will be induced on the conductor, and a force will be acting on the charged material, which may be pulled from its normal position and cling to the conductor. Fig. 6.1 shows a sheet of material with the surface charge

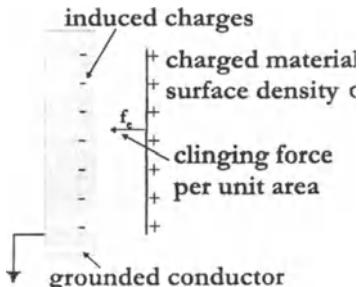


Fig. 6.1

density σ . If the material is much closer to the conductor than to other grounded objects the field strength from the charge towards the conductor will be $E = \frac{\sigma}{\epsilon_0}$. This field will induce a

surface charge density $-\sigma$ on the conductor, and the attraction between the opposite charges will result in a force per unit area f_e given by

$$f_e = \frac{\sigma^2}{2\epsilon_0} \quad (6.1)$$

This phenomenon is known as **static cling**.

Example 6.1

A sheet of paper has a specific mass of $m_s = 100 \text{ g}\cdot\text{m}^{-2} = 0.1 \text{ kg}\cdot\text{m}^{-2}$. The paper is charged with a positive charge density of $\sigma = 10^{-5} \text{ C}\cdot\text{m}^{-2}$. The paper is close to a vertical grounded surface.

The (electrical) specific force on the paper is

$$f_e = \frac{(10^{-5})^2}{2 \cdot 8.85 \cdot 10^{-12}} = 5.6 \text{ N}\cdot\text{m}^{-2}$$

The gravitational specific force is

$$f_m = mg = 0.1 \cdot 9.81 = 0.98 \text{ N}\cdot\text{m}^{-2}$$

It appears that the electrical force is about 6 times the weight of the paper.

Plateout of airborne particles.

Airborne particulate, like dust or aerosol particles, may move in an electric field either because they are charged or because the field is inhomogeneous.

Fig. 6.2 shows a part of the surface of a positively charged material. The material may be an insulated conductor or an insulator, but we are only

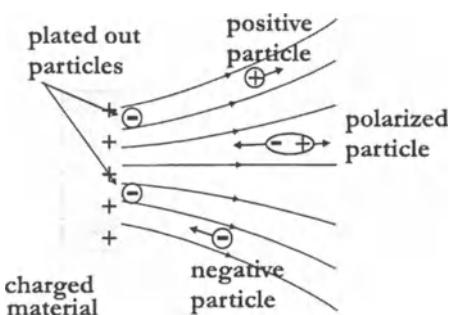


Fig. 6.2

concerned with the field in front of the surface. The field will in practice decrease with increasing distance from the charged material. Positive particles will be repelled and move away, negative particles will be attracted and plate out on the surface. Neutral particles will be polarized with a negative polarized charge closest to the charged material

and a positive polarized charge away from the material. Because of the inhomogeneity of the field there will be a resulting force towards the charged material, and eventually the neutral particle may also plate out. Obviously also the particles carrying a net charge will be polarized, but the force from the field on the net charge is dominating relative to the effect of polarization.

A well-known example of this phenomenon is the collection of dust on monitors and TV-screens. An additional effect is the plateout on the face of operators in front of a monitor. The possible hygienic effects of this will be treated in Chapter 9: STATIC ELECTRICITY AND PEOPLE.

6.2 ELECTROSTATIC ENERGY

An electrostatic field is a region where a charge feels a force, but it is more than that. It is also a region of stored energy. It takes energy to build up a field, and this energy can sometimes, but certainly not always, be released in a single burst, like a discharge or a current pulse.

Fig. 6.3 shows a grounded plane conductor A. At a distance d is a plane item B, which may be a conductor or an insulator. The area of B (and A) is S. B has a charge q evenly distributed on the side facing A. So the charge density on B is

$$\sigma = \frac{q}{S}$$

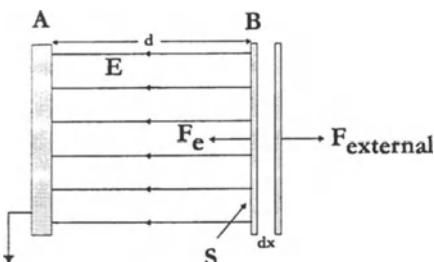


Fig. 6.3

As explained under static cling there's a force per unit area on B given by

$$f_e = \frac{\sigma^2}{2\epsilon} \quad (6.1)$$

The total force on B from the field is therefore

$$F_e = f_e \cdot S = \frac{S \cdot \sigma^2}{2\epsilon} \quad (6.2)$$

Let's now assume that we increase the distance between A and B with an amount dx . In order to do this we have to use an external force F_{external} which is numerically equal to F_e . The external work done in this operation is

$$dW = F_{\text{external}} \cdot dx = \frac{S \cdot \sigma^2}{2\epsilon} \cdot dx \quad (6.3)$$

This work appears as an increase in the energy stored in the electric field. As the additional volume of the field is $S \cdot dx$ the energy stored per unit volume is

$$w = \frac{\sigma^2}{2\epsilon} \quad (6.4)$$

Because the field strength E is given by

$$E = \frac{\sigma}{\epsilon}$$

the **energy density** of the field can be written

$$w_e = \frac{1}{2} \epsilon E^2 \quad (6.5)$$

Equation (6.5) is valid for any electric field.

It appears, eqs. (6.1) and (6.2), that the specific cling force f_e and the field energy density w are given by the same expression. That, however, does not mean that the two concepts are identical. f_e is a force per unit area, $N \cdot m^{-2}$, while w is an energy per unit volume, $J \cdot m^{-3}$. But both quantities have the dimension $ML^{-1}T^2$

Let's assume that the plate B in Fig. 6.3 is a conductor. The voltage V of B is then

$$V = E \cdot d \quad (6.6)$$

The total energy W stored in the field shown in Fig. 6.3 is

$$W = w \cdot S \cdot d = \frac{1}{2} \epsilon \cdot E^2 \cdot S \cdot d \quad (6.7)$$

Combining (6.6) and (6.7) we find

$$W = \frac{1}{2} \epsilon \frac{S}{d} \cdot V^2 \quad (6.8)$$

We recognize the factor

$$C = \epsilon \frac{S}{d} \quad (2.19)$$

as the capacitance of the system, and eq. (6.8) may thus be written

$$W = \frac{1}{2} CV^2 \quad (6.9)$$

Equation (6.9) is the general expression for the energy stored in a capacitive system, and thus also the maximum energy which may be taken out of the system by a discharge or a current pulse, as will be explained in the next section.

If the plate B in Fig. 6.3 is an insulator the energy of the field is still given by eq. (6.7). However, in this case the concept of capacitance has

no meaning, and further the energy stored in a field from a charged insulator can only be partly dissipated, and certainly not in a calculable or measurable way.

6.3 ELECTRICAL EFFECTS

For many years static electricity was considered to have only one detrimental effect of any importance. It produced sparks, which could give unpleasant shocks or even cause explosions.

A spark is a typical example of an ionization process in which charge carriers, electrons, in an electric field is accelerated to such high velocities, that new charge carriers are produced.

As explained in Chapter 5: BREAKDOWN an ionization process starts if the field strength exceeds a certain value, the breakdown field strength, typical for the medium in which the ionization takes place. However, the course of the resulting process, the **discharge**, depends among other factors strongly on the geometry of the body where the discharge starts and the nature of the material through which it develops.

6.4 DISCHARGES

6.4.1 CORONA DISCHARGE

If a conductive electrode in the shape of a sharp point (or a thin wire) is held at a sufficiently high voltage, maybe 2-20 kV the breakdown field strength may be exceeded in a region of a few millimeters around the electrode, Fig. 6.4.

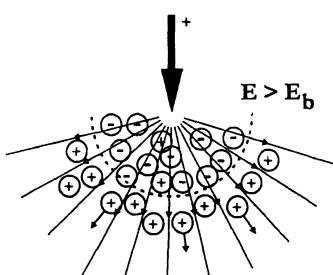


Fig. 6.4

In this region positive and negative ions are produced in equal numbers (see Chapter 7: ABATEMENT OF STATIC ELECTRICITY, Ionizer systems). If the electrode is held at a positive voltage the negative ions will be attracted to the electrode, where they'll be neutralized and cease to exist as ions. The positive ions will be repelled from the electrode and move away towards

grounded surroundings with velocities rapidly decreasing with the distance from the electrode from about $100 \text{ m}\cdot\text{s}^{-1}$ to maybe $1\text{-}2 \text{ cm}\cdot\text{s}^{-1}$. This kind of discharge is called a **corona** or **silent** discharge. In the dark a bluish luminescence may be seen in the region of ionization. Characteristic features of a corona discharge are the extreme limited region of ionization and the low energy density, which makes it impossible to ignite even the most flammable gas mixtures by a corona discharge.

In the set up suggested in Fig. 6.4 the corona discharge will take place as long as the voltage of the electrode is high enough to produce breakdown field strengths in front of the electrode, and if therefore the electrode is connected to a suitable voltage supply the discharge may take the form of a continuous corona current.

But also in nature do continuous corona currents occur. The so-called Saint Elmo's fire, which sometimes may be observed during thunder storms at the tips of branches and leaves or at lightning rods, is a corona discharge brought about by the charge at the base of the thundercloud.

The most common way for a corona discharge to occur is when a grounded conductor with sharp protrusions is brought close to a charged body, be it an insulated conductor or an insulator.

If the field at the protrusion, induced by the charge on the body, exceeds the breakdown field strength a corona discharge happens, which will partly neutralize the charge.

When the neutralization has lowered the field strength below the breakdown level the ionization and the corona discharge stops. A certain energy has been dissipated in the discharge. However, there's no method by which you can calculate or measure the energy of a corona pulse. Experience, however, shows that corona discharges are not incendive, i.e. they can not cause even the easiest ignitable gas mixtures to react.

6.4.2 BRUSH DISCHARGE

If a discharge takes place between a small electrode (radius of curvature in the order of millimeters) and ground, the discharge may be a **brush discharge**, characterized by moving irregular luminescent discharge paths. As explained above for corona discharges, also brush discharges

may be maintained as a continuous discharge current. However the more common case is when a “brush electrode” is brought close to a charged insulator. The field from the charge may again cause breakdown to start at the electrode, but in contrast to corona discharges the ionization takes place all the way from the electrode to the charged object.

Almost all discharges between charged insulators and conductors are either corona or brush discharges.

If for instance you take off a sweater and feel a tinkling at your ear, then that is not an electrostatic charging taking place. Quite the opposite. It is a discharge, a brush discharge.

There is no direct way to measure or calculate the energy dissipated in a brush discharge, but experiments with ignitable gas mixtures suggest that energies up to the order of mJ may occur.

6.4.3 SPARK DISCHARGE

The best known type of an electric discharge is a **spark**. Although the name is commonly used for almost any kind of charge transport through dielectrics (including air) it ought to be reserved for the discharge between two well-rounded conductors at different potentials.

In a spark ionization takes place along and the charge is transferred through a narrow channel between the two conductors. In this channel most of the energy stored in the system, i.e. in the field between the two conductors, is dissipated.

If the (partial) capacitance of the two conductors is C and the voltage difference is V, the energy W stored and possibly dissipated in a spark is

$$W = \frac{1}{2}CV^2 \quad (6.9)$$

Because the channel is very narrow and short and the discharge is very fast, the energy density in a spark discharge may be very high, making the spark discharge the most incendiary of all types of discharges.

In connection with **sparks** a few words should be said about **arcing**. This concept is sometimes used as almost synonymous with sparking. But the two concepts are very different. In a spark a high field strength ionizes the air and the charge carriers participating in the charge transfer

are air ions. Arcing, on the other hand, is the phenomenon which may occur when two conductors at different potentials touch and a current runs from one to the other. If the conductors are now being separated the current density at the last point (area) of contact may be so high that the material vaporizes and forms a conductive path between the two materials. The charge carriers are thus charged metal particles. So the difference between **arc**ing and **spark**ing lies in the nature of the charge carriers and in the fact that in order to produce arc^{ing} the two conductors have to touch before arc^{ing} can take place.

6.4.4 PROPAGATING DISCHARGE

A very special type of a discharge is the so-called **propagating discharge** or as it is also called **stemmed branch discharge**.

In Chapter 5: BREAKDOWN it was discussed that the maximum charge density on a plane conductor in air at atmospheric pressure is about

$2.7 \cdot 10^{-5} \text{ C.m}^{-2}$ (eq. (5.17)) However, if a thin dielectric is backed by a grounded conductor much higher charge densities may occur (eq. (5.18) and Fig. 4.2).

Fig. 6.5 shows a piece of a positively charged dielectric resting on a grounded plane conductor. The major part of the flux from the charge will run in the dielectric giving rise to the field E_d and as a consequence the field E_a in the air will be well below the breakdown field strength even at high charge densities.

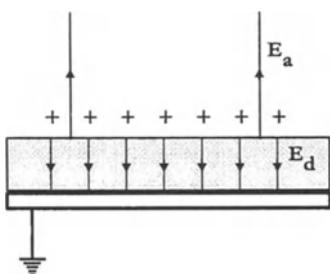


Fig. 6.5

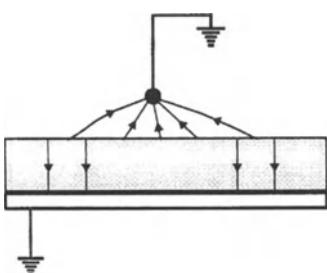


Fig. 6.6

If now a grounded electrode without sharp protrusions is brought close to the charged surface, Fig. 6.6, the field will be strongly distorted and the flux may now to a large extent be distributed towards the electrode.

If the breakdown field strength is exceeded the resulting discharge will run, "propagate" along the surface neutralizing the high charge density. The energy dissipated in this kind of discharges may run in the hundreds of mJ, making the discharges highly incendive.

Propagating discharges is largely a phenomenon taking place on the charged surface. The discharge pattern can be made visible in various ways, for instance by spreading special powders on the surface after the discharge or by letting the discharge take place in or on a photo emulsion. The resulting images, which can be very beautiful, have given rise to the name **stemmed branch discharges**. These same discharge figures are (were) also known as **Lichtenberg figures**.

It should finally be mentioned that although propagating discharges are very energy-rich and potentially destructive, it is very unlikely that such discharges happen by accident, for instance as part of a production process.

6.5 CHARGES ON INSULATORS

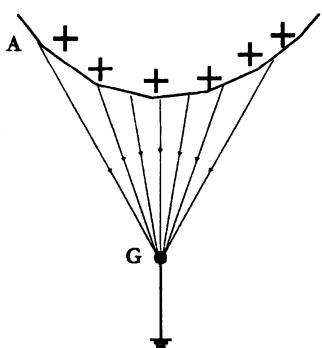


Fig. 6.7

Fig. 6.7 shows a part of a positively charged body A. As the field lines are not perpendicular to the surface, A must be an insulator. When a grounded conductor G is brought into the field from A the breakdown field may be exceeded around G and a discharge takes place. The discharge will be a corona or brush discharge forming positive and negative ions. The negative ions are moved towards A where they will plate out and partly neutralize the charge, Fig. 6.8.

An equally large, opposite charge is brought to A by positive ions. It thus appears as if a charge has been transferred from the charged surface to the grounded conductor. The area being neutralized and the amount of charge involved vary widely. For strongly charged surfaces the area may be a few tens of cm^2 and the charge about $10^{-8} - 10^{-7}\text{C}$.

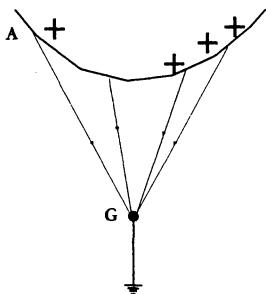


Fig. 6.8

During the discharge a certain amount of energy is dissipated in the air where the discharge takes place. It is not possible to measure neither the total energy nor the distribution of energy over the discharge volume, i.e. the energy density, but experience shows that in general discharges from insulators are much less incendiary than discharges and especially sparks between conductors.

6.5.1 DISCHARGE CURRENT

If G is a solid conductor the charge will pass through G as a current often without causing any damage. G may for instance be a person and the discharge will be sensed only as the tickling feeling one experience when nearing a finger to a piece of charged plastic. But G may also be a semiconductor component or device with one or more terminals grounded. In this case the discharge current may destroy the device or cause latent damage. This is a typical example of the electronic industry's electrostatic discharge problems, colloquially known as *ESD*.

6.6 CHARGES ON CONDUCTORS

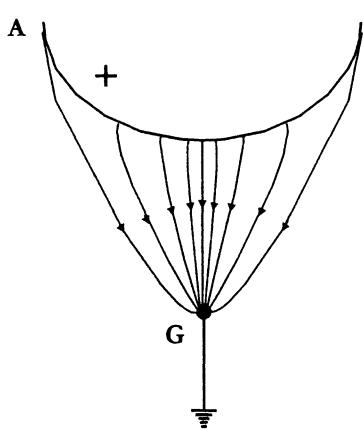


Fig. 6.9

In contrast to the situation with a charged insulator, the distribution of charge on an insulated conductor is an integral phenomenon.

It has already been explained that the charge on an insulated conductor will distribute itself over the surface of the conductor in such a way in such a way that a) the field strength inside the conductor is zero and b) the voltage with respect to ground of each point of the conductor is the same

If now a grounded conductor G is brought into the vicinity of a charged conductor A, Fig. 6.9, the field strength around G may exceed the breakdown field strength in more or less the same way as explained for charged insulators. But the discharge process may evolve very differently in the case of a charged insulated conductor. If either A or G have sufficiently sharp points the discharge may be a corona or brush discharge stopping when the field strength at any point no longer exceeds the breakdown field strength, leaving A partly but uniformly neutralized.

If neither of the conductors have sharp points the discharge will be a spark, which will cause an (almost) total discharge of the charged conductor.

The charge “transferred” and the energy dissipated in corona and brush discharges from charged conductors do not differ much from the same quantities in the case of charged insulators, and consequently their incendiveness and the current pulses through the grounded conductor are also about the same.

Spark discharges on the other hand differ from corona and brush discharges in three major ways:

- A spark discharge will normally neutralize all the charge on the insulated conductor.
- The energy dissipated in the air by a spark given by

$$W = \frac{1}{2}CV^2$$

may adopt a large range of values, depending on the capacitance C and the voltage V of the insulated conductor. As the volume of the discharge channel is very narrow, the energy density of a spark is, for the same total energy dissipated, much higher than for other types of discharges, making sparks generally more incendive. And although there are cases where a brush discharge has tripped an ignition, the cause of most static induced ignitions and explosions in air/vapor- and air/dust mixtures is a spark.

- The current pulse through the conductor G, or through any device forming a conductive or semi-conductive path from G to ground may be much faster and stronger than a corresponding pulse caused by any other type of pulse and may consequently be far more destructive.

6.7 EXPLOSIVE MIXTURES OF VAPORS AND GASES, IGNITION ENERGY

Although there are numerous examples of static electric discharges (almost all of them sparks) having set off explosions or deflagrations, it is conservative to say that most discharges have no noticeable effect, even when they take place in an environment with vapors from liquids like gasoline, ether, and acetone which often do form explosive mixtures even with atmospheric air. The reason for this is that most discharges do not have enough energy density to start the necessary interreactions between enough molecules of the vapor and the oxygen of the air. Or more precisely, the incidental ratio between the concentrations of the vapor and the oxygen requires more energy dissipated per unit volume than can be delivered by a likely static electric discharge.

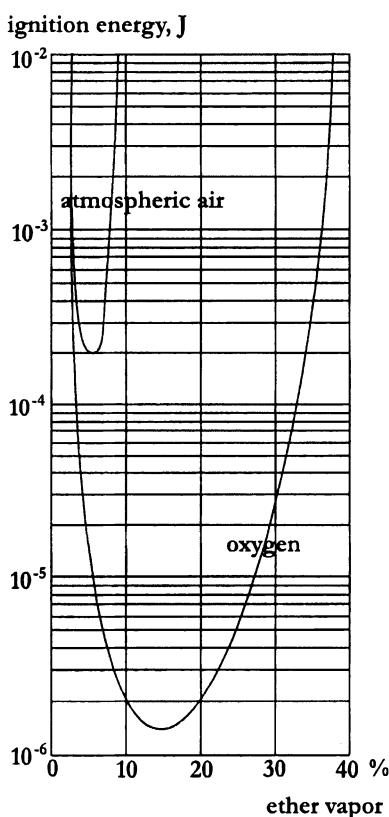


Fig. 6.10

This is illustrated in Fig. 6.10, which shows the ignition energy for mixtures of ether vapors and pure oxygen or atmospheric air. It appears that it is possible to ignite a mixture of ether vapor and pure oxygen with an energy of little more than $1 \mu\text{J}$ (if the concentration of the vapor is about 16 %), whereas it takes about 0.2 mJ, or about 200 times more energy to ignite a mixture of ether vapor and atmospheric air, and then only if the ether vapor concentration is very close to 6 %. The main reason it takes more energy to ignite a mixture with atmospheric air than with oxygen is that it also takes energy to heat the nitrogen in the air without it participating in the process, and this energy is therefore wasted. It also appears that the necessary

ignition energy of ether vapor increases rapidly if the concentration deviates only slightly from the 6 % value. Consequently only mixtures between maybe 4 and 8 % are in practice explosive.

The curves shown in Fig. 6.10 are typical; regarding both shape and energy values for many organic compounds, cyclic as well as aliphatic, like hydrocarbons, ketones etc. The 0.2 mJ value may therefore be taken as a good lower limit for vapor/gas mixtures.

Although a spark with the minimum(ignition) energy is potent enough to cause an explosion only in mixtures within a narrow concentration range, it should be kept in mind that in an open container with the kind of liquid discussed above the vapor concentration at the surface of the liquid is far too rich for the mixture to be ignitable, and at a height of maybe half a meter above the surface the concentration is far too lean. Therefore, somewhere in between the concentration has exactly the critical value, requiring only the minimum energy for the mixture to blow up.

6.8 EXPLOSIVE MIXTURES OF POWDERS AND GASES

It is a well-known fact that explosions may occur not only in vapor/gas mixtures but, under certain conditions, also in clouds of dust and powders. In the 1930es explosions in grain silos were reported at a rate of approximately one per week in the Midwestern United States.

As illustrated in Fig. 6.10 the (minimum) ignition energy for a vapor/gas mixture is only a question of the nature and concentrations of the vapor and the gas, but the situation is much more complicated for powders. First of all, whereas mixtures of vapors and gases (in closed containers) are normally homogenous with the vapor concentration being the same throughout the whole mixture, the concentration of powder particles in a cloud may easily vary from point to point making the determination of a minimum ignition energy very difficult. Further, the ignition energy normally depends on factors like the grain size of the powders involved. However, it generally takes more energy to start an explosion in a cloud of powders than in an ignitable vapor/gas mixture. The minimum ignition energies for vapors (in atmospheric air) are lower than 1 mJ, but powders will normally require a minimum of 10 to 100 mJ to combust.

6.9 EXPLOSION-SAFE VOLTAGE

As explained above, it can be assumed that any electrical discharge disseminating less than 0.2 mJ in atmospheric air is not incendive. For a capacitive system with a typical capacitance of, say 300 pF, this means that an “explosion-safe” voltage, V_{ex} , according to eq. (6.9), is

$$V_{ex} = \sqrt{\frac{2W_{min}}{C}} = \sqrt{\frac{2 \cdot 0.2 \cdot 10^{-3}}{300 \cdot 10^{-12}}} \approx 1100 - 1200 \text{ V} \quad (6.10)$$

It should be stressed that this safe-voltage level refers only to explosion risks. When dealing with electronic ESD problems the acceptable levels are often considerably lower. Also, as mentioned before, the safe-voltage level can only be applied to insulated conductors, as the concept of voltage has no meaning in characterizing an insulator as a whole.

6.10 VOLTAGE LEVELS OF CHARGED CONDUCTORS

Most static electric effects of charged insulated conductors, i.e. capacitive systems, are determined by the voltage of the system. Such a system, electrically characterized by its capacitance C and (decay) resistance to ground R , may attain its voltage in two distinctly different ways: by *bulk charging* or by *current charging*.

6.10.1 BULK CHARGING

If a charge q_0 is transferred to the (uncharged) system in a time short compared to the time constant $\tau = RC$ of the system, the voltage will rise almost instantaneously to an initial voltage V_0 given by

$$V_0 = \frac{q_0}{C}$$

After this the voltage and charge will decay exponentially with the time constant τ as explained in Chapter 4: DECAY OF CHARGE

It should be mentioned that the energy of the system decays with a time constant $1/2\tau$ as the energy is proportional to the square of the voltage.

Bulk charging may for instance happen when a piece of a charged material is dumped into an insulated conductive container. If the charged material itself is insulative it may represent very little if any risk at all, but once the charge is transferred to the capacitive system (maybe only by induction) the situation may be entirely different.

It is not possible to put any kind of upper limit on the initial voltage reached by a capacitive system by bulk charging.

6.10.2 CURRENT CHARGING

With many static charging processes the charge is transferred to the system as a more or less steady charging current I_c . This may for instance be the case when an insulated container is being filled with a charged liquid or powder or, with some approximation, when a person is walking on an insulative floor covering.

The current I_c will bring a charge to the system and cause the voltage to increase. But this, on the other hand, will produce an increasing decay current I_d , i.e. a flow of charge from the system to ground, until the two currents cancel each other and an equilibrium maximum voltage V_m is reached.

The net rate of increase of the charge q at a time t after the start of charging is given by

$$\frac{dq}{dt} = I_c - I_d = I_c - \frac{V}{R} = I_c - \frac{q}{RC} \quad (6.11)$$

where V is the voltage at the time t . The solution to eq. (6.11) is

$$q = RCI_c \left[1 - e^{-\frac{t}{\tau}} \right] \quad (6.12)$$

Here $\tau = RC$. The corresponding relation for the voltage is

$$V = RI_c \left[1 - e^{-\frac{t}{\tau}} \right] \quad (6.13)$$

The equilibrium maximum voltage is thus given by

$$V_m = RI_c \quad (6.14)$$

Example 6.2

Gasoline is being pumped into an insulated container at a rate of $u = 10$ liters per second ($10^2 \text{ m}^3 \cdot \text{s}^{-1}$). The gasoline is electrically charged with a volume charge density of $\rho = 10^5 \text{ C} \cdot \text{m}^{-3}$. The container has a capacitance of $C = 200 \text{ pF}$ and a resistance to ground of $R = 10^{11} \Omega$.

The flow of gasoline will produce a charging current

$$I_c = \rho u = 10^5 \cdot 10^2 = 10^7 \text{ A}$$

If the container is originally uncharged, the voltage V of the container will increase with a time constant

$$\tau = RC = 10^{11} \cdot 200 \cdot 10^{-12} = 20 \text{ s}$$

according to

$$V = RI_c \left[1 - e^{-\frac{t}{\tau}} \right] = 10^{11} \cdot 10^{-7} \left[1 - e^{-\frac{t}{20}} \right] = 10^4 \left[1 - e^{-\frac{t}{20}} \right]$$

with an equilibrium voltage of

$$V_m = 10^4 \text{ V}$$

At a time $t = 20 \text{ s}$ after the start of the filling the voltage will have reached a value of

$$V = 10^4 \left[1 - e^{-1} \right] = 6300 \text{ V}$$

The energy stored in the system at this time is

$$W = \frac{1}{2} CV^2 = \frac{1}{2} \cdot 200 \cdot 10^{-12} \cdot 6300^2 = 4 \text{ mJ}$$

6.10.2.1 Charging of a Person by Walking

A special case of current charging is that of a person walking across an insulative floor covering wearing shoes with insulative soles. The person can be considered a capacitive system with a capacitance $C \approx 200 \text{ pF}$

and a decay resistance to ground R ranging anywhere from a few $M\Omega$ to $10^{15} \Omega$ or more.

The contact and friction between the soles and the floor will cause charges to separate and make the person's voltage increase.

If the soles are highly insulative the charges may stay on the underside of the soles, and the person will be charged by induction. In the case of more conductive soles the person may get a net charge. But in either case his voltage will increase.

If a charge Δq is separated for each step and if we assume the person walks with a step rate of n steps per unit time, the charging process may be characterized by an average charging current

$$i_c = n\Delta q \quad (6.15)$$

and according to (6.14) the maximum voltage will thus be

$$V_m = Rn\Delta q \quad (6.16)$$

If the highest acceptable body voltage is V_{accep} we find that the grounding resistance R has to fulfil the condition

$$R \leq \frac{V_{accep}}{n \cdot \Delta q_{max}} \quad (6.17)$$

where Δq_{max} is the maximum value of the charge separated per step

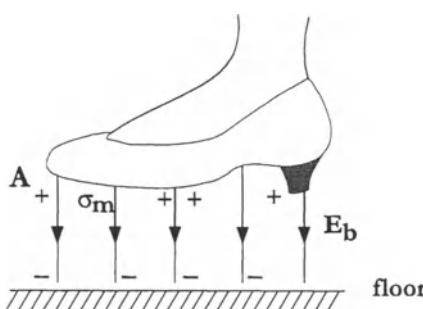


Fig. 6.11

It is possible to estimate Δq_{max} , Fig. 6.11.

We assume that the maximum possible charge density σ_{max} exists on the sole just after it has been lifted from the floor. This means that the field strength between the sole and the floor is equal to the breakdown field strength E_b , i.e.

$$\Delta q_{max} = \sigma_{max}A = \epsilon_0 E_b A \quad (6.18)$$

where $\epsilon_0 = 8.85 \cdot 10^{-12} \text{ F} \cdot \text{m}^{-1}$ (permittivity of air), $E_b \approx 3 \cdot 10^6 \text{ V} \cdot \text{m}^{-1}$ (breakdown field strength in air, between plane electrodes), and $A \approx 150 \text{ cm}^2$ (area of shoe sole).

Introducing these figures in eq.(6.18) we find

$$\Delta q_{\max} \approx 4 \cdot 10^{-7} \text{ C} \quad (6.19)$$

corresponding to a maximum charging current

$$i_{c,\max} = n \cdot \Delta q_{\max} = 8 \cdot 10^{-7} \text{ A} \approx 10^{-6} \text{ A} \quad (6.20)$$

assuming a step rate of 2 s^{-1} .

If we require $V_{\text{accep}} = 100 \text{ V}$ we find from eq. (6.17)

$$R \leq 100 \text{ M}\Omega.$$

The values for en acceptable floor resistance derived from eqs. (6.17) and (6.20) are very conservative. It is highly unlikely that the whole area of the shoe sole would be charged to the breakdown level, and then when lifting the foot no neutralizing discharge taking place.

In order to find more realistic values for Δq and V a series of measurements of the body voltage on a highly insulative floor covering (vinyl tiles) were performed. The body resistance to ground R was measured to $10^{11} \Omega$ (varying over the floor from 0.5 to $1.5 \cdot 10^{11} \Omega$). The body capacitance was 160 pF (two feet) and 100 pF (one foot). The person was connected to an electrometer, which could be run as a charge meter (high capacitance) or as a static voltmeter (low capacitance).

With the meter in the charge-measuring mode the charge Δq for a single step was determined. As the average of ten determinations the value was found as

$$\Delta q = 3 \cdot 10^{-8} \text{ C} \quad (6.21)$$

with a standard deviation on a single determination of $0.5 \cdot 10^{-8} \text{ C}$.

With a step rate of 2 s^{-1} we find from eq. (6.15) the charging current to be

$$I_c = 2 \cdot 3 \cdot 10^{-8} = 6 \cdot 10^{-8} \text{ A}$$

And from eq. (6.16) a maximum expectable voltage

$$V_m = Rn\Delta q = 10^{11} \cdot 2 \cdot 3 \cdot 10^{-8} = 6 \text{ kV}$$

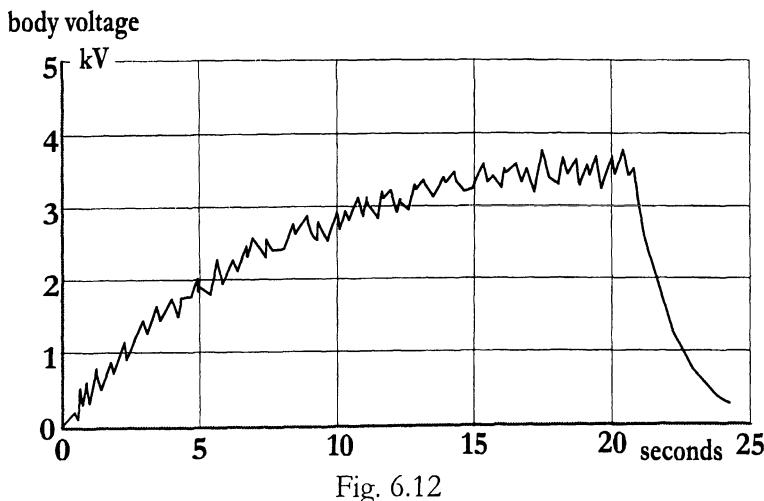


Fig. 6.12

Fig. 6.12 shows the person's body voltage as a function of time. It appears that the voltage reaches a maximum of about 3.5 kV after approximately 15 s.

The reason the predicted maximum value of 6 kV is not reached can be found in the decay curve starting at 21 seconds. At this time the person stands still and lets the charge be neutralized through the effective grounding resistance.

An analysis of the curve shows that the initial decay corresponds to a resistance of approximately $2 \cdot 10^{10} \Omega$ and ends up with a value close to $10^{11} \Omega$.

This must mean that the resistance (or rather the resistivity) of the floor (and sole) material decreases with increasing voltage (or rather field strength).

The direct measurement of the resistance of the person was done at a voltage of approximately 300 V and the measured resistance will thus be higher than the effective resistance at the maximum voltage.

The value of V_m predicted by eq. (6.16) thus appears to give a safe upper limit for the body voltage when walking on a floor characterized by a resistance R .

There are two reasons for the saw-tooth form of the voltage curve in Fig. 6.12. The voltage will increase at each step partly because of the extra charge Δq and partly because the capacitance is decreased as a foot

is lifted. When the foot is put down again the capacitance increases and the voltage decreases.

The voltage increase when a foot is lifted can be written

$$\Delta V = \frac{\Delta q}{C} \quad (6.22)$$

Using $\Delta q_{\max} = 3 \cdot 10^{-8}$ C and $C = 100$ pF (one foot) we find

$$\Delta V_{\max} = 300$$
 V

This value, which appears to be independent of the decay resistance, is sufficiently high to be a problem in many ESD scenarios.

However, it should be stressed that eq. (6.22) does not take into account the unavoidable decay during the time it takes to lift the foot from the floor and separate the charge Δq

If we call this time Δt the voltage ΔV at the end of Δt can be written

$$\Delta V = \frac{\Delta q}{C} \cdot \frac{RC}{\Delta t} \left(1 - e^{-\frac{\Delta t}{RC}} \right) \quad (6.23)$$

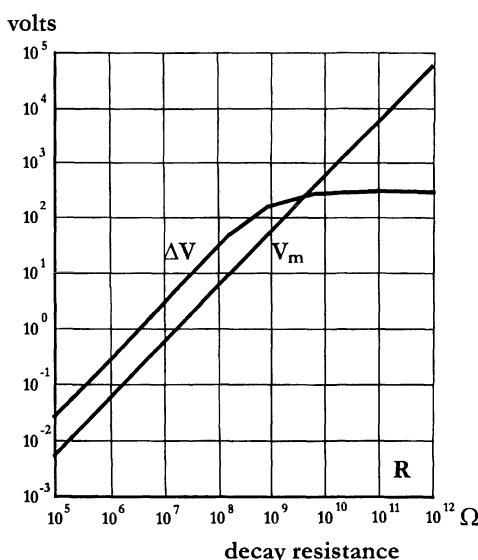


Fig. 6.13

If we assume $\Delta t \approx 0.1$ s, C (one foot) = 100 pF, $n = 2$ s^{-1} and $\Delta q = 3 \cdot 10^{-8}$ C we can find ΔV (eq. (6.23)) and V_m (eq. (6.16)) as a function of the decay resistance R , Fig. 6.13.

It appears that for low values of R , ΔV is higher than V_m , for instance at $R = 10^9$ Ω (1 gigaohm) the mean maximum voltage is $V_m = 60$ V while the one step voltage is $\Delta V = 180$ V.

It may seem peculiar that the body voltage after one step (rather at the end of

the first foot-lift) can be higher than the mean body voltage after many seconds.

The explanation is that the voltage is decaying in the time from one foot is lifted till the lifting of the next foot starts. Assuming $\Delta t = 0.1$ s and $n = 2 \text{ s}^{-1}$ this decay time is about 0.4 s, i.e. 4 times as long as the charging time.

The curves show that

$$\Delta V = V_m = 270 \text{ V at } R = 4.5 \cdot 10^9 \Omega.$$

The implication of the results plotted in Fig. 6.13 is that at resistances lower than approximately 4.5 gigaohm one should be concerned with the voltage “spikes” connected with a single step, while at higher resistances the equilibrium voltage integrated over many steps is the dominating factor.

6.11 CURRENT PULSES FROM CHARGED SYSTEMS

6.11.1 ESD DAMAGE MODELS

The decay of body voltage shown in Fig. 6.12 is an example of a weak current pulse from a charged capacitive system, in this case a person charged to 3 kV, the charge leaking slowly away, starting with a current of $0.1 - 0.2 \mu\text{A}$, which slows down to a few nA in 20 seconds. This kind of current pulse is not felt by the person participating in the process, and the pulse would hardly be capable of affecting any kind of system, electronic or otherwise, if the conditions were so, that the pulse could pass through such a system.

The situation is completely different, however, if a charged capacitive system is suddenly being discharged, for instance by being connected through a relatively low resistance to a sensitive device kept at ground potential.

It is obviously important to be able to test the sensitivity of electronic and other devices for the kind of current pulses originating from such discharges, for instance from charged persons. Such testing could of course, in principle, be carried out by using a live, charged person, but for obvious reasons it is more practical to utilize an electrical circuit simulating the (electrical) behavior of the charged person.

Several models have been developed to simulate the discharges from various systems, which possibly might be harmful to sensitive devices. The primary models are the *human body model (HBM)*, the *machine model (MM)* and the *charged device model (CDM)*.

6.11.1.1 Human Body Model

In certain situations an insulated person is electrically adequately represented by a capacitance C ($\approx 100 - 400 \text{ pF}$) in parallel with a resistor R which may have values from a few hundred ohms to petaohm or more. This is the case for a freestanding person. This is the situation for a freestanding person, Fig. 6.14.

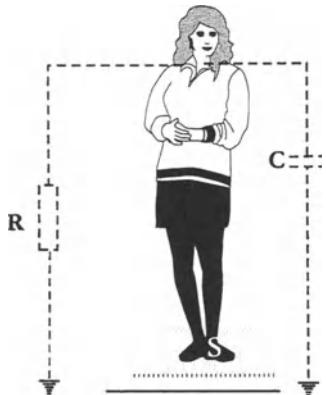


Fig. 6.14

If the person is charged, the major part of the charge is located on those areas of the body, where the distance to grounded surroundings is the shortest, which in practice means on the soles of her feet. The actual distance in question is the **dielectric distance**, i.e. the geometrical distance divided by the relative permittivity of the interdistance material, and as the permittivity of the shoe soles and the floor covering is normally 2-5 times higher than of atmospheric air, this makes the soles of the feet an even more predestined charge location.

Example 6.3

The person in Fig. 6.14 has a capacitance of $C = 200 \text{ pF}$ and a decay ground resistance of $R = 10^{11} \Omega$. She is charged to a voltage of $V = 3 \text{ kV}$. The charge on the person is thus

$$Q = CV = 200 \cdot 10^{-12} \cdot 3000 = 6 \cdot 10^{-7} \text{ C}$$

Of this charge maybe 30 % or $\approx 2 \cdot 10^7 \text{ C}$ is distributed unevenly over her body, whereas the major part of the charge ($\approx 4 \cdot 10^7 \text{ C}$) is located on the underside of her feet.

All parts of the freestanding person have the same voltage V , and the field strength inside the person and along the skin is zero.

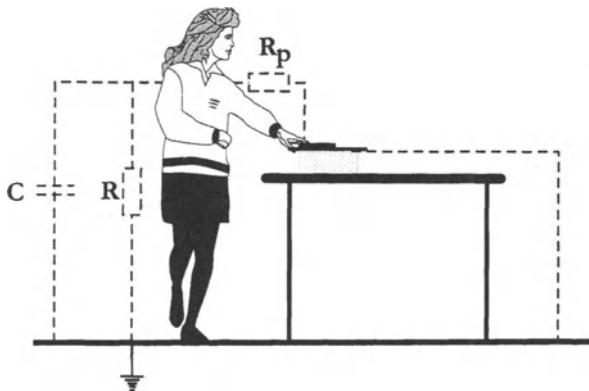


Fig. 6.15

If now the person touches a grounded device, Fig. 6.15, the point of contact, often the tip of a finger, is brought at ground potential, causing charges to flow from their

equilibrium location to the point of contact, through an average body resistance R_p of 1 to 2 k Ω . The resulting current pulse, however, is not adequately described by a simple exponential function as in eq. (4.5), nor even by a simple monotonous decay with increasing time constant like in Fig. 6.12.

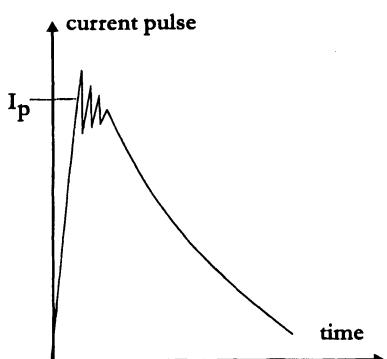


Fig. 6.16

The current will start at zero and rise to a peak value I_p , within maybe 10 ns, after which it will decay with a time constant of some hundred ns, Fig. 6.16. The peak value of the pulse may easily have a magnitude of several amperes, and there will normally some oscillations in the initial part of the decay.

The time constant for the pulse $\tau = R_p C$ obviously depends on the individual values of R_p and C , and it

is interesting to note that over the years there has been quite some uncertainty regarding the likely range of values for R_p as well as C . For test purposes R_p is now usually chosen as $1.5 \text{ k}\Omega$ and the test circuit is designed to give a pulse with rise and decay times as suggested above.

6.11.1.2 Other Models

The **machine model (MM)** simply consists of a capacitor of 200 pF , the one side of which is grounded, and the MM thus differs from the HBM mainly by having no series resistor. The MM represents charged insulated conductors like metallic containers, vehicles, and conductive tote boxes. The peak current in MM discharge may be much large than in a HBM discharge

The **charged device model (CDM)** deals with the effect on a component or device from the decay of charges on the part itself, where the charging can be caused by contact and friction between the part and insulative packaging material. The model applies to any device that has a capacitance to ground and is characterized by this capacitance, the inductance of the leads, and the resistance of the discharge path. The discharge will be a damped oscillation with a period of maybe 1 ns , and although the total charge on a device may only be of the order of nC , the amplitude of the current may be several amperes.

The **field induced model (FIM)** describes the inductive effect of an electric field on a device or insulated conductor. Other models the **capacitive-coupled model (CCM)**, the **floating device model** and the **transient-induced model**. For more details on all the models the reader is referred to the special literature, for instance, Owen J. McAtee, *Electrostatic Discharge Control*, McGraw-Hill, New York, 1990.

Chapter 7

ABATEMENT OF STATIC ELECTRICITY

Although useful applications of static electric effects are numerous, in most peoples' mind static electric phenomena are harmful, and their effects should be avoided and abated

The first thought that comes to mind in this context is probably. "Isn't it possible to avoid static chargings in general, i.e. avoid charges from being separated?"

In situations where friction between two solid materials is essential for the charging, a reduction in the degree of friction will reduce the rate of charge separation. In the case of charging by flow of insulative liquids a reduction in the flow rate will likewise reduce the charging. Also, because spraying of almost any kind of liquid often results in charge separation, free jets of liquids should be avoided whenever possible, for instance by keeping the flow rate low when filling containers until the tip of the filling tube is immersed in the liquid.

But these are probably the only examples in which the actual magnitude of the charges separated can be affected.

Nevertheless, there are quite a few remedies and procedures on the market, which are claimed to reduce or remove static electric problems by reducing the charging. However, it is likely that the efficiency of these methods depends on an increased rate of neutralization or recombination of the charges separated, rather than on an actual reduction of the charging rate.

NEUTRALIZATION OF CHARGES

Most static "removal" processes do not involve any kind of actual removal of electric charges from the charged object. The exception is charged conductors. If a negatively charged metallic conductor is connected to ground by another metallic conductor the excess charge, electrons, may flow to ground through the metallic connection.

In all other situations the neutralization consists of oppositely charged carriers, ions or electrons, being drawn to the excess charge. The field from the neutralizing charge will superimpose the original field, and the resulting, reduced field is then interpreted as a reduction or removal of the charge.

7.1 GROUNDING OF CONDUCTORS

The basic rule in fighting static electricity is to ground all conductors that might possibly get charged or exposed to induction from other charged objects. Insulated charged conductors can produce energetic spark discharges, but even if the atmosphere contains no explosive mixtures, it is important to discharge capacitive systems in order to avoid other bothersome effects of static charge buildup.

The grounding must include all conductive objects, not only machinery and main structures, but also part of any piping and tubing system, containers, and fixed and moving parts. A literal, direct connection to ground is in principle not necessary, as long as all conductive parts are interconnected, so that no voltage differences occur (bonding). It should also be mentioned that bolting of flanges in tubing systems does not necessarily ensure sufficient contact between the individual parts of the system, as paint, rust, and grease may create insulating layers. An efficient connection can be established by the use of special wire loops, soldered or screwed onto the tubes, across the couplings.

Containers may become charged during filling with liquids and powders. If such a container is placed on a concrete floor that is kept wet, this will normally ensure a sufficiently low resistance to ground. As a general rule, however, receiving containers should be connected with the (grounded) filling system before filling starts. This is especially important when handling liquids like gasoline and acetone, whose vapors may form explosive mixtures with the air.

Tank trucks should be connected with a special ground wire to the storage tank structure, during filling as well as emptying. This should be done even though the tires are normally made of carbon-loaded (semi)conductive rubber (see page 105). Although the conductivity of the tires is high enough to prevent dangerous charge buildup on the truck during driving, the charge separation caused by the flow of gasoline may be so high that the leakage through the tires is insufficient to keep the voltage of the truck at a safe level, especially if the ground is dry.

But even when handling relatively small volumes, like a few gallons, of volatile liquids, suitable grounding procedures for all conductive items

should be strictly followed. Apart from the basic rule of interconnecting storage and receiving containers, it is also important to connect any other kind of conductors, like filling heads, anywhere in the flow system to either end of the flow line. Also, non-grounded (conductive) devices like level gauges or more incidental items, like metal cans floating on the surface of the liquid, should be avoided.

The charge separation by flow of insulative liquids can also be reduced by adding antistatic agents to the liquids (see page 103).

7.2 METHODS OF GROUNDING PERSONS

The question of persons and static electricity can be looked at from two different points of view. One deals with the way in which a static electric charging may bother a charged person, e.g. the nuisance of electric shocks when touching the banisters or elevator button or kissing one's spouse, the possible induction of rashes and eczema by field-induced plateout of airborne allergens, or even the rather questionable effects of inhaling fewer or more air ions when charged. These problems will be further discussed in Chapter 9: STATIC ELECTRICITY AND PEOPLE

From the other point of view, a person is just another conductor, who, in certain environments, may pose a risk or even hazard, and who therefore has to be grounded in a safe, practical manner.

7.2.1 FOOTWEAR AND FLOOR COVERINGS

The most common way for a person to become charged is by walking on an insulative floor covering wearing shoes with insulative soles. This problem is discussed in details in Chapter 6: ELECTROSTATIC EFFECTS.

It follows from the analysis and from measurements that a total decay resistance of a person in the order of $10\text{-}100 \text{ M}\Omega$ is sufficiently low to keep the voltage at an acceptable level, see Fig. 6.13. These values will actually also ensure that most other charging processes in addition to walking do not lead to unacceptably high body voltages.

Often a lower limit for the grounding resistance (from $250 \text{ k}\Omega$ to $1 \text{ M}\Omega$) is suggested or even required. Part of the logic behind such a requirement has been the risk of personnel touching live wires while

being too effectively grounded through the footwear and floor covering. The extra safety obtained by this precaution does, however, seem somewhat marginal and even false considering the variety of permanently grounded objects that a person might accidentally or unknowingly contact.

For many years the major concern about static electric risks was that of discharges, mostly sparks, causing ignitions in inflammable atmospheres. Although this is still a real and serious risk in certain areas, over the past several decades the emphasis in abating static electric charge accumulations has moved to the electronic world. Computers and printers may fail if a person, charged to maybe 1-2 kV, is discharging himself to some grounded object in the neighborhood of the equipment. And this problem is obviously solved by fulfilling the same kind of grounding requirement for footwear and floor covering as discussed above.

7.2.2 WRIST STRAPS

In the electronic industry, however, and especially when dealing with MOSFETs or similarly sensitive components, where a current pulse from a person charged to, say, 100 V or less can be destructive, grounding through footwear and floor covering may prove inadequate. And although the idea of keeping a person at zero voltage by tying him physically to a ground point by a conductive wire may seem odd and impractical to many people, this is nevertheless an accepted procedure in many areas of the electronic world.

The gadget employed for this purpose, called a **wrist strap**, consists of a band or chain made of metal like an expandable watch band, and conductive plastic or conductive fibers, connected to ground by a strap. The strap is made of either solid conductive plastic or multistrand wire. Normally the strap includes a series safety resistor of $1 \text{ M}\Omega$ for minimizing the shock from accidentally touching a live wire while being tied to ground via the strap. For the normal household peak voltage of 160-170 V, the maximum current through the person would be less than $0,2 \mu\text{A}$, well below fatal values.

Even though wrist straps appear as simple enough devices, their use does involve a series of problems to be considered, like intermittent skin

contact with loose fitting bands, bad skin contact caused by excessively dry skin or too much body hair, or sluffing of the band material resulting in contamination of electronic components.

Also, the actual grounding of the strap should be done carefully to a separate ground terminal and not be left to a chance connection through an alligator clip hooked onto some “suitable” point.

7.3 NEUTRALIZATION OF CHARGES ON INSULATORS

Although discharges from charged insulative surfaces are usually less energetic and less incendive and otherwise destructive, than the spark-type discharges from conductors, there are numerous examples of charged insulators causing ignitions of explosive vapor/air mixtures, attracting dust to exposed surfaces, and, probably most importantly, inducing destructive ESD events.

It is therefore important to be able to neutralize charges located on insulative materials. This can in principle be done in three different ways: by conductance the **bulk** of the material, conductance along the **surface** of the material, or by the use of oppositely charged **ions** from the surrounding air.

7.3.1 BULK-CONDUCTIVE INSULATORS

Basically, it's self-contradictory to talk about transporting charges through an insulator. If this is possible the material is not really insulative. Over the years many attempts have been made to give insulative materials a suitable conductivity, without ruining their other (usually mechanical) desirable properties. Normally this is done by mixing the material with inherently conductive additives. The best known example of such an intrinsic antistatic agent is carbon black. Carbon black can be added to a variety of polymeric materials and is used when the resulting blackening of the base material is acceptable. For many years the most important area of use was that of manufacturing conductive rubber.

Ordinary vulcanized rubber may have a bulk resistivity of $10^{13} \Omega \cdot \text{m}$, but adding carbon black may lower the resistivity by a factor of up to 10^{15} .

Normally, however, a resistivity of about 10^5 – 10^6 $\Omega\cdot\text{m}$ will be low enough to prevent dangerous or annoying charge accumulations.

Conductive rubber is used extensively in hospital operating rooms, in tubing for anaesthetic machines, for wheels on carts, as parts of soles for antistatic footwear and in the manufacturing of car tires. It was actually the need for antistatic tires that led to the development of conductive rubber. In the middle 1930ies two new aspects of Western civilization brought the concept of static electricity to the attention of the general public, at least in the United States. One was the appearance of car radios. The quality of reception of often distant AM stations was severely impeded by the crackling caused by discharges from the car, charged by the rolling friction between the tires and the road surface. The other innovation was the introduction of toll roads. When the unsuspecting driver handed over his nickel to the toll collector, both parties might experience an unpleasant chok. With the development of conductive or antistatic tires, all this became history. If the road surface is not excessively dry and insulative, a car will not be charged.. Nevertheless, many drivers, at least in Europe, equip their cars with trailing conductive tails to bleed odd static charges that the tires have already taken care of. And even if the surface conditions in exceptional cases do lead to a charging of the car, the tail will not remedy this problem.

It should be mentioned that the shock many a driver (or passenger) receives when getting out of a car is not caused by discharging the car to ground. What happens is that the driver may get charged when sliding over the seat cover, in much the same way as one might get charged when getting up from a chair with an insulative seat. As a result a spark may jump between the person and any metal part of the car, which is virtually at ground potential.

Another use of carbon black is in the manufacturing of antistatic, solid as well as textile, floor coverings. The textile fibers may be made with either a central core of carbon black and a sheath of, for instance, polyamide, or conversely with a polyamide central core and a sheath of carbon black. When such combination fibers are mixed with ordinary highly insulative fibers, in a ratio of a few per cent, the result is a material that rarely produces substantial chargings.

The most important, at least economically, use of carbon black is no doubt in the electronic industry. By loading the base materials for carrier trays, holders, tubes, tote boxes, bags etc. with carbon black, these items are made sufficiently conductive to ensure a rapid neutralization of static charges on the material itself.

Usually the loading is done uniformly throughout the matrix of the material, increasing the bulk conductivity, but it may also take the form of a thin conductive surface layer.

7.3.2 SURFACE-CONDUCTIVE INSULATORS

It is well known that static electric problems seldom occur in environments with high relative air humidity, say above 50-60 %. This fact has sometimes been erroneously interpreted as humid air having higher conductivity than does dry air. But if anything, humid air is less conductive, as the mobilities of small air ions decreases slightly with increasing humidity. The effect of increased air humidity is to increase the thickness of the moisture layer on and/or in all surfaces. This layer will contain (electrolytic) ions which will provide the neutralizing charges. The amount of water absorbed or adsorbed from the air is strongly dependent on the materials in question. At humidities as low as 30-35 % a material like cotton may show little charge retention, whereas a material like polyamide may require humidities of 50 % or more to be considered antistatic. Generally speaking, no resulting charges appear at humidities of 60 % or higher. Humidities at such high levels, on the other hand, will often pose practical, technical or hygienic problems if they are to be maintained over extended periods of time.

7.3.2.1 Antistatic Agents, Topical Antistats

It is often possible to render highly insulative materials sufficiently surface conductive, even at relatively low humidities, by treating the surface with antistatic agents, commonly known as **topical antistats**. These agents function by forming a thin layer (a few molecules thick) on the surface, and this layer will attract moisture from the air much more readily than will an untreated surface.

Antistatic agents obviously have to be hygroscopic, but it is further required that they have a low vapor pressure in order not to evaporate

too fast from the surfaces treated. Further requirements concern color, toxicity, inflammability etc.

Chemically speaking antistatic agents are amphipathic compounds, their molecules containing a hydrophobic group to which is attached a hydrophilic end group. According to the nature of the end group, the agents are divided into cationic, anionic and non-ionogenic agents. Cationic materials are usually high-molecular quaternary ammonium halogenides, see for instance Fig. 7.1, showing cetyl-trimethylammonium-chloride, $C_{17}H_{35}(CH_3)_3NCl$, or ethoxylated fatty amines or amides; anionic materials may be sulfonated hydrocarbons and non-ionogenic materials polyalkylene oxide esters.

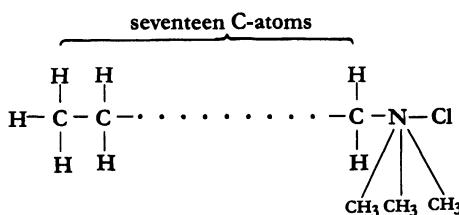


Fig. 7.1

Topical antistats are used extensively in the textile, plastic, printing, and many other industries. A common use is the treatment of floor coverings to reduce the level of body voltage of persons walking across the floor. With

textile floor coverings a proper antistatic treatment may work for two to three months. With hard floor coverings the antistatic treatment normally has to be repeated after each washing.

7.3.3 PERMANENTLY ANTISTATIC MATERIALS

In some cases antistatic agents may be compounded with a polymer, either before polymerization or at least before extrusion. The best known example of this technique is probably the manufacture of antistatic polyethylene, commonly known as **pink poly**. Ethoxylated fatty amines or amides are mixed with a resin, like low-density polyethylene, and an antiblock, like calcium carbonate, to prevent stickiness. After extrusion or molding to the required end product (film, sheets, trays, boxes etc) the additive has to diffuse ("bloom") to the surface in order to be able to attract moisture from the air and thus render the material antistatic.

Pink poly, which may appear in a variety of color shades besides pink, is no doubt the most widely used material in the electronic industry for packaging, storing and transporting sensitive components and circuits.

Materials with built-in additives will maintain their antistatic properties as long as the additive is present on the surface. Although the vapor pressure of most additives is fairly low a certain evaporation is always taking place from the surface. For fresh materials this evaporation is counterbalanced by a diffusion from the interior of the material. As the supply of additive in the solid is depleted, the surface concentration can not be maintained. The surface is said to "dry out", the surface resistivity will increase, and the material will eventually lose its antistatic properties. The effective lifetime of a permanently antistatic material depends upon a lot of factors, the most important of which is the temperature of the environment and the thickness of the material, which (for a given volume concentration) determines the amount of additive available for diffusion to the surface. It should also be mentioned that the additive diffusing to the surface, besides attracting moisture from the air, may react in unwanted ways with component and devices coming into contact with the material. Examples of this are PCBs and other items made of polycarbonate being crazed and cracking when packed in antistatic materials containing fatty amines.

7.4 CHARGE NEUTRALIZATION BY AIR IONS

All the methods discussed previously for neutralizing charges on insulators are based on some kind of modification of bulk or surface properties of the insulative material. However, often such modifications are not feasible or acceptable. In such cases only one method remains: neutralizing the charges by oppositely charged air ions. The nature of air ions and the mechanism of neutralization by air ions are discussed in Chapter 4: DECAY OF CHARGE and Chapter: 5: BREAKDOWN.

7.4.1 IONIZATION METHODS

Although the concentration of air ions may vary with time, space and production method any ionization process in air starts with the removal of an electron from a neutral oxygen or nitrogen molecule. The necessary energy may be delivered to the molecule from a colliding particle or from a quantum of electromagnetic radiation energy.

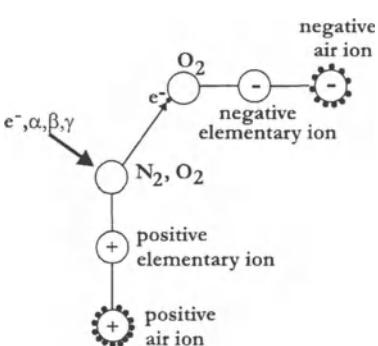


Fig. 7.2

Fig. 7.2 shows the various steps in the formation of a pair of air ions. When an electron is knocked off a neutral oxygen or nitrogen molecule, this molecule is left as a so-called elementary positive ion. This ion, however, will in a matter of microseconds have attached a number (10-15) polar molecules, mostly water around itself. And this molecular cluster is what constitutes a positive air ion (also called a small positive ion).

The electron will move away and, as explained later, possibly cause further ionization, but eventually it will attach to an oxygen molecule, forming a negative elementary ion. This ion will also attach a number (8-12) polar molecules around itself, creating a negative air ion (or small negative ion).

In technical practice only two ionization methods are used: *radioactive ionization* and *field ionization*.

7.4.1.1 RADIOACTIVE IONIZATION

The nuclides used for radioactive ionization are usually alpha-emitters. The alpha particles leave the decaying mother atom with energies in the order of 4-8 MeV ($\approx 6 - 13 \cdot 10^{-13}$ J). On its way through the air an alpha particle will knock off electrons from neutral air molecules, Fig. 7.3, at

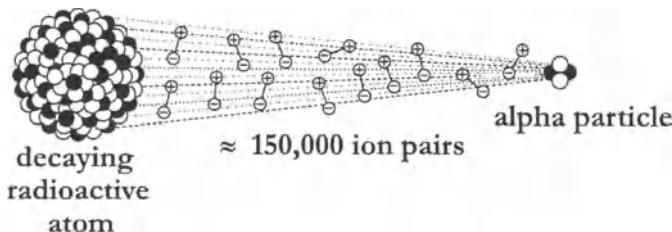
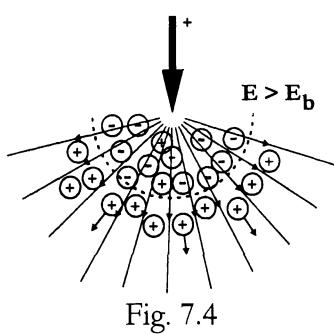


Fig. 7.3

the expense of about 34 eV for each successful collision. After having traveled a distance of 2 – 7 cm the alpha particle has lost its energy (and velocity) and has produced about 150,000 ion pairs along its track.

7.4.1.2 FIELD IONIZATION



In any atmosphere there are always a few free electrons originating from the decay of naturally occurring airborne nuclides, primarily radon and radon daughters. If an electric field is established in the atmosphere, these electrons may be accelerated to such high velocities that they themselves will cause breakdown, see Chapter 6: BREAKDOWN.

And this is the principle in **field ionization**. A pointed electrode, Fig. 7.4, is kept at such a potential, that the breakdown field strength is exceeded in a small volume in front of the electrode.

Such an electrode is often called an **emitter**, but it is important to note that the electrode does not actually emit ions. The ions are created by the field immediately in front of the emitter, and the apparently emitted ions (positive in Fig. 7.4) have never been in contact with the emitter. Actually the emitter receives ions (negative in Fig. 7.4). When these negative ions have been neutralized at the emitter they cease to exist as ions and turn once more into air and water molecules. If an ammeter is inserted in series with the electrode, a current may be measured. This **ionization (or corona) current** is the current it takes to neutralize the ions arriving at the emitter. Under steady state conditions it has the same magnitude, but is not identical to, the current of ions moving away. If the corona current is used as a measure of the output of ions from the ionizing device to the surrounding air, it should be kept in mind that often a (substantial) fraction of the ions emitted plate out on more or less grounded parts of the ionizer or on neighboring surfaces without ever reaching those regions where their neutralizing (or other) effects are wanted.

7.5 TYPES OF IONIZERS

7.5.1 RADIOACTIVE IONIZER

The (radio)-active material (almost always an alpha emitting nuclide with a half life in the order of half a year) is placed on a base material and

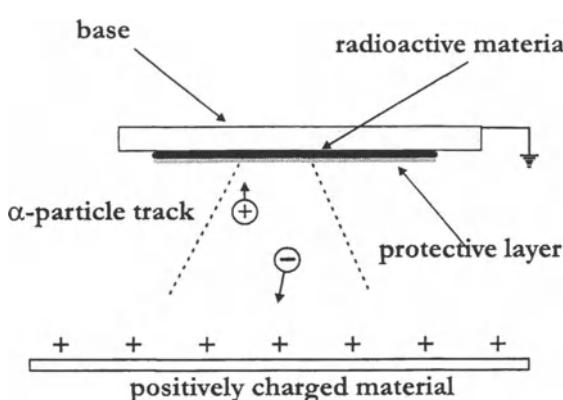


Fig. 7.5

covered by an extremely thin protective layer, often made of gold, Fig. 7.5.

The alpha-particles are emitted from the nuclide with an energy of, say, 5 MeV ($\approx 8 \cdot 10^{-13}$ J). A small part of this energy is dissipated in the protective

layer, but still the alpha-particle is able to create maybe 150,000 (positive and negative) ion pairs along its range of some few centimeters.

The ionizer is consequently placed in front of the charged material at a distance which is a little larger than the range of the alpha-particles. If the material is positively charged negative ions will be attracted and plate out on the material gradually reducing the field.

The neutralizing efficiency of radioactive ionizers is not very high, but when one is dealing with relatively low levels of static charges and especially in confined spaces, radioactive ionizers are very handy. They do not require any electrical installation and they cannot cause potentially harmful electrical discharges.

Since a fairly short-lived nuclide is used, one can be reasonably sure the ionizer is replaced at regular intervals and not left unattended for extended periods of time. Since alpha-active nuclides are used the *external* radiological dose is insignificant. If, however, the radioactive material, by carelessness or accident, is spread in the environment and, for instance, becomes airborne, it may be inhaled. In this case the highly energetic alpha radiation may give off an *internal* dose, which eventually may cause radiological damage to the respiratory tract. With modern ionizers, however, the risk is extremely low.

7.5.2 PASSIVE IONIZER

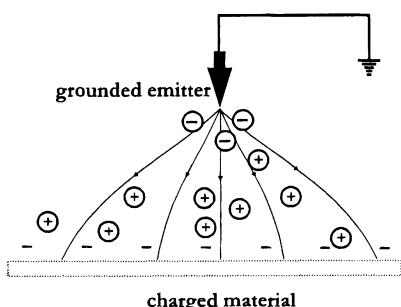


Fig. 7.6

ions formed in this region. In the situation shown in Fig. 7.6 negative ions will move to the emitter and become neutralized and positive ions will move to the charged material and gradually neutralize the charge located here.

When the charge density becomes too low the ionization and hence the neutralization stops. A passive ionizer will thus not be able to render a material total neutral, but it will be able to reduce high levels of charges, which in many industries is sufficient.

It is interesting to note that the electrode at which the ionization takes place is a ground potential, and still the field strength in front of the electrode may be high. So once more we are reminded of the fact that ionization is not caused by a high voltage, but by a high field strength.

Sometimes passive ionizers are made as brushes of carbon fibers, which sweep over the charged material. Direct contact between the brush and the charged material does not improve the efficiency of the neutralization. The charges are not “wiped” off the material, but neutralized by oppositely charged air ions, and as a consequence the grounded brush should be kept at a (small) distance from the charged surface.

7.5.3 AC-IONIZER

In cases where a passive ionizer does not provide sufficient neutralization an AC-ionizer, Fig. 7.7, will often do the job.

The emitter is connected to an AC-voltage supply, usually some kV. Positive and negative ions will alternatingly be formed in front of the

The simplest form for a field ionizer is the passive one, Fig. 7.6. It is essentially a grounded emitter, or more often a row of emitters, placed parallel to and close by the charged material..

The charge will provide an electric field, and if the charge density is high enough, the breakdown field strength will be exceeded near the emitter and positive and negative

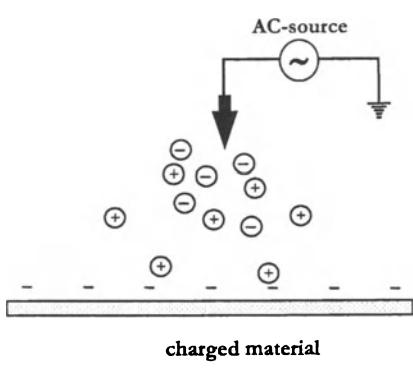


Fig. 7.7

the AC-signal should not be symmetrical since the breakdown voltage is lower for negative ionization than for positive.

7.5.4. DC-IONIZER

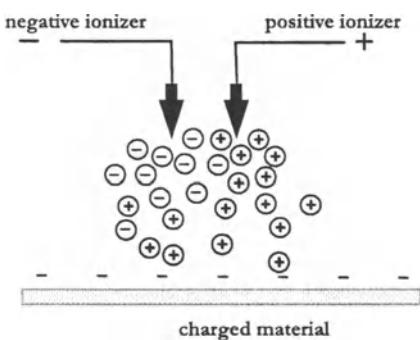


Fig. 7.8

the polarity of the charge determines what kinds of ions are being used for the neutralization.

If one is reasonably sure that the charge to be neutralized is always of the same polarity, for instance negative as shown in Fig. 7.8, it might seem natural to use only a positive DC-ionizer. This, however, may not assure neutralization but instead lead to a positive charging caused by the ionizer. It is therefore important that the ionizer is able to balance the ion concentrations where the neutralization is going to take place.

emitter, and the polarity of the charged material will determine which polarity of ions will be attracted and cause neutralization. It's a short-coming with AC-ionizers that ionization only happens in that part of each half-period where the voltage of the emitter exceeds the breakdown voltage. If thus the charged material is moving rapidly past the ionizer the neutralization may be less than complete. Further

The most effective neutralization is obtained by the use of a DC-ionizer, usually consisting of two emitters held at a positive and a negative potential respectively, Fig. 7.8

When the ionizer is properly balanced, positive and negative ions will be provided in the same concentrations in front of the charged material, and as explained with the AC-ionizer,

7.5.6 ION BLOWERS

The ionizers described above are all designed to be mounted in front (or back) of the charged material. However, in many cases this approach is not practical or possible and the ions have to be transported an appreciable distance from their site of production to the place of neutralization, usually aided by an air flow.

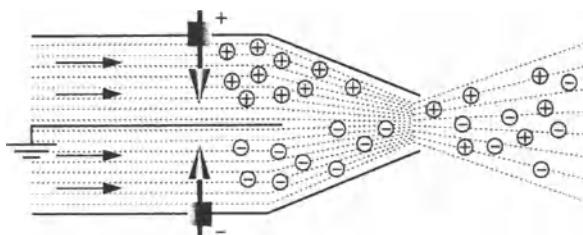


Fig. 7.9

An ion blower, Fig. 7.9, often a benchtop device is essentially an electrical (AC or double DC) or possibly a radioactive ionizer encapsulated in a (at least partly) conductive house (often forming the counter electrode) with an air orifice or opening.

By blowing air past the region where ionization takes place it is possible to create an air stream with a relatively high ion content. Because of the small distance between the emitters and the grounded surroundings a substantial fraction of the ions formed will never reach the air outside the ionizer, and the ion concentration is further reduced because of diffusion, repulsion and combination processes. It is further of importance that the air stream is balanced in terms of positive and negative ions and most benchtop ionizers are therefore equipped with some kind of auto- or self-balancing feature.

7.5.7 WHOLE-ROOM IONIZATION

When working with very static-sensitive devices, the localized neutralization provided by normal ion blowers may not be sufficiently effective. In such cases **whole-room ionization** may offer a good solution. The name is somewhat misleading, as the ionization with this kind of system does not take place in the room as a whole (as is the case with the ionization from airborne radioactivity), but in a rather limited

volume near the ceiling. Here a series of point emitters are mounted in a pattern, which may vary from system to system.

There are two essentially different principles for whole-room ionization systems. In one type of system alternate emitters are connected to positive and negative voltage supplies, and the ion production is continuous. In the other type all emitters are connected to the same voltage supply, delivering an AC-voltage, which may be sinusoidal (50 or 60 Hz) or squared-pulsed (1-2 Hz).

With the square-pulse technique ions are constantly produced (with alternate polarities), and because the pulses are fairly long, ions of a given polarity have a chance of moving away from the emitter before ions of the opposite polarity are produced and recombination sets in. This process can be enhanced by separating (shorter) positive and negative pulses by maybe half a second in the **stepped pulse** technique. The ions are brought down to the work place and to items, where neutralization is needed, by field movement, diffusion, and often by a (laminar) air flow.

7.5.8 UNIPOLAR IONIZERS

It has already been pointed out that in order to avoid recharging or overcompensating, proper neutralization of electrostatic charges by ionizing the air requires a balanced distribution of positive and negative ions around the charged object. It should thus be obvious that unipolar ionizers, emitting ions of one polarity only, are unsuited for neutralization purposes. If, however, the field from the emitters extends throughout the room where a unipolar ionizer is operated, airborne particulates will be removed from the air by the combined effect of ions and the field. This feature will be discussed in Chapter 10: APPLICATIONS OF STATIC ELECTRICITY.

7.5.9 OZONE

With any kind of electrical discharge in atmospheric air, ozone (O_3) is produced. Ozone is probably best known as part of the stratosphere that absorbs harmful UV-radiation from the sun. Ozone is chemically extremely active. It has been used extensively, because of its effect on bacteria and germs, for disinfecting drinking water and in fruit storage

and transport rooms etc. The use of ozone producing devices have even suggested for improving the quality of indoor air.

However, ozone is also one of the most poisonous gases known. The maximum acceptable concentration is (in most countries) 0.1 ppm. Ozone will when inhaled attack the respiratory tract, and it appears that the effect may depend on the integrated exposure (like radioactive exposure), which makes the concept of a safe threshold limit somewhat dubious.

Consequently most modern instruments that utilize corona charging, like laser printers and photocopiers, are equipped with filters that adsorb most of the ozone produced. However, this is not possible with systems intended to distribute ions to the surrounding air, as the ions would also be filtered out, probably even more efficiently than the ozone. The ozone production rate increases with the corona current and, especially in arrangements where a high emitter voltage is used together with short emitter-ground distances, the ozone levels should be monitored, especially in small rooms.

It should be mentioned that also radioactive decay may give rise to production of ozone, but that the levels of (radio)activities used in radioactive ionizers is far too low to produce worrisome ozone levels.

7.6 LIQUIDS

The methods for abating static electricity described in the previous sections can practically be utilized only in connection with solids. However, as already mentioned, many types of liquids are likely to be charged by flowing or spraying, and if the vapors of the liquids mixed with atmospheric air are explosive, it is obviously important to reduce the possibility of creating larger charge accumulations, normally by leading the charges away whenever possible.

To avoid the build-up of charges, first of all a suitable grounding of all conductive parts should be employed. If such a grounding is not possible all conductive parts, e.g. filling tubes and containers, should be bonded. By suitable bonding and grounding high voltage difference between different parts of the structure cannot arise, but this kind of precaution does not reduce the charging of the liquid. It is, however,

possible to modify the flow pattern in such a way that the charge separation is kept at a minimum.

The charge separation rate is proportional to the linear flow velocity and to the tube diameter. At the same time the decay resistance of the liquid is inversely proportional to the square of the tube diameter, and consequently the equilibrium voltage difference between the ends of the liquid column is proportional to the linear velocity and inversely proportional to the tube diameter. As an example the following flow rates are known to give rise to only moderate charge separations: diethyl ether and carbon disulfide $1\text{-}2 \text{ m}\cdot\text{s}^{-1}$ (at small tube cross sections); esters, ketons and alcohols $9\text{-}10 \text{ m}\cdot\text{s}^{-1}$ (as a maximum).

When filling containers it is important to bring the filling tubes all the way to the bottom of the container in order to avoid free jets of liquids. At the start of a filling this requirement can not be fulfilled, and hence the flow rate should be kept low until the outlet nozzle is completely immersed in the liquid.

The charge of the liquid can sometimes be (partly) neutralized by means of a grounded screen immersed in the liquid. Such a precaution is of special importance when working with easily chargeable (and volatile) liquids like diethyl ether and carbon disulfide. The screen should be mounted so that it is not struck by jets of the liquid promoting turbulence and spraying.

Mixing of the liquid with other substances, especially colloids, may increase the charge separation rate. But, on the other hand, antistatic additives may often increase the conductivity of the liquid to such a degree that static charges can hardly be detected; such additives are used for instance when pumping gasoline at high flow rates.

7.7 SPECIAL PRECAUTIONS

Railway tankers and stationary tank units normally do not need special grounding connections with the exception of the piping system for filling of containers. Road tankers and airplanes may, although it is not very likely, be charged during the drive or flight. Because of the possible serious consequences of a discharge in an explosive atmosphere, tankers and airplanes should be grounded before any transmission of fuel takes place. The connection of grounding or bonding wires should not

be established close to the outlet of inflammable liquids or explosive vapor mixtures.

In pneumatic transport the use of atmospheric air or other gases containing oxygen should be avoided when handling volatile liquids. The transport gas should not pass through the system in order to avoid spraying.

Metallic pipe connections will normally be sufficiently conductive. But, as already mentioned, paint, rust or grease can form insulative layers, making special wire connections across couplings necessary. When movable filling pipes (for instance swinging links for filling railroad tankers) are used, it is especially important to secure a safe grounding of the filling pipe, because during operation it will be very close to the grounded container at the outlet for the possibly charged liquid; thus a discharge might occur at the potentially most dangerous site.

All hoses should, if possible, be made of conductive rubber, or of a material with a woven-in thread of Monel or a similar material. It is important to connect the metal thread and the couplings at the end of the hose securely. The resistance between the end of the hose should be checked frequently and should not exceed a few megohms. Only couplings with conductive surfaces should be used, and connections should be established without the use of insulative grease and other fillers.

When handling relatively small volumes of liquids (less than, say, 10 gallons), it is (except for very volatile liquids like diethyl ether and carbon disulfide) sufficient to secure bonding of all conductive parts, especially metal funnels and containers. When handling liquids like diethyl ether it is advisable to use conductive containers with filling pipes brought down to the bottom of the receiving container, and any funnels must be properly grounded.

7.8 POWDER, DUST, AEROSOLS

With dust/air mixtures any charging occurs via interparticle friction, by friction between the particles and the surroundings (tubing or room walls), or by the production (for instance spraying) process. For powders and dust the following general rules apply:

- If the particle material itself is nonflammable the charging itself does not pose any risk, as long as other inflammable materials are not present.
- When handling combustible materials it is important, when possible, to avoid fine-partitioning, as the ignition energy decreases with decreasing particle size. By adding an inert gas, like nitrogen, to the powder mixture, the ignition energy is increased and the explosion energy reduced.
- Inserting a grounded screen in the dust flow and grounding any other conductive item in the system may also reduce the charging.
- Flow rates should be kept to a minimum and elevated air humidity should be employed when possible.
- Any interparticle will further the charging processes, so any excess friction should be avoided. It is therefore better to transport powders on conveyer belts or in a free fall than let the powder slide down a chute.
- Machinery and means of transportation should be made of conductive materials and grounded or at least placed on a conductive (and grounded) floor.
- If insulative materials have to be used, for instance in tubings, they should be metalized or made conductive in other ways, for instance by the addition of carbon black.
- Finally, one should frequently check if the formation of films of dust, oil etc. has ruined ways for charges to leak away.

Chapter 8

ELECTROSTATIC MEASUREMENTS

Most static electric measurements involve the determination of fundamental electric quantities, like voltage difference, current, resistance, and capacitance. In practice, however, electrostatic measurements differ from traditional electrical measurements, first of all because the voltage differences are caused by static charge distributions, which are unable to deliverer a current without ruining the voltages.

As a consequence, normal voltmeters, analog as well as digital, are unsuited for static measurements, because their functioning is based on a current, however minute, passing through the instrument. Similarly, the resistances of interest in static electric context are often so high that they cannot be measured by ordinary resistance measuring equipment. Further, investigations of static electric phenomena often require the determination of specially static related quantities like electric field strength and charge, and although the methods used for such measurements are primarily based on the principles for measuring voltage differences and current, a series of special requirements have to be considered.

8.1 STATIC VOLTAGE

The voltage of a statically charged insulated conductor can in principle be determined in two ways: by directly connecting the charged conductor to a suitable electrometer or static voltmeter, Fig. 8.1, or by using a field meter or a so-called non-contacting voltmeter reacting to

the field from the charged conductor.

We shall return to the second possibility after having discussed field measurements.

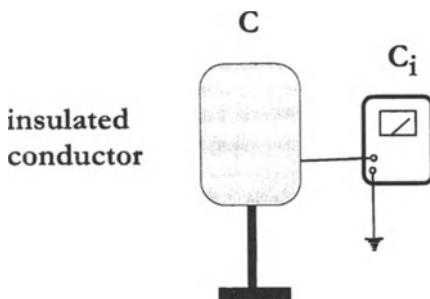


Fig. 8.1

8.1.1 STATIC VOLTMETERS

Static voltmeters are also known as electrometers. Ordinary voltmeters are primarily characterized by their internal or meter resistance. The higher the meter resistance is relative to the total resistance between the points to which the meter is connected the smaller is the influence of the voltmeter on the voltage difference to be measured. The concept of capacitance of an ordinary voltmeter is rarely of importance. The internal (or input) resistance of an electrometer should in principle be infinitely large, which in practice normally means higher than maybe $10^{14} \Omega$. An electrometer can be considered a capacitor, and the internal capacitance, the input capacitance, plays a similar, although inverted role to that of the meter resistance of an ordinary voltmeter.

Suppose an insulated conductor with the capacitance C has a charge q . The conductor then has a voltage

$$V = \frac{q}{C}$$

If we want to measure this voltage we connect the conductor to a static voltmeter with the capacitance C_i . The charge q will distribute itself on the two capacitances, and the voltage measured, i.e. the reading of the static voltmeter, V_e , is

$$V_e = \frac{C}{C + C_i} \cdot V \quad (8.1)$$

If for instance $C = 200 \text{ pF}$ and $C_i = 20 \text{ pF}$ we have

$$V_e = 0.91 \cdot V$$

The measured voltage of the charged conductor is thus 9 % lower than it would have been if the conductor had not been connected to the static voltmeter. It appears that the smaller the meter capacitance, the smaller is the influence of connecting the static voltmeter to the conductor.

8.1.2 MECHANICAL ELECTROMETERS

Electrometers have been in use for more than two hundred years. Already as early as 1785 Bennet constructed the electroscope, which was later developed into the **Braun electrometer**. This is an example of an

mechanical electrometer in which the functioning depends upon the electric forces on a light movable system. Braun electrometers are still in use and their functioning still give rise to discussions between Physicists. The range for a Braun electrometer is approximately 100 – 5000 V and the capacitance in the order of 10-20 pF.

Another type of mechanical electrometer is the so-called **quadrant electrometer** which looks more or less like an ordinary moving-coil instrument. Quadrant electrometers have capacitances and sensitivities in the same range as Braun electrometers.

About 50 to 100 years ago a whole series of different mechanical electrometers were in common use, mostly in scientific investigations. Some of these instruments were extremely sensitive (down to about 1 mV), but they were difficult or at least cumbersome to handle and are today completely out of use. Generally mechanical electrometers can be characterized as instruments of low capacitance and sensitivity and they suffer from the drawback that the reading cannot be (easily) automatically recorded.

8.1.3 ELECTRONIC ELECTROMETERS

We shall describe two types of electronic electrometers, which work on different principles.

8.1.3.1 Vibrating Electrometer

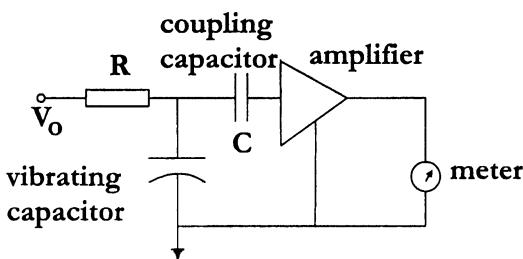


Fig. 8.2

The principle of a **vibrating electrometer** (also called a **vibrating reed** or **vibrating capacitor electrometer**) is as follows. Let the distance between the plates in a capacitor C, Fig. 8.2, vary with time, for instance sinusoidally.

The capacitance of the capacitor will then vary correspondingly. Let one plate of the capacitor be grounded and the other plate connected through a high-ohmic resistor R to a charged conductor with the voltage V_o . If the time constant RC is large compared to the period of

the capacitor oscillations, an alternating voltage with an amplitude proportional to V_o will be found across the capacitor C. This voltage can be amplified and measured, and V_o can thus be determined without any current been drawn from the charged conductor.

The input resistance of a vibrating electrometer is essentially the leakage resistance of the vibrating and the coupling capacitor, and may thus be extremely and sufficiently high for most purposes. The meter capacitance is about 20-30 pF, but may, by use of special couplings, be reduced to an effective value of 1-2 pF. The maximum voltage to be measured directly by a vibrating electrometer is normally 100 V or less. The sensitivity may be as high as a few μ V.

8.1.3.2 Solid-state Electrometers

Most modern electrometers are of the solid-state type, employing for instance a MOSFET-input, coupled to have the necessary $> 10^{14}$ - 10^{15} Ω input resistance. When the voltage to be measured is applied to the gate, the current through the transistor will be proportional to the voltage, and this current can be amplified and measured in the normal way. The direct meter input capacitance is usually a few tens of pF, but most electrometers are supplied with a series of capacitors, for instance from 100 pF to 0.1 μ F, which can be connected between the input and ground. One application of this feature will be discussed in the section on *Capacitive Voltage Dividing*.

Solid-state electrometers may be battery or line operated. Usually the voltage range covered is lower for the battery type (maybe 0 – 10 V) than for the line operated type (0 – 100 V). The sensitivity may be about 10 – 50 μ V.

8.1.4 CAPACITIVE VOLTAGE DIVIDING

The direct measuring range for modern electrometers is usually a few hundred volts at the most. But on the other hand static voltages of charged conductors may often run into many kilovolts. It is therefore important to be able to expand the measuring range of the electrometers.

With ordinary voltmeters the range is expanded by simply attaching a resistor R_e in series with the input resistance R_i . If $R_e = (n-1) \cdot R_i$, the range has been expanded by a factor of n. Because of the very high

and normally uncertain input resistance of electrometers, it is not possible to expand the measurement range of electrometers in the same way. The solution is to use the fact that the input resistance is so high that it, for practical purposes, can be considered infinitely large.

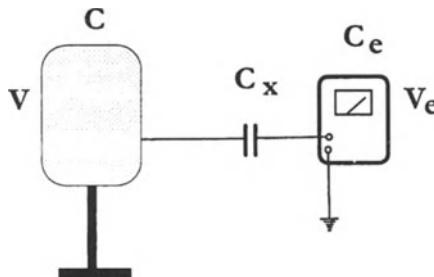


Fig. 8.3

A capacitor C_x is attached in series with the input of the electrometer with the capacitance C_e , Fig. 8.3. If the free end of C_x is connected to a conductor with the voltage V , the relation between V and the electrometer reading V_e will be

$$V = \frac{C_e + C_x}{C_x} \cdot V_e \quad (8.2)$$

If thus $C_e = (n-1) \cdot C_x$, the range of the electrometer has been expanded by a factor of n . Thus by using the built-in capacitors it is possible to change the range of the electrometer over several decades.

Example 8.1

Let an electrometer have a full scale reading of $V_e = 1 \text{ V}$ and let C_e be chosen as $0.1 \mu\text{F}$ (10^{-7}F). If $C_x = 50 \text{ pF}$ ($5 \cdot 10^{-11}\text{F}$) we can now measure voltages up to

$$V_{\max} = \frac{10^{-7} + 5 \cdot 10^{-11}}{5 \cdot 10^{-11}} \cdot 1 \approx 2000 \text{ V}$$

It should be noted that the capacitor C_x must have a high leakage resistance and be able to withstand a voltage difference of

$$\frac{C_e}{C_x} \cdot V_{\max}$$

which in the above example is 2000 V.

8.2 FIELD STRENGTH

The electric field strength is probably the single most important static electric quantity, but it is also the most difficult to measure and interpret.

Although the field strength is defined as the force per unit charge, eq. (2.2), there's no way this definition can be used in practice for measuring a field strength. All measurements of an electric field are based on the ability of a field to cause induction in a conductor, see

Induction, p. 19.

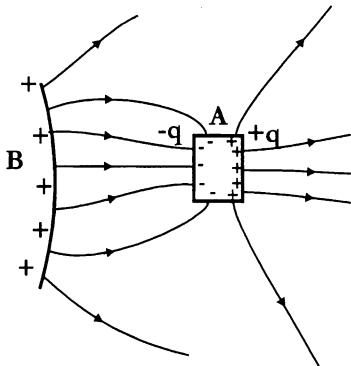


Fig. 8.4

Let an insulated conductor A be placed in the field from a charged body B, Fig. 8.4. The field will bind a (negative) charge $-q$ on A. If the field strength in front of A is E and the area of the conductor facing the field is S , it follows from eq. (2.9) that

$$E = \frac{\sigma}{\epsilon_0} = \frac{q}{S\epsilon_0} \quad (8.3)$$

The charge q and thus the field strength can be determined in two different ways: by the *probe method* and by a *field mill* (or *rotating field meter*).

8.2.1 PROBE METHOD

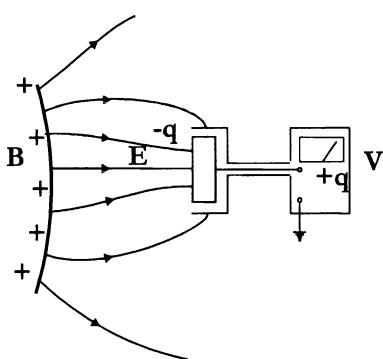


Fig. 8.5

Let the conductor A form Fig. 8.4 be a shielded disk connected to an electrometer with a (total) input capacitance C , Fig. 8.5.

The free charge $+q$ will charge the electrometer to a voltage V given by eq. (2.16). From eqs. (8.3) and (2.16) we then get

$$E = \frac{C}{S\epsilon_0} \cdot V \quad (8.4)$$

The voltage V of the electrometer will thus give the field strength E in front of the probe.

However, this method has an intrinsic possibility of error. If the probe is directly charged (for instance by airborne particulates) by an excess charge Δq , this will cause an excess reading ΔV on the electrometer, and the field will be over- or underestimated by an amount

$$\Delta E = \frac{\Delta q}{S\epsilon_0} = \frac{C}{S\epsilon_0} \cdot \Delta V \quad (8.5)$$

This possibility of error may, however, be avoided by the use of a *field mill* or *rotating field meter*.

8.2.2 FIELD MILL

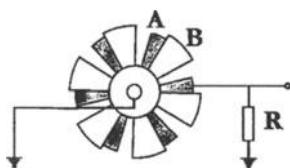


Fig. 8.6

In a field mill, Fig. 8.6 the conductor A from Fig. 8.4 is segmented and connected to ground through a resistor R . In front of A is placed a grounded, similar segmented electrode B, which can be brought to rotate. If the

system is placed in an electric field E , the electrode A will alternatively be screened from and exposed to the field. In the latter situation a charge q is bound on the electrode given by

$$|q| = S\epsilon_0 E$$

where S again is the area of the electrode. An equivalent, equally large, opposite charge will flow through R to ground. In the screened situation the field-bound charge is released and will thus flow to ground. When A is again screened the whole process is repeated. The result is that across R an alternating voltage is developed, the amplitude of which is proportional to the field strength E at the surface of the electrode. This voltage can easily be amplified and measured, and by the

use of a phase-sensitive amplifier the polarity (direction) of the field can also be determined.

8.2.3 FIELD DISTORTION

It should be stressed that the field measured by either the probe or the field mill method refer to the field at the surface of the probe or electrode, and, as suggested in Figs. 8.4 and 8.5, this field may be significantly different from (larger than) the field at the surface of the charged object.

The placing of the meter in the field is said to distort the field to be measured.

8.3 FIELD STRENGTH AND VOLTAGE

It follows from the definition of voltage difference

$$V(A) - V(B) = \int_A^B E \cdot da \quad (2.11)$$

that field strengths and voltage (differences) are intimately related, and the equation suggests that it is possible to do a non-contacting evaluation of the voltage of a charged conductor by measuring the field strength.

8.3.1 Conductor At Constant Voltage

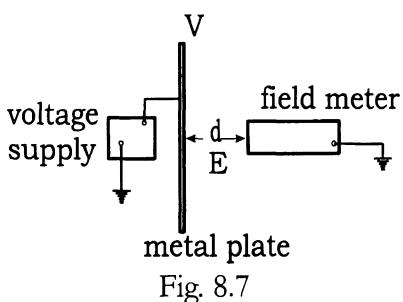


Fig. 8.7 shows a metal plate ($30 \times 30 \text{ cm}^2$) connected to a voltage supply set at 3 kV. In front of the plate is mounted a field meter, and the field strength is now measured as a function of the distance d from the plate.

For each distance the product $E \cdot d$ is calculated. The results are

shown in Fig. 8.8.

It appears that the field strength E , as expected, decreases with increasing distance d .

If, however, the voltage V of the plate is estimated by eq. (2.10) as

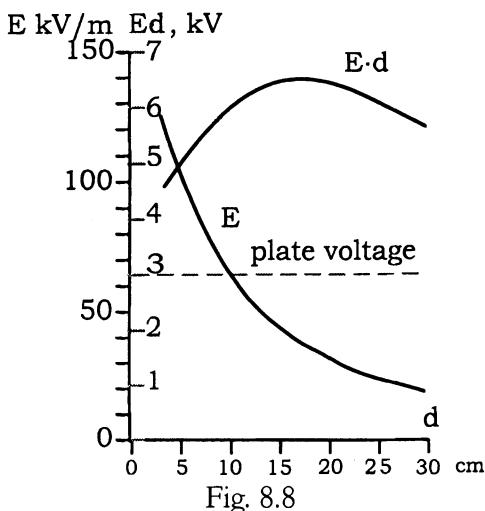


Fig. 8.8

read on the field meter is therefore higher than the mean field strength between the meter and the target, and the $E \cdot d$ -approximation of the voltage will therefore be too high.

It appears, that in the range of distances from 4 cm to 30 cm the estimated voltage $E \cdot d$ varies between 4.5 and 6.2 kV as compared to the true value of 3 kV.

The problem of the instruments distorting the field can be partly corrected by surrounding the meter with a grounded screen parallel to the face of the target, as shown in Fig. 8.9.

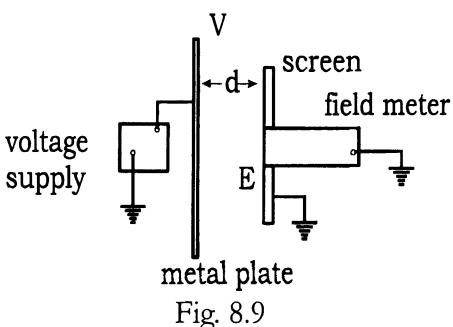


Fig. 8.9

V of the metal plate is adequately determined by the product $E \cdot d$ out to a distance of approximately 15 cm between the plate and the field meter.

$$V = E \cdot d$$

we find that we get a very poor approximation to the true value (3 kV) of the plate voltage.

The reason for this is, that eq. (2.10) assumes the field to be homogeneous, as shown in Fig. 2.14. But the set-up in Fig. 8.8 resembles much more closely the situation in Fig. 2.15, since the housing of the field meter is essentially at ground potential. The field strength

The screen has the dimensions of $25 \times 25 \text{ cm}^2$ and the target is again a $35 \times 35 \text{ cm}^2$ metal plate.

In Fig 8.10 the field strength E and the apparent voltage $E \cdot d$ is shown as a function of the distance d .

It appears that with the screen attached the voltage

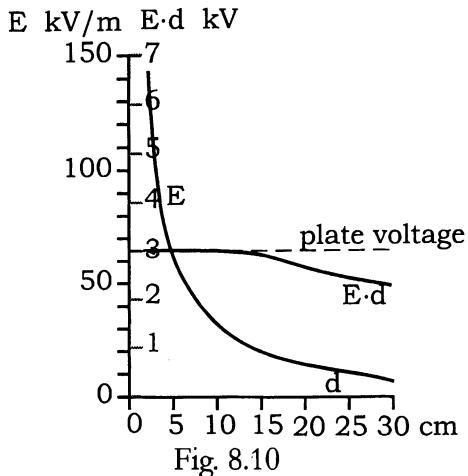


Fig. 8.10

At larger distances the field again becomes inhomogeneous, in this range underestimating the voltage. The distance to which the voltage can be determined with reasonable accuracy also depends on the target size. If the measurements in Fig. 8.10 are repeated with a $15 \times 15 \text{ cm}^2$ -plate the readings yield reliable results only out to a distance of approximately 6-7 cm.

8.3.2 CONDUCTOR WITH CONSTANT CHARGE

In the cases discussed above the target conductor was locked to a voltage supply. The voltage of the conductor would thus be constant independently of the placing of the field meter. The charge, on the other hand, might vary with the inter-capacitance of the conductor and the field meter, i.e. with the distance d .

This is not the ordinary every-day situation where a conductor has been charged and you want to measure its voltage by pointing a meter at the conductor. In that case the charge stays constant while the voltage may change because of the coupling with the meter capacitance.

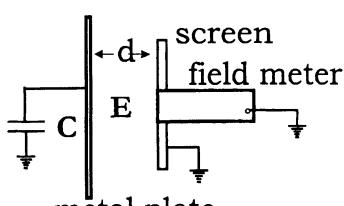


Fig. 8.11

In Fig. 8.11 an experimental set-up for investigating this situation is shown. A metal plate, $35 \times 35 \text{ cm}^2$, is charged to an initial voltage of 3 kV (in the absence of the field meter) and the connection to the voltage supply is broken.

The field meter is placed at various distances d from the metal plate and

the field strength E is measured.

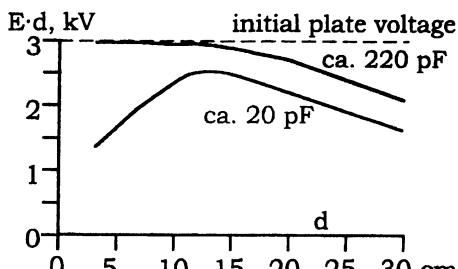


Fig. 8.12

Fig. 8.12 shows the product $E \cdot d$ (the apparent voltage) as a function of d for the plate capacitances $C = ca. 20\text{ pF}$ (the plate alone) and $C = ca. 220\text{ pF}$ (the plate + an additional external capacitor).

With the larger plate

capacitance of 220 pF we get a curve, which is very similar to the one plotted in Fig. 8.10, where the metal plate is locked at 3 kV. This means that the presence of the field meter does not significantly change the total capacitance and hence also not the plate voltage for a given distance.

With the smaller plate capacitance of 20 pF we find that the calculated voltage is lower at all distances than with the larger capacitance. This is due to the added value of the meter capacitance. At the very short measuring distances the presence of the meter makes the original value of the capacitance increase from 20 pF to about 45 pF, resulting in the voltage dropping from 3 kV to about 1.3 kV.

The measurements reported in Fig. 8.12 were repeated with an unshielded field meter. The general trend was the same as demonstrated in Fig. 8.8. At all distances (and with both capacitances tested) the unshielded fields overestimated the true values of the plate voltage by up to one hundred per cents.

8.3.3 NON-CONTACTING VOLTmeter

An alternative way of determining the state of a charged insulated conductor is by the use of a so-called **non-contacting voltmeter**. This is, like a field meter, a field-sensing device. When the meter is pointed at a charged object, the voltage of the probe is raised until the field in front of the probe is zero, and this state is then taken as an indication of the probe having the same voltage as the charged object.

A non-contacting voltmeter will, unless properly screened, like a field meter, in most cases distort the field to which it is exposed.

8.4 INSULATORS

The previous sections have dealt with the determination of the voltage of charged insulated conductors, either through direct contact to a static voltmeter or through the effect of the electric field produced by the charged items.

And although charged insulated conductors do appear in many practical, industrial as well as everyday, situations, there is no doubt that charged insulative materials are far more common.

While charged insulated conductors can be characterized by their capacitance and voltage these concepts can not be applied to insulators. So a natural question arises: What actually can you measure when dealing with a charged insulator? And the simple answer is: you can measure (the effect) of the field from the charge and possibly the charge density and the total charge. As with conductors the instruments to be used are field meters and non-contacting voltmeters.

Also there are only two cases where it is possible to make quantitatively reliable measurements of charged insulators. Those two cases are:

- 1) Uniformly charged free insulative sheet and 2) Uniformly charged insulative sheet backed by grounded conductor

8.4.1 FREE INSULATIVE SHEET

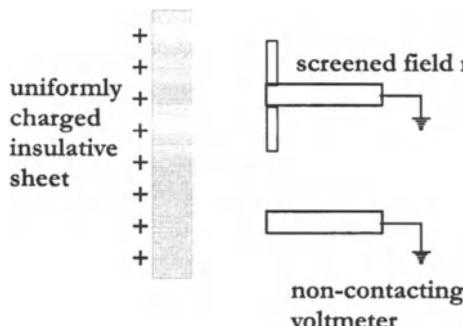


Fig. 8.13

Fig. 8.13 shows a uniformly charged insulative sheet. If the field strength read on the meter is E we should expect the charge density σ on the part of the insulator in front of the meter to be

$$\sigma = \epsilon_0 E \quad (2.9)$$

(We can not use eq. (2.8) as the whole flux is directed towards the grounded meters)

If a non-contacting voltmeter is placed at a distance d the **surface voltage** V_s read on the meter is given by

$$V_s = E \cdot d = \frac{\sigma}{\epsilon_0} \cdot d \quad (8.6)$$

Fig. 8.14 shows the field strength E from a free plastic sheet, charged with a total charge $q \approx 0.5 \cdot 10^{-7}$ C. The area of the sheet is 21×29 cm 2 which gives an average charge density

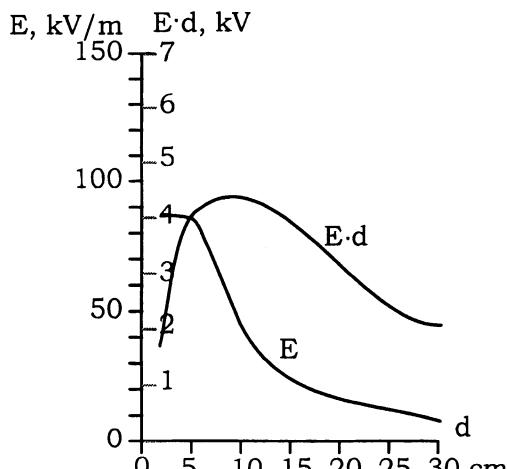


Fig. 8.14

$$\begin{aligned}\sigma_{ave} &= \frac{0.5 \cdot 10^{-7}}{21 \cdot 29 \cdot 10^{-4}} \\ &= 0.82 \cdot 10^{-6} \text{ C} \cdot \text{m}^{-2}\end{aligned}$$

It appears that the field strength is relatively constant, about 88 kV·m $^{-1}$ out to a distance of approximately 5-6 cm.

According to eq. (2.9) this corresponds to a charge density of

$$\sigma = 8.85 \cdot 10^{-12} \cdot 88 \cdot 10^3 = 0.78 \cdot 10^{-6} \text{ C} \cdot \text{m}^{-2}$$

Considering the uncertainty of the measurement of the total charge as well as of the field strength, the agreement between the calculated and measured value of the charge density seems satisfactory.

It thus appears that measurement of the field strength near a free, charged sheet leads to information about the charge density and distribution on the surface.

In the region where the field is homogeneous the **surface voltage** of the sheet is proportional to the distance from the sheet, and may (eq. (8.6)), for instance measured by a non-contacting voltmeter, also lead to the

surface charge density, if the measuring distance can be estimated with a reasonable accuracy.

But it should be stressed that a measurement of the **surface** voltage does not give any more or better information about the charged state of the insulative sheet than a measurement of the near-surface field strength does.

8.4.2 INSULATIVE SHEET BACKED BY GROUNDED CONDUCTOR

It was shown, pp.13-14, that an insulative sheet or disk, with a thickness t and permittivity ϵ , charged to a surface charge density σ and backed by a grounded conductor, will have a surface voltage V_s given by

$$V_s = \frac{\sigma}{\epsilon} \cdot t \quad (2.15)$$

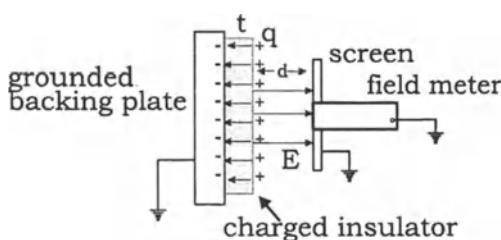


Fig. 8.15

Fig. 8.15 shows an arrangement where a sheet with the thickness t backed by a grounded conductor is uniformly charged with a charge q . This could for example be a charged web or an electret.

In a certain experiment

we had the following values: $t = 1$ mm, $q \approx 2.7 \cdot 10^{-7}$ C, $\epsilon_r = 2$ ($\epsilon = 1.77 \cdot 10^{-11}$ F·m⁻¹) and the dimensions of the sheet 21×29 cm² leading to a mean charge density of $\sigma \approx 4.4 \cdot 10^{-6}$ C·m⁻².

In the absence of the field meter (and other grounded objects, except the backing plate) we should expect a **surface** potential of each point of the surface, eq. (2.15)

$$V_s = \frac{4.4 \cdot 10^{-6}}{1.77 \cdot 10^{-11}} \cdot 10^{-3} \approx 250 \text{ V}$$

When a field meter is placed in front of the charged sheet the electric flux from the charge is shared between the field meter and the backing plate, and consequently the internal field and the surface voltage will be slightly lower, depending on how far away the meter is placed, and there will also be a field E_d in the space between the charged plate and the field meter.

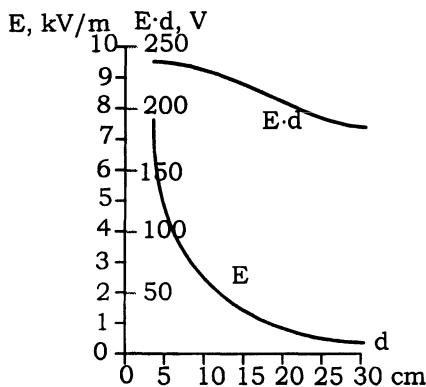


Fig. 8.16

And this field is the only quantity of the charged plate you can (possibly) measure.

Fig. 8.16 shows the field strength from and surface voltage of the sheet. At a measuring distance of 5 cm we find a field strength

$$E_5 \approx 4.6 \text{ kV} \cdot \text{m}^{-1}$$

and a surface potential

$$V_s \approx 235 \text{ V}$$

Comparing this with the estimated (calculated) value of 250 volt and considering the

uncertainties of the quantities involved, especially on the uniformity of the initial surface charging, but also on the effective distance to the meter, the agreement between the calculated and measured values is (surprisingly) good.

As shown in Fig. 8.16 the surface voltage ($E \cdot d$) is relatively independent of the distance to the meter, and this feature will be even more pronounced in the case of thinner insulators, like real electrets and webs with thickness in the order of 50-100 μm .

8.4.3 GENERAL COMMENTS ON CHARGED INSULATORS

The two cases discussed above, free insulative sheet and insulative sheet backed by a grounded conductor are the only cases where it is possible from a non-contacting measurement to extract reliable information of the charged state of an insulator. In both cases the electric field from the charge is the deciding factor. With a free sheet (or just a relatively plane insulator) the electric field measured at a short distance (a few centimeters) will give you all the possible information, i.e. the charge

density. If a non-contacting voltmeter is used you also have to measure the distance in order to convert the surface voltage to surface charge density. Surface voltage in itself tells you nothing extra.

In the case of a sheet backed by a conductor, the surface voltage is relatively constant, and if you know the thickness and permittivity of the material you are able from the surface voltage to calculate surface charge density. If you are using a field meter, you also have to measure the distance. Field strength depends on the surface parameters (thickness and permittivity) in the same way as surface voltage does.

So even in the well-defined situations described above, free charged sheet and backed charged sheet, will a non-contacting measurement at the best give you information about the charge density. Sometimes a field measurement is the most relevant (free charged sheet) and sometimes a “direct” surface voltage (backed charged sheet). But either measurement only leads to the charge density.

8.4.4 STATIC LOCATORS

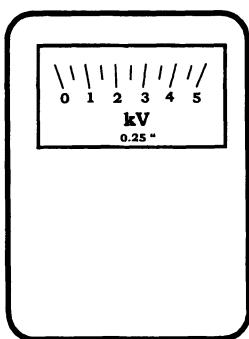


Fig. 8.17

Probably the most common way to do a fast static survey is to point a hand held meter at the suspicious item and pronounce a voltage. And often this is the only “measurement” done. And very often this is not enough.

The meters are known as, and often even called, *static locators*. And that is exactly what they are: instruments to locate a static electric field. And as long as that is the only thing they are being used as, everything is fine. But often their use is being

extrapolated into the absurd.

So let's look a little closer at such an instrument, Fig. 8.17

The meter may have two ranges, both of them scaled in volts. Still the meter is not a voltmeter, meaning it doesn't react to a voltage, but rather to an electric field. Often it is a regular field meter, for instance a field mill, or it may essentially just contain an operational amplifier reacting to the charge induced on a sensor plate at the front of the meter housing

The meter also has a stipulated measuring distance, in the case shown $\frac{1}{4}$ ". This means that the meter has been calibrated by being placed $\frac{1}{4}$ " from and parallel to a metal plate, which is then raised to a range of voltages and a corresponding scale is drawn.

So the question is now, after this calibration, what can you use your meter for? And the answer is very simple:

You can use the meter to measure the voltage at a distance of $\frac{1}{4}$ " of a metal plate with the same dimensions and the same capacitance as the one used for the factory calibration.

But the problem is now, that the manufacturers seem to be very reluctant to tell you this, or just to tell you what the calibration conditions are and what happens if you use the instrument under other and maybe even more every-day conditions.

It is very rare, if it ever happens at all, that the dimensions of the calibration plate not to mention its capacitance are given in the manual.

Nor are you ever warned that if you point the meter towards an insulator the reading in volts never refers to the insulator as a whole. An insulator does not have a voltage. If you're lucky you may get a kind of surface voltage.

It is something of a puzzle why static locators are always calibrated in volts. After all they are just ordinary field meters pretending to be voltmeters, without really being so. All they can do is measure the voltage of a certain metal plate at a certain distance.

If these meters were calibrated in units of field strength, i.e. $V \cdot m^{-1}$, they could much better be used to evaluate the static conditions of insulators as well as conductors.

But isn't the explanation simply that most people understand voltage better than they do field strength? No, that doesn't seem possible. Just look at equations (2.11), (2.12) and (2.13). A voltage is always defined by a field strength (and a distance), so if you don't understand one, you don't understand the other.

8.5 RESISTIVITY

8.5.1 BULK RESISTIVITY

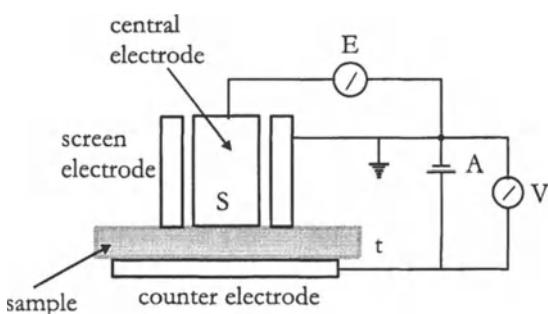


Fig. 8.18

The bulk (or volume) resistivity of a sheet or plate material may be measured by an arrangement as shown in Fig. 8.18. This corresponds in principle to the German norm DIN 53482 for determination of resistiv-

ity of insulative materials.

The sample (with the thickness t , is placed on a metal counter electrode. On top of the material is placed a cylindrical central electrode surrounded by a concentric cylindrical screen electrode. The screen electrode is grounded, and the central electrode is connected to a one side of a sensitive ammeter, E , (normally an electrometer in current mode) the other side of which is grounded. The counter electrode is connected to one terminal of a voltage supply, A , and the other terminal is grounded. The output voltage of the voltage supply is measured by the voltmeter, V .

Let the current measured on E be I and the voltage difference be V . The bulk resistance of the part of the sample between the central electrode and the counter electrode is then, eq. (2.28)

$$R = \frac{V}{I}$$

If the distance between the central electrode and the screen electrode is much smaller than the radius of the central electrode this is with good approximation the resistance of a cylindrical sample with a cross section

$$\rho = R \frac{S}{t} \quad (8.7)$$

equal to the area S of the central electrode and with a length equal to

the thickness t of the sample. According to eq. (2.29) the bulk resistivity is then given by

It is recommended to use a central electrode with a mass of about 1 kg (or rather 10 N) and a diameter of about 50 mm. The difference in radii for the two cylinders should be about 1 mm.

When measuring intermediate resistances, say, about $1 \text{ M}\Omega$, contact resistances between the electrodes and the sample may play a significant role. If the actual intrinsic resistivity of the material is wanted, it is therefore necessary to secure good contact, for instance by using conductive paste or wet filter paper. It should be stressed, however, that the value of the resistivity obtained under such conditions may be considerably lower than the effective resistivity of the material in a normal environment.

The unit for bulk resistivity is Ωm .

8.5.2 SURFACE RESISTIVITY

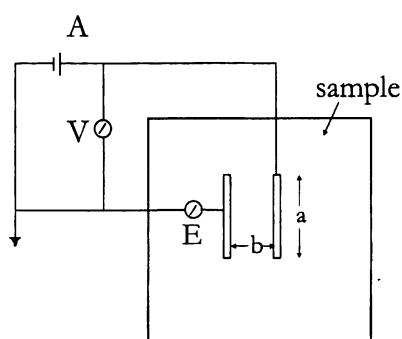


Fig. 8.19

The concept of surface resistivity and its definition is treated in Chapter 2: FUNDAMENTAL CONCEPTS, pp.27-30.

The surface resistivity ρ_s , defined by eq. (2.31)

$$\rho_s = \frac{E_s}{j_s} \quad (8.8)$$

may be determined by an arrangement as shown in Fig. 8.19.

On top of the sample to be tested are placed two electrodes, both of length a and parallel to each other at a distance b . One of the electrodes is connected to one of the terminals of a voltage supply, A , the other terminal of which is grounded. The output voltage of A is measured by the voltmeter, V .

If the output voltage is V_s and the current is I_s the surface resistance R_s is given by

$$R_s = \frac{V_s}{I_s}$$

and the surface resistivity

$$\rho_s = R_s \frac{a}{b} \quad (2.34)$$

When deriving eq. (2.34) the field strength E_s was approximated with a voltage difference V_s over the electrode spacing b , and the current density j_s with the total current I_s over the electrode length a , in both cases neglecting the stray field at the end of the electrodes.. It is possible at least for extensive samples

to correct for these approximations, but a more direct way around the problem is to avoid the approximations by using cylindrical electrodes like shown in Fig. 8.20.

The set-up is similar to the one shown in Fig. 8.18 for the measurement of bulk

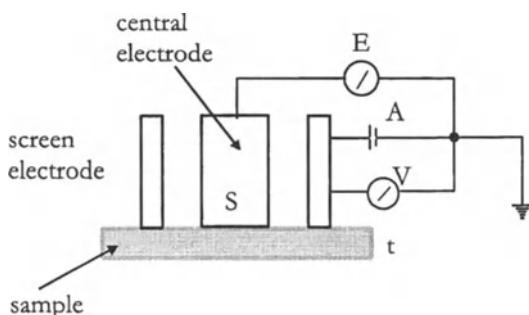


Fig. 8.20

resistivity. The central electrode is placed on top of the sample to be tested and connected to ground through the ammeter E . The screen electrode is connected to one terminal of the voltage supply, A , the other terminal of which is grounded. The output voltage V_s of the voltage supply is measured on the voltmeter V . If the surface current between the screen and the central electrode is I_s , the surface resistance R_s is

$$R_s = \frac{V_s}{I_s}$$

If the radius of the central electrode is a and the inner radius of the screen is b , the surface resistivity ρ_s of the material is

$$\rho_s = R_s \cdot \frac{2\pi}{\ln \frac{b}{a}} \quad (2.36)$$

It appears from eq. (2.34) as well as (2.38) that the unit for ρ_s is Ω .

8.5.3 EFFECT OF ELECTRODE GEOMETRY

There is no doubt that the surface resistance R_s does represent the the resistance between the electrodes used, be they linear or cylindrical, for the sample shosen for the measurements. But it is not obvious if the calculated (differential) quantity ρ_s , determined from eq. (2.34) or eq. (2.38), actually represents a *material property*, characteristic for the material tested and independent of electrode geometry and dimensions (and sample shape and size).

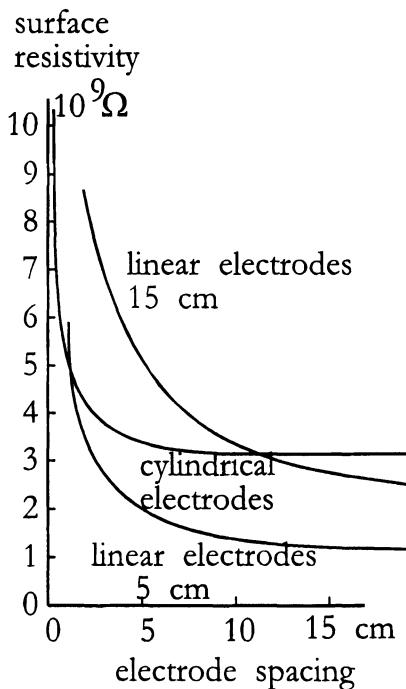


Fig. 8.21

Fig. 8.21 shows some results of determining the surface resistivity of a sample consisting of a stack of 20 sheets of paper placed on, but insulated from, a grounded plane.

The resistivity was measured by two sets of linear electrodes (lengths 5 and 20 cm) and a set of cylindrical electrodes (central electrode radius $a = 25$ mm) and inner radius of screen $b = 30, 35, 40, 65, 80$ and 135 mm. The output voltage was chosen as 200 V. For the cylindrical electrodes the difference $b-a$ was used as the electrode spacing.

It appears that for all three set of electrodes the resistivity decreases rapidly with increasing electrode spacings up to about 2-4 cm. For larger distances the surface

resistivity measured by cylindrical electrodes (eq. (2.38)) seems fairly constant, whereas the quantity determined by the use of linear electrodes (eq. (2.34)) seems to show a steady, but slow, decrease with increasing electrode spacing. This is probably caused by the uncorrected effect of the stray field at the edges of the electrodes. There is no obvious explanation of the small difference in the results with the two sets of linear electrodes. But it should be pointed out that with the kind of uncertainty of definition of the quantities involved, all three sets of measurements must be considered to have yielded identical results, suggesting that the most important requirement when measuring surface resistivity is to avoid too small an electrode spacing.

8.6 CHARGE

The classic, basic way of measuring a static charge is to place the charge on a capacitive system connected to an electrometer. If the collective capacitance of the system plus electrometer is C and the voltage, the reading of the electrometer, is V , the charge is according to eq. (2.16)

$$q = C \cdot V$$

8.6.1 FARADAY PAIL

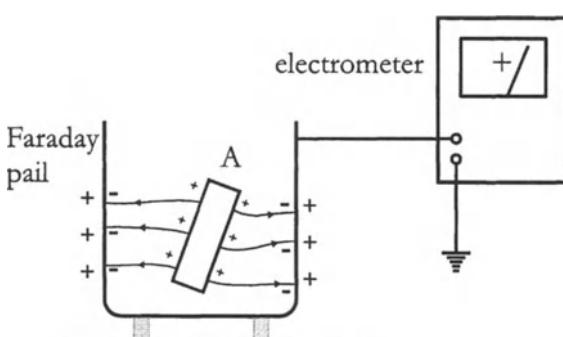


Fig. 8.22

If the charge is located on an object of small dimensions, the charge may be measured by placing the object in an uncharged, insulated, conductive container connected to an electrometer, Fig. 8.22.

Such a container is known as a **Faraday pail** (or cup).

If the charged object is conductive and touches the inside of the pail the charge will immediately be located on the outside of the capacitive system and charge it to a voltage V to be read on the electrometer. The charge can then be calculated from eq. (2.16)

But even if the charged object does not touch the pail or if it is insulative, the same method can be used. Let the charge q to be measured be positive. The field from q will by induction bind a negative charge on the inside of the pail, and even by the use of a fairly open pail, this charge is very close to $-q$. The pail and electrometer as a whole was originally uncharged, so a charge $+q$ will be free to charge the system to a voltage V , and the charge q can again be calculated from eq. (2.16). Even if the field from the charge causes a discharge inside the pail and a partial neutralization, the voltage V read on the electrometer still corresponds to the total charge $+q$.

8.6.2 CORONA TRANSFER OF CHARGE

Another way of (apparently) transferring a charge to a capacitive system is through a corona discharge.

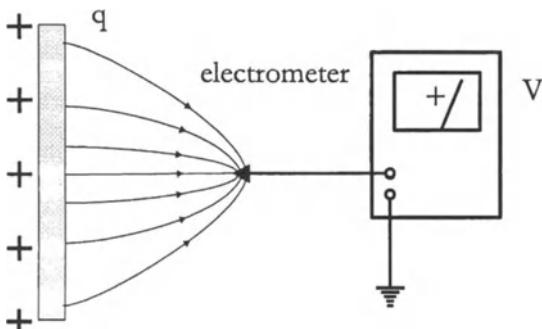


Fig. 8.23

Suppose the charge is located on an extensive sheet of material that can not conveniently be placed in a Faraday pail, Fig. 8.23.

If an electrode in the shape of a needle or a thin wire, connected to an electrometer, is placed in front of the charged material, the field in front of the

electrode may be strong enough to cause breakdown, causing positive and negative ions to be formed.

In the example shown negative ions will be attracted to the charged material, partly neutralizing the positive charge, and an equally large number of positive ions will move to the electrometer and charge it to a voltage V , and eq. (2.16) will again give the magnitude of the charge, which is being neutralized. The process will stop when the field in front of the electrode no longer exceeds the breakdown field strength. Experience shows that if the surface is carefully scanned by the electrode 80-90 % of the total charge may have been neutralized.

It should be stressed that the transfer of charge from the material to the electrometer is only apparent, and that the whole process consists of sharing an equal number of positive and negative ions formed in the air in front of the electrode.

Chapter 9

STATIC ELECTRICITY AND PEOPLE

Static electricity has often, at least in some parts of the world, in a rather unspecific way been attributed effects on human beings – usually unhealthy and/or unpleasant effects. In this chapter we shall discuss such effects, which are documented, or at least have a scientifically based possibility of being real.

9.1 CHARGING OF PERSONS

9.1.1 CHARGING BY WALKING

The most common way in which a person can become electrostatically charged is by walking across an insulative floor covering. We have already discussed the Physics of this problem in details (Chapter 6, p. 91). In the example shown in Fig. 6.12 the maximum (equilibrium) voltage of the person charged was about 3 kV, but under special conditions, especially very low relative humidity, voltages as high as 10 - 15 kV may be encountered. The often quoted upper value of 35 kV (see for instance Owen McAteer's *Electrostatic Discharge Control*, p. 356) is (even at very low humidity) in this author's belief apocryphal. Long before this value is reached, even if the charging conditions were optimal, corona and other types of discharges would start from the person's ears, nose or fingertips keeping the voltage down.

9.1.2 CHARGING FROM CLOTHING

It has often been claimed that wearing certain types of clothing, such as nylon fabrics, can charge a person electrostatically. This, however, can only happen under two conditions: 1) the clothing is rubbed against other surfaces in the surroundings, for instance a chair seat. If a person wearing insulative outer wear gets up from a chair, his voltage may be as high as that from walking on an insulative carpet. 2) the insulative piece of clothing is completely removed from the body. The effect of this kind of charging is what you experience when you take off a sweater or blouse and hear a crackling or feel a discharge to your ear. What you hear or feel is not the charging, quite the contrary, it's the discharging and partly neutralizing of the charges being separated by removing the clothing. This also explains why the very wearing of insulative clothing does not cause a charging of the person. Although the various layers of

clothing may rub against each other and cause a charge separation, the charge on the person caused by the clothing will essentially be the sum of equally large opposite charges and thus not contribute to the total voltage of the person.

9.1.3 OTHER MODES OF CHARGING

People may, however, also be charged in other ways, primarily by contact with already charged materials. A well-known example is that of handling photocopies. When the copies leave the machine they will often be heavily charged, in spite of the use of passive and other ionizers. Even if the copies fall in a grounded metal tray they lose very little of their charge. A person picking up a bunch of such copies may cause a discharge between herself and the copies causing a part of the charge on the copies to be neutralized and an equally large charge going to the person (see also Fig. 8.23). The rest charge on the copies will induce a charge on the person. If she is standing on an insulative floor, she will be charged to a voltage caused by a charge almost equal to the total charge on the copies.

There are many other examples of, direct or inductive, charging, such as pouring of insulative powders or liquids from hand-held containers, or just by standing near a charged sheet of plastic. If the person performing these tasks is not properly grounded, this may result in a considerable body voltage.

9.2 EFFECTS OF CHARGES ON PERSONS

An insulated, charged person may, like any other insulated, charged conductor produce a discharge, for instance a spark, through the surrounding air or cause a current pulse through some suitable conductive grounding path. These phenomena have already been discussed in Chapter 6. In this chapter we will concern ourselves with the effect of the charges on the person herself.

9.2.1 ELECTRIC SHOCKS

The best known and most direct effect of an electric charge on a person is the shock the person may experience by discharging to a grounded, or at least uncharged, conductor or to another person.

A person may walk around a floor charged to a voltage of, say, 5 kV without any discharge taking place, because the breakdown field strength is not exceeded in any point. If she now reaches for a door handle the field around her hand (or maybe around her fingertips) will be distorted, the breakdown field strength may be exceeded, a discharge may occur and the person may feel an electric shock. The level of body voltages at which these shocks become noticeable or even unpleasant has often been discussed and it is fair to say that this is a very individual and uncertain matter.

It can be mentioned that at levels of about 300 V or lower no sparks can occur at all (see Paschen's law, p. 66). At such low voltages the breakdown distance is too low to allow the ionization to develop to a spark.

There are very few investigations on the question on (non)acceptable body voltages, the main reason being that test persons probably react differently if they know they are going to experience an electric shock, than if they get the shock without expecting it. Such tests should therefore preferably be performed as an undisclosed part of completely different experiments. It does seem, however, that hardly any people will feel discomfort at discharges from voltages around 1000 - 1500 V.

At 2000 V many people start complaining, and above 3000 V almost everybody will characterize the shocks as unpleasant.

There is also some indication that women seem to be more sensitive to electric shocks than men, i.e. they can detect discharges at lower voltages. This, of course, does not necessarily mean, that they also complain more than men do.

9.2.2 INDIRECT EFFECTS

It has often been suggested that static electric charging of people might have other effects, than the purely physical ones, described above; effects that could rather be considered physiological or hygienic.

Many people may feel discomfort in certain types of dwellings, they get headaches, feel tired, get dry skin or mucosa, the air is stuffy etc., and at the same time they may experience static electric chargings in the form of electric shocks.

And often the two types of phenomena are tied together, and the static charging is considered to be the cause of the lack of well-being. However, it should be stressed that there are no trustworthy scientific

investigations suggesting any direct physiological or hygienic effects of a static charging of people.

There is, however, one way in which a static charging of a person may indirectly lead to a physiological effect, namely through the electric field surrounding the charged person.

9.3 ELECTRIC FIELD AND AIRBORNE PARTICULATES

It has been demonstrated that an operator exposed to the (positive) field from a computer monitor may experience a considerably increase in the plateout of airborne particulates on her face.

The particles do not necessarily have to be (negatively) charged, although such particles obviously will be moved in the field, but also such particles which can be polarized (or even are conductive) will move along the field lines in the direction where the field increases, i.e. towards the face of the operator. (see plateout of airborne particles, p. 76). But the same kind of effect can obviously happen, if the person is charged, and thus surrounded by an electric field, and the static charge may thus cause airborne particles, some of them harmless, some of them possibly less innocent, to deposit on exposed skin.

It should be stressed, that it has not been scientifically shown, that the effect described above, has led to increases in skin diseases.

But the possibility does exist.

One more thing should be mentioned in this context. While a person sitting in front of a computer may be exposed to a field of 20 kV/m or more for periods of several hours, an electrostatically charged person will only be surrounded by a strong field as long as she is highly charged, and it should be remembered, that any time she receives an electric shock, she is instantly brought to zero voltage, and the field effect disappears. The high voltage and the strong field will normally exist only in relatively short periods.

9.4 ELECTRIC FIELDS AND IONS

The field around a charged person will obviously also affect the ions in the air. If the person is negatively charged more positive and fewer negative ions will plateout on her skin, but more interestingly is it, that the number of ions of both polarities, inhaled will be lower than if the

person is not charged. In the case of a negatively charged person, negative ions will be repelled and positive ions will be attracted to the skin and thus moved out of the air flow to the nostrils or the mouth.

If thus the number of ions inhaled has any physiological or other significance an electrostatic charge of the person may interfere with this. Almost from the discovery around 1900 air ions have been attributed rather specific as well as more diffuse effects on people's well-being.

Let us mention an example on each of these types of effects.

It was long claimed that an excess of negative ions in the inhaled air would increase the frequency of the mucociliary function in trachea and thus enhance the natural cleaning of the airways. And an excess of positive ions would have a corresponding detrimental effect.

As an example of a more diffuse effect can be mentioned that it has often been claimed that air with an excess of negative ions is fresh, while positive ions make the air heavy and stuffy.

Unfortunately neither of these, or any other, alleged effects of ions in the inhaled air, have ever been satisfactorily scientifically documented.

As far as the cili-effect is concerned, it was on the contrary proven without doubt not to exist as long back as 1971, but funny enough the claim of the effect still appears now and then.

As far as the negative ions/fresh air claim is concerned, it should be kept in mind that the fresh air on a mountain top is rich in positive ions, while the stuffy air under and during a thunder storm has an excess of negative ions.

Obviously there is more to freshness and stuffiness than just the ions. But it is a fact that a charged person will inhale fewer ions of both polarities than an uncharged person, and the above considerations just serves to stress, that it has not yet been proven if this has any significance for your well-being.

In the next chapter on applications of static electricity an example on the use of ions and an electric field for air-cleaning will be discussed. The effect of this principle is sometimes misinterpreted as an effect of ions being inhaled.

In conclusion of this chapter it should be mentioned that atmospheric ions may have a more indirect physiological effect by just being carrier of a charge. It seems like a flow of ions to the skin of a properly grounded person has a beneficial effect on a variety of ailments, like the healing of wounds, maybe especially burns, on asthma and maybe even

on the side effects of chemotherapy and radiation treatment of cancer patients. It should be stressed that investigations of such effects have not been performed in recognized laboratories nor reported in the usual scientific reviewed journals.

That is, not yet.

But it seems that within the year of 2002 a study of the possible effect of this kind of treatment on the side effects of various cancer treatments will start at one of the very prestigious university hospitals in Asia.

Chapter 10

APPLICATIONS OF STATIC ELECTRICITY

In the previous chapters we have discussed the effects of mostly fortuitous static charge distributions and most of the time we have considered the concepts of static electricity and static electric fields as one of nature's more useless whims only causing inconveniences to mankind. But this attitude is not really fair. An increasing number of important processes, industrial as well as some at a more modest scale, are totally or in part based on electrostatic phenomena. Although the use of these processes is common and widespread, many people do not realize their static background. Among the many examples of such processes let us mention: *precipitation of airborne particulates, separation of different materials, electrostatic surface treatment (with liquids as well as powders) and electrostatic copying and printing.* Of more specific applications are constructions like: *electrostatic generators, motors, speakers and microphones.*

Many electrostatic processes involve the handling of very small and light particles and the following features are common and characteristic for such processes.

- the force from an electric field on a small charged particle may be much larger than gravity;
- it is very easy to monitor the electric force by monitoring the applied field;
- the electric forces acting upon airborne particles interfere insignificantly with the air and its movement.

With practically all applications of static electricity one or more materials have to be electrified. The electrification may take place in several ways of which the more important ones are:

- corona electrification
- contact and triboelectrification and
- polarization or induction in an electric field.

Often two or more electrification processes are active. For some of the

fields of application mentioned here we have, for example:

- *precipitation: corona,*
- *separation: corona and triboelectrification,*
- *surface treatment: contact and triboelectrification and induction,*
- *copying and printing: corona, triboelectrification, induction and conduction.*

10.1 PRECIPITATION

Many industrial processes produce airborne particulates to an extent and of various kinds that makes it necessary to clean the air before it is being released. A prime example of this is the production of fly ash in coal-fired electric power generation, but steel and cement production, fertilizer processing, and many other chemically oriented processes also create particulate air pollutants on a large scale.

And even in the household, every day activities like cooking and cleaning, not to mention smoking, will produce particle concentrations in the air at often unacceptable levels.

Although particulates may be removed from the air by mechanical filters, it should be stressed that, especially as far as the industrial pollution is concerned, the use of electrostatic precipitation is by far the most important remedial method.

Electrostatic precipitation is also the oldest application of static electric principles to be put to industrial use, going back to Cottrell, who built his first precipitator in 1907.

10.1.1 ELECTROFILTER

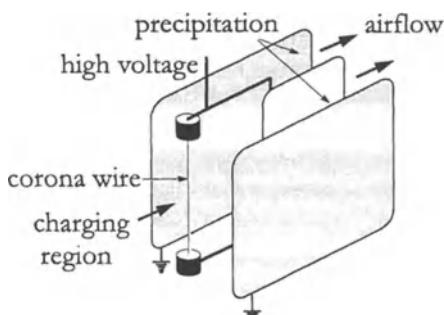


Fig. 10.1

The basic principle of an electrostatic precipitator or electrofilter, be it used in a power plant or in the living room, is shown in Fig. 10.1.

A (series of) thin wire(s) are kept at a high potential with respect to ground, causing a corona discharge to take place in a thin sheath around the wire.

If the wire is kept a positive potential the positive ions formed will move away from the wire to grounded surroundings.

The air to be cleaned is drawn past the corona wires and the ions will tend to attach to particles in the air.

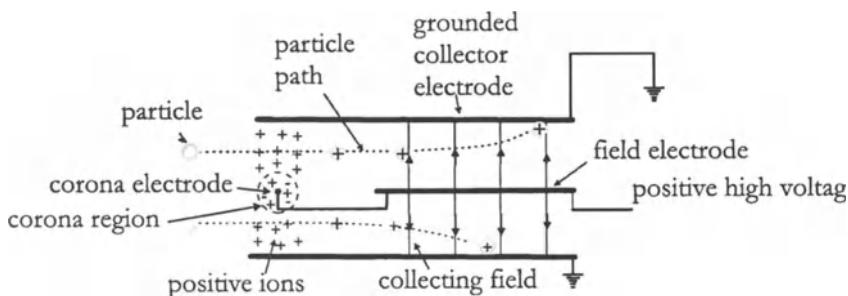


Fig. 10.2

The charged particles are carried into a precipitation volume, Fig. 10.2, where an electric field is established between a series of electrodes alternately grounded and kept at the same polarity as (but often lower potential than) the corona wires.

The particles will be moved towards and deposit on the grounded electrodes from where they can later be removed by various means, depending on the type of filter.

In industrial plants you may have to use big mechanical shakers and scraping arrangements, with household devices it may be enough to place the filter unit in the dish washer every second week.

An electrofilter may be operated at positive as well as negative voltages. For a given voltage the corona current, and thus the ionization, is higher at negative voltages, but as explained earlier so is the ozone production. The efficiency of an electrofilter may be close to 100 %, as far as particles above approximately $0.5 \mu\text{m}$ are concerned, in the sense that such particles are effectively removed from the air passing the filter.

But obviously the effect of an electrofilter on a given source of air pollution, like smoking, is also determined by the filtration rate, i.e. the volume of air passing the filter per unit time and especially this figure taken relative to the volume of the room to be treated and the strength of the pollution source.

The advantage of an electrofilter is obviously that the particulate material plated out is deposited inside the filter from where it can be

more or less easily removed.

A disadvantage is that the functioning of the filter requires the operation of a fan which involves some power consumption and a certain amount of noise.

10.1.2 OPEN FIELD IONIZER

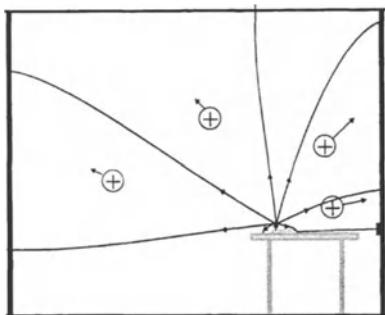


Fig. 10.3

An open field ionizer is essentially a corona electrode, in the shape of a sharp metal needle or a bundle of thin carbon fibers, connected to a high voltage supply, and placed unscreened in a room, Fig. 10.3

The electrode, somewhat misleadingly called an *emitter* (p. 111), will be surrounded by an electric field extending to all grounded surroundings, including the faces of the room, furniture and people.

If the potential of the emitter is high enough ($\approx 2 - 20$ kV) ions of both polarities are formed in a small volume in front of the emitter and the ions of same polarity as the emitter will move away along the field lines. If the ions on their way meet airborne particles they may attach to these, thus charging the particles.

And these charged particles will now move (slowly) and eventually plate out on the surfaces where the field lines end.

An open field ionizer thus operates on the same basic principles as an electrofilter.

Both devices remove particulates from the air by 1) creating ions by a corona discharge, 2) charging the particulates, and 3) moving the charged particles out of the air by the action of an electric field.

But while an electrofilter deposit the particles in a well-defined region from where they can be removed, the plateout of particles caused by an open field ionizer takes place in a more incidental way and often in a very uneven pattern.

The plateout rate will be high at such surfaces where the field strength is high, i.e. in the neighborhood of the ionizer, and the result is often an unattractive smudging of the surroundings of the ionizer. It is, however,

possible to reduce this effect by the use of a suitable counter electrode, a so-called collector.

It should be stressed that although a collector reduces the ionizer-near smudging the major part of the particles still plate out on the walls, ceiling etc.

The advantages of an open field ionizer over an electrofilter are the small size, the low power consumption and the noiselessness.

An open field ionizer works equally well with negative and positive voltages with the exception of the case where the purpose is to remove the short-lived airborne daughter products of radon.

For this purpose positive fields and ionization are by far the most effective.

It has sometimes been claimed that an open field ionizer is suited for neutralizing static electric charges.

This is not the case. Because an open field ionizer produces ions of only one polarity there is even a risk that the operation may charge a material instead of neutralizing it.

10.2 SEPARATION

The principle of electrostatic precipitation, as explained above, is a charging of airborne, solid or liquid, particles with the same polarity which consequently makes them move in the same direction in an electric field. The principle of electrostatic separation, on the other hand, is by various means to charge the components in particulate mixtures with opposite polarities (or leave conductive components

uncharged), and subsequently separate the components, by mutual repulsion or by an external electric field, and possibly aided by gravity.

In Fig. 10.4 is shown a so-called drum-separator.

A mixture of conductive and insulative particles are fed from a hopper onto the grounded drum.

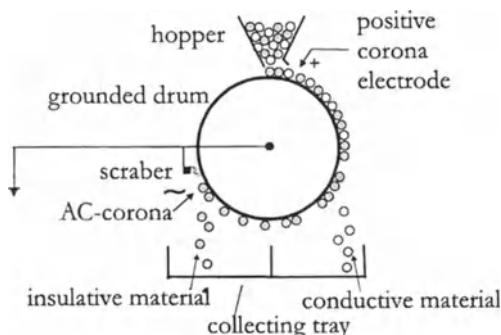
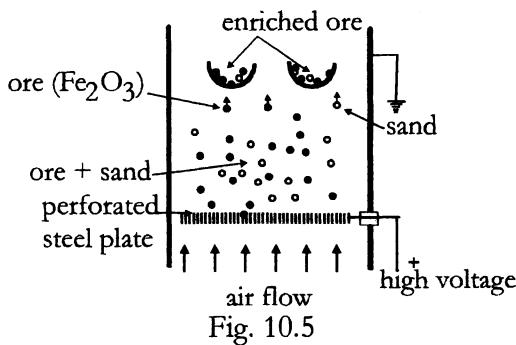


Fig. 10.4

All the particles are charged by a corona discharge, positively in the case shown. When the particles leave the corona region, the conductive particles loose their charge to the drum and move away by gravity (and "centrifugal" forces).

The insulative particles stick to the drum until they are removed by a brush or scraber, possibly assisted by an AC-corona discharge.

Often the charging of particles to be separated is achieved by contact between the different particles or between the particles and an external material. The exchange of charge depends upon factors like the properties of the materials themselves, the state of their surfaces and external parameters like electric fields and temperature gradients across interfaces. When the particles are separated a part of the charges exchanged may remain on the respective surfaces, and the motion of the particles may be controlled by an electric field.



In Fig. 10.5 is shown an example on the application of this principle in the electrostatic separation of iron ore from sand by the use of a fluidized bed.

Under certain temperature and humidity conditions iron ore in the

form of Fe_2O_3 will charge positively because of triboelectric effects by contact with steel as well as sand.

The mixture of iron ore and sand is fluidized over a perforated plate of stainless steel by means of an air jet. The steel plate is kept at a high potential creating an upward electric field in the fluidization region.

The positively charged Fe_2O_3 -particles will move upwards because of the field into the transport region where they can be collected in various ways, for instance on conveyer belts running over grounded rollers.

The Fe_2O_3 -particles, being somewhat conductive, will get an extra (field induced) positive charge by contact with the positive steel plate, but the sand, principally consisting of insulative SiO_2 -particles, may by contact with the steel charge positively as well as negatively, and primarily through triboelectric effects.

As a result the ore collected has a much higher relative content of iron than the untreated ore, as the negatively charged sand particles are being retained.

If the polarity of the steel plate is changed to negative the efficiency of separation is drastically reduced because the field induced charging of the Fe_2O_3 -particles is partly neutralized by the triboelectric charging.

<i>asbestos/silicates</i>	<i>limestone/silicates</i>
<i>coal/pyrite</i>	<i>nickel/copper ore</i>
<i>coal/shale</i>	<i>zirkonium/sand</i>
<i>cobber ore/silicates</i>	<i>cocoa beans/shells</i>
<i>coke/iron</i>	<i>cotton seeds/stems</i>
<i>diamonds/silicates</i>	<i>photographic film/paper</i>
<i>feldspar/quartz</i>	<i>nut meat/shells</i>
<i>Fly ash/carbon</i>	<i>polyvinyl/polyester</i>
<i>iron/silicates</i>	<i>grain/garlic seeds</i>
<i>kaolin/iron contaminations</i>	<i>barley, rice, soybeans/rodent excrements</i>

Table 10.1

Table 10.1 shows a few of the very large number of mixtures of materials in particle form which can be separated electrostatically with a commercial benefit.

10.3 COATING

Almost all articles and products manufactured and used today have been coated in one or more ways. This is true for the paper we write on, the clothes we wear, the cars we drive, the furniture we sit in etc.

For practical, economic, and environmental reasons, it is desirable to use only the necessary amount of material, and this consideration makes electrostatic coating superior to most other methods.

An electrostatic coating process may take place in the following manner. The object to be coated is placed in such a way that its surface is freely accessible. The coating material is rendered airborne in the form of small particles, liquid or solid, in the region in front of the object. The particles are charged with one polarity and the object with the opposite

out on its surface.

There are a series of variations of this process, and we shall here discuss only a single example, where the coating material is in liquid form, Fig. 10.6.

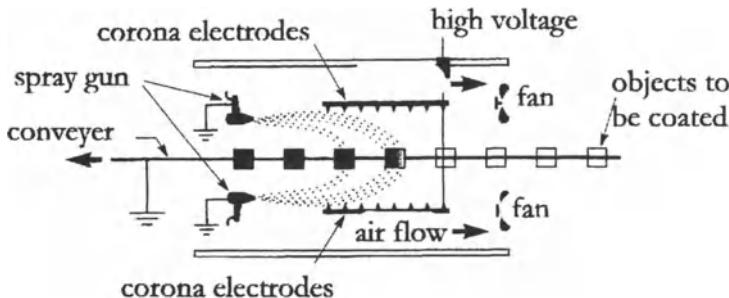


Fig. 10.6

The objects to be coated are placed on a grounded conveyer system which will bring them close to a system of corona electrodes connected to a suitable high voltage supply (for instance 100.000 V). The ions formed by the corona discharge will move in the field towards the grounded objects. A fine mist of the coating material is sent from one or more spray guns into the ionization region, where the droplets will catch ions from the air, become charged and move onto the grounded objects. It follows from the explanation above that the objects to be coated has to be (somewhat) conductive. In many cases this can be achieved, even with normally insulative materials, by working at a temperature of a few hundred degrees centigrades.

As suggested in Fig. 10.6 the air is sucked past the moving objects with a velocity in the opposite direction. A charged particle will thus move because of the air flow as well as because of the electric field. Because the field lines end on all parts of the surface of the object, although very unevenly, also such area which, so to speak, are in the shade will also be coated. Often the objects to be coated are rotated during the passage of the field in order to make the coating more even.

The advantage of an electrostatic surface coating over for instance traditional spray painting lies partly in the ability of the field to reach and coat areas in the dark and partly in a very essential reduction in the necessary amount of coating material. It is characteristic for the example

shown that the droplets are formed by spraying, charged by ion capture, brought into the electric field by an air flow, and deposited by a combined effect of the field and the air movement. The spraying will, however, cause a certain waste of coating material. In order to reduce this waste the particles may be formed at a relative low velocity in a strongly divergent field. In this way the particles may be charged from the start and move primarily by field forces towards the objects to be coated.

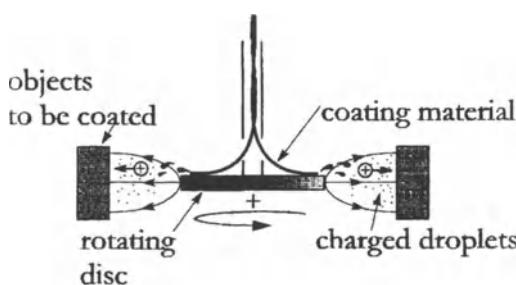


Fig. 10.7

In Fig. 10.7 is shown an example on an electrostatic spray device based on this principle. A disk is made to rotate around a vertical axis at, say a couple of thousands revolutions per minute. The coating material is fed to the center of the disk and will, because of

the rotation, spread across the disk and leave the rim as irregular drops because of the "centrifugal" force (or rather the lack of centripetal force). If the disk is given a high voltage with respect to the surroundings, the field at the rim will be strongly inhomogeneous; this will cause the drops to be charged by induction and split up in small droplets each carrying a large charge. The objects to be coated are kept at ground potential and brought into the field by a conveyer in a circle around the disk while rotating slowly. If there was no electric field the coating would only apply in a narrow band on the objects, but because of the field the coating may spread out to a width on the order of half the distance between the disk and the objects.

There is no fundamental reason that the material to be deposited electrostatically has to be in liquid form, and there are actually many processes where the deposition of a powder on a surface is governed or enhanced by electric forces. The powder may be made airborne for instance by the use of a fluidized bed or by a disk system similar to the one shown in Fig. 10.7

10.3.1 MANUFACTURING OF SANDPAPER

A surface coating of a completely different type from the ones described above is the manufacturing of sandpaper. In Fig. 10.8 is shown the principle of this process.

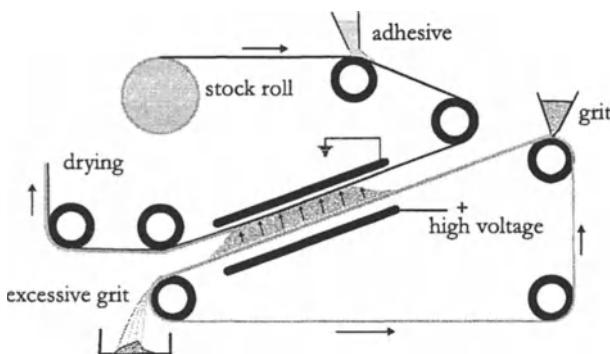


Fig. 10.8

By help of two plane electrodes, one grounded, the other connected to a high voltage supply, an electric field is established.

A continuous

belt of a suitable (semiconductive) material passes through the field in contact with the lower electrode. The paper or textile to become the backing of the sandpaper is fed from a stock roll through the field in contact with the upper electrode. Before the paper enters the field a layer of adhesive is placed on the side of the paper that will face downwards. The abrasive, for instance sand or ground agate, is fed from a hopper onto the lower belt outside the field. When the abrasive enters the field the grains will be polarized and also charged directly with the same polarity as the lower electrode. The grains may align their longest axis with the field and when the field strength is high enough (about $1 \text{ MV}\cdot\text{m}^{-1}$) they will move towards the upper electrode and embed themselves in the adhesive with a sharp tail sticking out. If a grain hits a point already occupied by another grain, the late arriver will be neutralized and charged with the opposite polarity, repelled and move back to the lower belt, where the process may start all over again. When the grit-covered face leaves the field, loose material is removed by means of a shaker, and the adhesive set in a drier.

The electrostatic deposition of the abrasive will give a more uniform distribution and a more beneficial orientation of the single grains than is possible by a purely mechanical process.

10.4 FLOCKING

Flock is made by gluing bundles of aligned, short fibers, for instance of nylon, onto a suitable material. By cutting the fibers to the same height a suede- or felt-like material is produced. The quality of the material depends upon how evenly and parallel the fibers are distributed and oriented, and by using a principle very much like the one described above for sandpaper a high degree of uniform distribution and parallel orientation can be achieved. By shaping the electrodes, and thereby the orientation of the field lines, in a suitable way, it is possible to produce patterns and lettering, as used for instance, on sweaters and "brocade" wallpaper.

10.5 IMAGING

The distribution of a static charge on an insulative surface may be extremely inhomogeneous, and over the years many attempts have been made to visualize this distribution. The best known method was the application of fine powders like lycopodium or resin.

Conversely a related process is to try to transfer the differences in printing or drawing density of an ordinary picture or drawing to differences in charge density on a suitable surface. If subsequently this electric picture can be transferred back to a visible image on a sheet of paper or a screen, we have an electrostatic copy of the original picture.

This can be done in several ways. We shall here only give the main features of the electrophotographic process known as xerography.

Xerography is based on the physical phenomenon called photoconductivity, i.e. some materials have a much higher conductivity when they are exposed to light than when they are in the dark. This is the case for a material like selenium (amorphous), but also several chemical compounds, like zinc oxide (specially treated) can be used.

Let us consider a sheet of paper of a suitable high conductivity, covered by a layer of zinc oxide. The backside of the paper is placed in contact with a grounded conductor, Fig. 10.9a. By means of a corona wire at a positive direct voltage of for instance 5 kV the zinc oxide-layer is charged with a positive charge, while kept in the dark. This charge binds by induction an equally large negative charge in the paper, and the resulting field in front of the layer is therefore very weak. As long as the

will recombine very slowly.

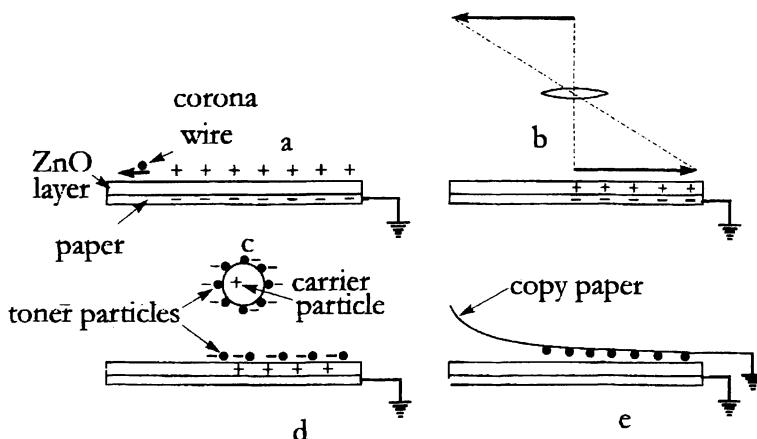


Fig. 10.9

A picture of the object to be copied is now formed briefly on the zinc oxide by a suitable optical system, Fig. 10.9b.. On the areas exposed to the light the charges will disappear (combine), partly or totally, and what is left is a charge distribution corresponding to the distribution in density of the optical picture. Apart from the brief exposure the zinc oxide is kept in the dark during the rest of the process.

The "electric picture" is now brought into contact with a so-called toner consisting of small (about $1 - 10 \mu\text{m}$) plastic particles to which is added carbon. The toner particles are charged negatively by mixing with larger (about 0.5 mm) carrier particles of glass or plastic-covered glass. The mixing will charge the carrier particles positively and cause the toner particles to form a thin layers on the carrier particles, because of the attraction between the opposite charges, Fig. 10.9c. When these larger particles (toner + carrier) are brought into contact with the zinc oxide the negatively charged toner particles will stick to the positively charged areas, while the carrier particles fall off, and we thus have an (inverted) copy of the original object, Fig. 10.9d.

The last step in the process consists in transferring the inverted picture to another surface, usually paper, as a noninverted copy. This can be done by bringing the (copy)paper into contact with the zinc oxide, while the back of the paper is grounded, Fig. 10.9e. This will pull the toner particles onto the paper because of the attraction to an induced charge

the back of the paper is grounded, Fig. 10.9e. This will pull the toner particles onto the paper because of the attraction to an induced charge in the paper. And finally the paper is heated to fuse the toner particles to its surface, and we have the final copy.

It should be stressed that the whole process is much more complicated than suggested here, and many of the subprocesses may take place in completely different ways from those explained above.

10.6 PERMANENT POLARIZATION, ELECTRETS

It was mentioned earlier (p.22) that a dielectric exposed to an electric field will be polarized. We can also state this by saying that the external field will be superimposed by a (dipole) field from the dielectric. Normally the polarization will relax and the field will disappear when the dielectric is removed from the external field.

In certain materials, however, it is possible to maintain the polarization without the presence of an external field, and such a permanently polarized material is called an **electret**. The methods for the actual polarization or charging of electret materials will not be treated here, but we will discuss the properties and a few applications of electrets.

A practical electret will often be a thin (maybe 20 - 100 μm) sheet of, for instance, Teflon (polytetrafluoroethylene) backed by an aluminium foil.

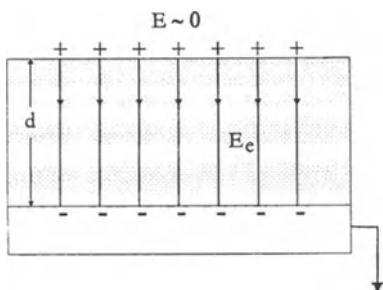


Fig. 10.10

In Fig. 10.10 is shown an electret with the thickness d and the relative permittivity ϵ_r . The backing foil is grounded and the electret is polarized (charged) with a surface density σ . The distance to grounded surroundings is x and it is assumed that $x \ll d$.

The field strength inside the electret is then

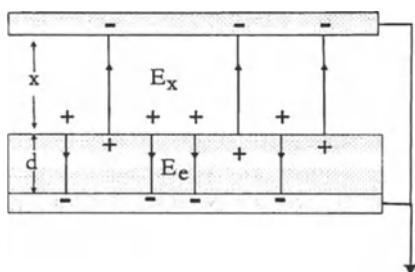
$$E_e = \frac{\sigma}{\epsilon_0 \epsilon_r} \quad (10.1)$$

and the field on the free side of the electret is negligible since the distance to ground through the air is much larger than the thickness of the electret.

The electret will have a surface potential

$$V_s = E_e d = \frac{\sigma d}{\epsilon_0 \epsilon_r} \quad (10.2)$$

If the distance to grounded surroundings is of the same order of magnitude as the thickness of the electret the conditions are somewhat more complicated.



In Fig. 10.11 is placed a grounded counter electrode parallel with the electret in a distance x from the charged surface.

The electric field E_x in the air can now be written

Fig. 10.11

$$E_x = \frac{\sigma}{\epsilon_0 \left[\epsilon_r \frac{x}{d} + 1 \right]} \quad (10.3)$$

and the surface potential is

$$V_s = E_x x = \frac{\sigma d}{\epsilon_0 \left[\epsilon_r \frac{x}{d} + 1 \right]} \quad (10.4)$$

Most applications of electrets are based on the utilization of the effect of the external field, as given by (10.3).

10.6.1 RADIOLOGICAL EXPOSUREMETER

If an electret of the type shown in Fig. 10.11 is placed in a location where radioactive gases (normally radon) create an (essential) ionization in the air, the field E_x will make (negative) ions move to the charged

surface and cause the surface potential V_s to decrease with a rate proportional to the ionization rate and hence, under given radioactive conditions, with the radioactive exposure. The surface potential is measured by a field meter through an opening in the counter electrode. Although the device measures the exposure it is often erroneously called a dosimeter.

10.6.2 ELECTRET MICROPHONE

One of the most important applications of electrets is as the active element in sensitive microphones, Fig. 10.12.

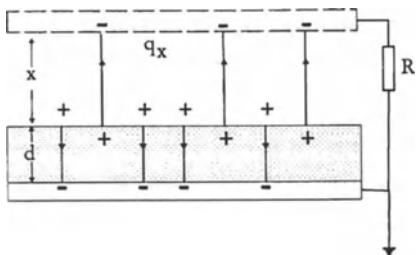


Fig. 10.12

The counter electrode is a porous metal plate at the distance x from a membrane, consisting of the charged electret sheet. The counter electrode is connected to ground through a resistor with the resistance R .

When the membrane is at rest, the potential of the counter electrode is zero, and the field

strength E_x is given by (10.3).

If the area of the counter electrode is A a charge q_x is bound on the electrode, and, according to (2.9) given by

$$q_x = A\epsilon_0 E_x = A\sigma \frac{d}{\epsilon_r x + d} \quad (10.5)$$

The polarity of q_x is opposite of that of σ .

If now the membrane is brought to oscillate, for instance by being hit by a sound wave, the distance x and thus the charge q_x will vary with time.

Let us assume that

$$x = x_0 + a \cdot \sin \omega t \quad (10.6)$$

and that the amplitude a is much smaller than x_0 .

The charge q_x will thus vary with time and through R will flow a current I_x given by

$$I_x = \frac{dq_x}{dt} = (-) \frac{A\sigma\epsilon_r a\omega}{(\epsilon_r x + d)^2} \cos \omega t \cong I_0 \cos \omega t \quad (10.7)$$

where the amplitude I_o of the current is given by

$$I_o = \frac{A\sigma d \epsilon_r a \omega}{(\epsilon_r x_o + d)^2} \quad (10.8)$$

Across the resistor R will appear an alternating voltage with the amplitude

$$V_o = I_o R \quad (10.9)$$

and this voltage may be amplified in a conventional way.

It appears that the microphone works without any external voltage supply, and it is believed that the electret will easily remain active as long as the rest of the microphone is in working condition.

GLOSSARY

air ion

An air ion (or atmospheric ion) is a molecular cluster of 10-15 molecules (mostly water) around an oxygen (negative ion) or nitrogen molecule (negative or positive) having gained or lost an electron. An ion is characterized by its **mobility**. The mobility of a negative air ion is about $1.8 \cdot 10^{-4} \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$ and of a positive ion about $1.4 \cdot 10^{-4} \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$.

See also ionization

ampere, A

fundamental unit (in SI, international system of units) for electric current, defined by the forces between parallel wires carrying DC-currents.

antistatic agent

Substance to be applied to insulative material to make it sufficiently conductive. Surface-active antistatic agents (for instance quaternary ammonium halogenides) form a thin layer on the surface; this layer will attract moisture from the surrounding air. Bulk-active agents (often amines or amides) are compounded with a polymere and will diffuse to the surface where it attracts moisture (pink poly). In some materials (for instance rubber and many plastics) conductivity may be increased very substantially by adding of carbon black.

antistatic material

Old designation for material with **surface resistivity** $\rho_s < 10^{10} \Omega$. Often used colloquially for materials which do not retain static charges.

astatic material

Old designation for material with a surface resistivity
 $\rho_s = 10^{10} - 10^{14} \Omega$.

breakdown, electrical

If the field strength exceeds the **breakdown field strength** along some path from a charged conductor to ground (or to a conductor at a different potential), ions are formed along the whole path resulting in an electrical breakdown.

breakdown field strength,

Field strength at which incidental electrons in a dielectric, for instance air, receive sufficient energy over their mean free path to cause ionization by collision.

Breakdown field strength (between plane electrodes): air = $3 \cdot 10^6$ V·m⁻¹, plexiglass = $4 \cdot 10^7$ V·m⁻¹

breakdown voltage

Minimum voltage between insulated conductor and ground (or between two conductors) where **breakdown field strength** is exceeded along some path.

brush discharge

Electrical discharge between electrode of small radius of curvature (a few millimeters) and ground along irregular, luminiscent paths. Low energy density. May ignite certain vapor/air mixtures.

capacitance

An insulated conductor has a capacitance C with respect to ground if a charge q raises the conductor to a voltage V related by $q = CV$. Unit for capacitance is farad (F) defined by:

$$1 \text{ farad} = 1 \text{ coulomb/volt.}$$

The concept of capacitance can only be applied to insulated conductors. In electrostatic context most capacitances are in the order of 10 - 1000 pF, i.e. 10^{-11} - 10^{-9} F.

capacitor

In static electric context any insulated conductor is a capacitor, with a certain **capacitance** with respect to ground.

carbon black *see antistatic agent***CDM** *see charged device model***charge**

Property of certain elementary particles, primarily electrons (negative) and protons (positive). Opposite charges (positive/negative) attract each other, like charges (positive/positive and negative/negative) repel each other.

Unit for charge is coulomb (C) defined by

$$1 \text{ coulomb} = 1 \text{ ampere} \cdot 1 \text{ second}$$

All electrical phenomena are caused by inter-charge forces. *See also electric field.* A body is negatively charged if it has an excess of electrons, positively charged if it has a deficit of electrons.

charge carriers (mobile)

All materials contain mobile charge carriers to some extent. In metals the carriers are electrons in plentitude, in electrolytes and air, they are ions (although very different in character), and in insulators and semiconductors they are holes (or electron vacancies) in widely varying concentration.

See also mobility

charge decay

A charge located on an insulator or insulated conductor will gradually be neutralized by attracting oppositely charged charge carriers. Except for a negatively charged conductor (where the charge is electrons) a charge may never be literally removed from a charged body. The **decay rate** depends upon the **resistivity** of the contacting medium and upon the geometry of the set-up.

charge density

The concentration of charge on a surface determines the **field strength** in front of the surface. Maximum charge density in atmospheric air at the surface of conductor is about $3 \cdot 10^{-5} \text{ C} \cdot \text{m}^{-2}$.

charged plate monitor, CPM

Instrument for comparing efficiency of different ionization systems. A bare metal plate with capacitance $\sim 15 \text{ pF}$ is charged (e.g. to 1000 V) and its voltage is monitored as a function of time by a field meter or non-contacting voltmeter

charged device model *see ESD damage models***conductance** *see Ohm's law***conductive material**

Material with **surface resistivity** $\rho_s < 10^5 \Omega$.

conductivity

Reciprocal of **resistivity**. Unit for conductivity is $\Omega^{-1} \text{m}^{-1}$.

See also resistivity, resistance, surface resistivity, Ohm's law.

conductor

Body made of material with (bulk) **resistivity** lower than about $10^{-6} - 10^{-7} \Omega \text{m}$. Most conductors are metals.

contact electrification

Charging of materials primarily by contact, caused by difference in work functions. *See also triboelectrification.*

corona discharge

Electrical discharge from conductive electrode (sharp point or thin wire), where the **breakdown field strength** is exceeded in a small region in front of the electrode and where positive and negative ions are formed in equal numbers. Also called silent discharge. Low energy density. A corona discharge can not ignite any vapor/gas mixture.

coulomb, C

Unit for charge defined by 1 coulomb = 1 ampere · 1 second.

see also charge

current, current density

Transport of charge caused by an electric field. Unit for current is **ampere, A**. Current density is current per unit area perpendicular to direction of current, unit: **A · m⁻²**.

D-field *see dielectric displacement***D-flux** *see flux***decay rate**

Rate of **neutralization** of field from charge on a body. In the case of a capacitive system with the capacitance C and grounding resistance R the charge will be neutralized exponentially according to the formula

$$q = q_0 e^{-\frac{t}{\tau}}$$

where the **time constant** τ is given by $\tau = RC$. In the case of a material with a (bulk) resistivity ρ and permittivity ϵ a charge will be neutralized exponentially with the time constant $\tau = \rho\epsilon$. τ is the time it takes the charge to decay to $1/e \sim 0.37$. In case of surface charge decay the decay rate can not be predicted from material parameters.

decay of charge *see charge decay***dielectric**

Material which is being polarized (i.e. **dipoles** being formed) when exposed to an electric field. The name dielectric is normally used only on polarizable insulators. If a field E from a constant charge is being filled by a dielectric the field strength is reduced by a factor ϵ_r , the **relative permittivity** or **dielectric constant** characteristic for the dielectric. *See also polarization, permittivity*

dielectric constant

see dielectric

dielectric displacement, electrical field density, D

Quantity characterizing the ability of an electric field to cause **induction**. An induced charge density σ is caused by a dielectric displacement $D = \sigma$. Unit for dielectric displacement: $C \cdot m^{-2}$. In isotropic media the dielectric displacement D is related to the electric field E by $D = \epsilon E$ where ϵ is the **permittivity** of the medium.

See also flux

dielectric strength

same as breakdown field strength

dipole

An electric dipole is a positive and negative charge of same numerical value at a fixed distance from each other. Dipoles are formed in **dielectrics** when these are exposed to an external field. The field from the dipoles will be superimposed on the external field resulting in a lowered field strength (for a fixed field-creating charge).

An airborne particle (dust) in an electric field will be polarized and form a dipole and move in the direction of (numerically) increasing field strength. *See dielectric*.

discharge

See brush discharge, corona discharge, spark discharge

E-field

See electric field

electret

Permanently polarized material, for instance Teflon. (approximately electrical equivalent of permanent magnet).

electric field

Region where an electric charge experiences a force (from other charges). If the force on a charge q is F the **field strength** E is defined by $F = qE$. Unit for field strength is newton/coulomb which is identical to volt/meter.

See also flux, breakdown field strength

E-flux

See flux

electrofilter

Device in which airborne particulates are being charged in a corona discharge and precipitated (plated out) by an electric field.

electrometer

Instrument for measuring voltage (difference) with very low current ($< \sim 10^{-15}$ A) passing through the instrument.

electrostatic energy

If a capacitive system with capacitance C is charged to a voltage V by a charge $q = CV$ the system stores an electrostatic energy

$$W = \frac{q^2}{2C} = \frac{1}{2}CV^2$$

which may be dissipated in a **spark** and possibly cause ignition of an explosive atmosphere.

see **ignition energy**

electrostatics, static electricity

The science of the effects of electric charges located on insulators or insulated conductors. These effects may well include the movement or displacement of charges, for instance by **induction**, **polarization**, **ionization** and **plateout**. The designation **static electricity** is sometimes used colloquially to mean primarily the harmful or unwanted effects of electrostatic charges.

elementary ion

Nitrogen or oxygen molecule having lost an electron (positive elementary ion) or oxygen molecule having captured an electron (negative elementary ion) before clustering with water molecules to form ordinary air (or atmospheric) ions.

emitter

Conductive electrode in the form of thin wire or sharp points. If emitter is held at a voltage of a few kV with respect to surroundings air ions are formed in a corona discharge in a small region in front of the electrode. If electrode is positive the positive ions are repelled as if they are emitted from the electrode, but the emitter **does not** emit ions, it collects ions, in this case negative ions. The ions are formed by the high field strength in front of the electrode, not by the high voltage.

electrostatic discharge, ESD,

Originally simply meaning any discharge caused by an electrostatic charge collection, whether in the chemical, textile or other industries. Today more or less copyrighted by the electronic industry to mean any kind of electrostatic problem involving semiconductor components or devices.

ESD

See electrostatic discharge

ESD damage models

There are two main circuit models for damaging components or circuits by an electrical discharge: the **human body model** imitating the effect of the discharge from a charged person, consisting of a capacitor (often 100 pF) with one terminal grounded in series with a resistor of $1000\ \Omega$; and the **charged device model** imitating the discharge from a charged insulated conductor consisting of a capacitor with one terminal grounded. Other models are the **charged device model** and the **field induced model**.

farad

Unit for **capacitance** defined by 1 farad = 1 coulomb/volt

faraday cage, faraday screen

Conductive enclosure that cuts off the (static) field from external charges.

faraday pail

Insulated conductive container to be connected to charge meter. When charged item is placed in pail the charge may be read on meter.

field

See electric field

field ionization

See ionization

field lines

Mathematical lines to give a qualitative impression of a field. A two-dimensional plot, however, will never give a true picture of a three-dimensional field.

field meter

Instrument for measuring electric fields. A field meter will normally distort the field to be measured and show a higher field strength than the undisturbed value. The reading of a field meter (determined by

the D-field rather than the E-field) refers to the field strength at the face of the sensor, not at the surface of the charged body.

flux

Surface integral of perpendicular component of a field over a surface S. Flux of electric field E

$$\Phi_E = \int_S E \cdot dS$$

If the surface S is a closed surface surrounding a charge q we have the **Gauss' theorem (or law)** for the E-field

$$\Phi_E = \int_{\text{closed surface }, S} E \cdot dS = \frac{q}{\epsilon}$$

where ϵ is the **permittivity** in the region of the surface S and correspondingly

for the D-field

$$\Phi_D = \int_{\text{closed surface, } S} D \cdot dS = q$$

Gauss' theorem (or law)

See flux

ground

Conductive region (not necessarily the earth) with sufficiently high capacitance relative to which potentials are measured and to which charges may decay.

hand-held meter

Instrument for locating electric charges by reacting to the electric field (or rather the D-field).

human body model

See ESD damage models

ignition energy

Necessary energy to ignite vapor/gas or dust (powder)/gas mixture. Minimum ignition energy for mixtures of many organic vapors (ethyl ether, acetone, cyclo propane etc.) with atmospheric air is about

0.2 mJ, with pure oxygen about 1 μJ . Minimum ignition energy for powder/atmospheric air mixtures about 10 - 100 times higher.

incendiveness

The ability of an electrical discharge to start an ignition or explosion in a gas/vapor or dust/vapor mixture.

See ignition energy, corona discharge, brush discharge, spark discharge

induction

An electric field E will induce and bind a charge q with the surface density

$$E = \sigma/\epsilon$$

on a conductor placed in the field. If the conductor is grounded, a charge $-q$ will leak to ground. If the conductor is insulated the charge $-q$ will charge the conductor to a certain voltage although the total charge on the conductor is zero. Electrostatic induction should not be mistaken for electromagnetic induction involving changing magnetic fields

See also polarization.

insulative material

Material with surface resistivity $\rho_s > 10^{12} \Omega$.

ion

See air ion

ionization

When an electron is knocked off an oxygen or nitrogen molecule an elementary positive ion is formed, which will attract 10 - 15 molecules (mostly water) forming a cluster called a positive air ion (or positive small ion). The electron attaches to an oxygen molecule to form an elementary negative ion, which attract a little fewer water molecules to form a negative air ion (or small negative ion). Ions are always formed in pairs (positive/negative). Necessary energy to form an ion (about 34 eV or $5.4 \cdot 10^{-18} \text{ J}$) is delivered by radioactive radiation or by electrons accelerated in electric field.

See air ion, ionizer

ionizer

Device to produce air ions.

Radioactive (nuclear) ionizer contain an alpha-active nuclide, often polonium (Po). Each alpha particle (energy $\sim 5 - 7 \text{ MeV}$ (0.8 -

$1 \cdot 10^{-12} \text{ J})$ produces 150.000 - 200.000 ion pairs along its range of 2 - 6 cm. *Advantage:* small dimensions and simple construction, no electrical circuits, very little **ozone** production.

Electrical ionizer produces ions by **corona discharge** from wire or point **emitters**. Can be driven by the charge on the object to be neutralized (**passive ionizer**) or at a few kV of AC- or DC-voltage.

Advantage: Easy to regulate output.

machine model

See ESD damage models

mobility

If a mobile charge carrier in an electric field **E** moves with a constant velocity **v** the mobility **k** of the carrier is given by

$$\mathbf{v} = \mathbf{kE}$$

Unit for mobility is $\text{m}^2\text{V}^{-1}\text{s}^{-1}$.

See air ion.

neutralization

Charges on negatively charged insulated conductors may be removed by grounding the conductor. Charges on positively charged insulated conductors and charges of both polarities on insulators can not be removed, but the field from the charges can be neutralized by attracting oppositely charged carriers from the surrounding medium (for instance ionized air or other conductive fluids) or from (semi-) conductive layers on the charged body itself.

See decay rate.

nuclear ionizer

See ionizer

ohm, Ω

Unit for electrical **resistance** and **surface resistivity**.

Definition of 1 ohm is

$$1 \Omega = 1 \text{ volt}/\text{ampere}$$

Ohms' law

If a material contains charge carriers with a charge **q**, concentration **n** and **mobility** **k**, a field strength **E** will make the carriers move with a velocity **v** = **kE** causing a current density

$$\mathbf{j} = \mathbf{nqv} = \mathbf{nqkE} = \gamma \mathbf{E}$$

$\gamma = nqk$ is called the **bulk** or **volume conductivity** of the material.

Unit is $\Omega^{-1}\text{m}^{-1}$.

$j = \gamma E$ is **Ohm's law** (in differential form). Often written

$$E = \rho j$$

where $\rho = 1/\gamma$. ρ is called the **bulk or volume resistivity** of the material. Unit is Ωm .

If the current density is integrated over the whole current carrying area to give the **current** I and the field strength along the whole current path to yield the **voltage difference** V we get

$$I = GV \text{ or } V = RI$$

where $R = 1/G$.

This is **Ohm's law** (in integral form). G is called the **conductance**.

Unit is **siemens**, Ω^{-1} . R is the **resistance**. Unit is ohm, Ω .

If a field strength E_s along a surface releases a current with the **linear current density** j_s ($\text{A}\cdot\text{m}^{-1}$) the **surface resistivity**, ρ_s of the material is defined by $E_s = \rho_s j_s$ which is **Ohm's law** for surface conduction.

Unit for surface resistivity is

$$\frac{\text{volt}/\text{meter}}{\text{ampere}/\text{meter}} = \frac{\text{volt}}{\text{ampere}} = \text{ohm}, \Omega$$

and certainly *not* ohms per square

ohm(s) per square (!)

Peculiar mixture of a unit and a geometrical concept. Still sometimes (stubbornly) used in some countries instead of the proper unit for **surface resistivity** which is ohm. See **Ohm's law**.

ozone, O_3

Chemically very active gas, formed at all types of electrical discharges (and to some extent with radioactive decay, production rate increases with corona current. Harmful to respiratory tract. Maximum permissible level (in many countries) 1 ppm.

passive ionizer

See ionizer

permanent polarization

See electret

permittivity

In vacuum the relation between the dielectric displacement D and the corresponding electric field E is $D = \epsilon_0 E$ where

$\epsilon_0 = 8.85(4187818) \cdot 10^{-12} \text{ F} \cdot \text{m}^{-1}$ is the **vacuum permittivity**. In a dielectric the relation may be written $\mathbf{D} = \epsilon \mathbf{E} = \epsilon_r \epsilon_0 \mathbf{E}$. ϵ is the **absolute permittivity** and ϵ_r the **relative permittivity** of the dielectric. For many common dielectrics ϵ_r is about 2-6. If the field volume in a vacuum (or air-) capacitor is filled with a dielectric, the capacitance becomes ϵ_r times greater.

See also polarization.

pink poly

See antistatic agent.

polarization

If a fixed charge creates an electric field E_0 and dielectric displacement D_0 in vacuum, and the field is filled with a dielectric the dielectric displacement \mathbf{D} remains unchanged equal to D_0 , but the field \mathbf{E} will be

$$\mathbf{E} = \frac{1}{\epsilon_r} \mathbf{E}_0$$

This is caused by the formation of **dipoles** in the dielectric.

plateout

The deposition of airborne particulates by diffusion or aided by an electric field.

potential, potential difference

same as **voltage, voltage difference**.

The potential is a property of a point in an electric field \mathbf{E} . The **potential difference** between two points A and B in a field \mathbf{E} is defined by

$$V_A - V_B = \int_A^B \mathbf{E} \cdot d\mathbf{a}$$

The **potential** V_p of a point P is defined by

$$V_p = \int_P^\infty \text{or ground} \mathbf{E} \cdot d\mathbf{a}$$

Unit for potential difference is **volt** where

$$1 \text{ volt} = 1 \text{ joule/coulomb}$$

The potential of an insulated conductor G is

$$V_G = \int_G^{\text{ground}} E \cdot da$$

with the same value for all points on or in the conductor.

The **surface potential**, V_S of a point S on the surface of any body is

$$V_S = \int_S^{\text{ground}} E \cdot da$$

For insulators V_S will change from point to point and is therefore not suited to characterize the insulator (except for uniformly charged **electrets**).

precipitation

The removal from the air of solid or liquid particulates in an electric field.

See electrofilter.

radioactive ionizer

See ionizer

resistance

See Ohm's law

resistivity

See Ohm's law

separation

The separation by an electrical field of components of mixtures of materials with different electrical properties.

spark

Discharge between insulated, charged conductor and ground or between two conductors at different **potentials** when neither conductor have sharp points or protrusions. If the capacitance of the charged conductor is C, the charge q and voltage V the energy

$$W = \frac{q^2}{2C} = \frac{1}{2} CV^2$$

may be dissipated in a discharge. The spark discharge is characterized by a narrow discharge path with high energy density, which makes sparks the most incendiive of all types of discharges.

static dissipative material

Material with **surface resistivity** $\rho_s = 10^5 - 10^{12} \Omega$.

static electricity

See electrostatics

static eliminator

See ionizer

static material

Old designation for material with **surface resistivity** $\rho_s > 10^{14} \Omega$.

static voltmeter

See electrometer

surface conductivity

See Ohm's law

surface resistivity

See Ohm's law

surface potential

See potential

time constant

See decay rate

triboelectrification

Charge separation between two materials caused by contact and friction.

See triboelectric series.

triboelectric series

List of materials arranged so that one material may be positively charged when rubbed against and separated from another material farther down the list. Almost a list of decreasing permittivity. Main use of list is to indicate polarities of charges separated and (with caution) to qualitatively estimate magnitude of charges based on interlist distance of materials.

volt

Unit for **potential** and **potential difference (voltage and voltage difference)** defined by

$$1 \text{ volt} = 1 \text{ joule/coulomb}$$

voltage

See potential

wrist strap

Conductive bracelet connected to ground through resistor ($1 \text{ M}\Omega$) to secure person is at ground potential.

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About the Author



Niels Jonassen received his M.S. from the University of Copenhagen in 1954 majoring in Physics, and minoring in Mathematics, Chemistry and Astronomy. In 1962 he received the dr. techn.- (D.Sc.-)degree from the Technical University of Denmark and the same year the Danish Esso Prize for his work on industrial static electricity.

He has worked several periods in the US (mostly New Mexico) on atmospheric electric and radioactive problems. He has twice been a UN-specialist for IAEA (International Atomic Energy Agency) to the Philippines advising on radon projects. He has for 40 years been teaching electromagnetism, static electricity and airborne radioactivity at the Technical University of Denmark and has been conducting about 70 extended courses on static electricity, ions and indoor climate.

He received the ESDA (Electrostatic Discharge Association) *Outstanding Contribution Award* in 1989. Since 1998 he has been writing a column “*Mr. Static*” in *Compliance Engineering* on static

electric topics.

He has officially retired from the Technical University, and divides his time between the laboratory and his home when he is not attending cooking classes in up-state Thailand.