TPH 0441

Engineering Training Publication

Introduction to Electrical Theory – ETP 0074

Issue 1,1972

Prepared by:
Training Group.

Authorised by:
Superintending Engineer,
Operations Planning and Programming Branch, HQ.

Distribution Code: 4L
Filing Category: K

Telecom Australia

Telecom Australia
ENGINEERING TRAINING
210 Kingsway, South Melbourne. 3205

Training
PUBLICATIONS
ETP 0074

INTRODUCTION TO ELECTRICAL THEORY

Published 1970

1. INTRODUCTION.

1.1 Any study of the principles of operation of telecom equipment must start with a study of the electrical properties involved. Similarly, any study of electrical principles must begin with an appreciation of the study of matter. In the course of our studies, we shall find that all matter is composed of atoms, and that the electrical and chemical properties of atoms are attributed to their component electrons.

1.2 For many years, electrons were visualised only as particles of matter which whirled around the central part of the atom in much the same way as the planets orbit the sun. Now, the motion of electrons is visualised as a limited number of three-dimensional "wave patterns" within a defined space. The term "orbital" is used to denote the whole space in which each electron moves, and the electron is located at a transient and indeterminable position within its orbital. An orbital can be spherical, dumb-bell shaped, or pear shaped, according to the energy of the electron in that orbital.

The modern concept of the electron's path is harder to visualise than the planetary concept, but this need not divert us. We are more concerned with the behaviour of electrons than with atomic structure, and our studies are based on certain aspects of electron behaviour which are now fairly well established.

1.3 This paper gives basic information about the structure of matter and the production of electric charges. It explains how the charges can constitute an electric current, and gives detailed information about the basic quantities which relate to electrical theory.

2. THE MAKE–UP OF MATTER

2.1 Matter is defined as any thing that has mass and that occupies space. All matter exists either as a solid, as a liquid or as a gas.

Matter cannot be created or destroyed, but it can be changed from one form to another by changing its temperature and the pressure applied to it. For example, water is a solid at temperatures below its freezing point, a liquid at normal room temperature and a gas at temperatures above its boiling point.

2.2 MOLECULAR STRUCTURE. A molecule is the smallest particle into which a substance can be divided and still retain all its chemical and physical properties. All matter is made up of molecules, and there are as many types of molecules as there are different types of substances.

In all forms of matter, the molecules are in a state of rapid and continuous motion. When a solid is heated, the speed of the molecules increases, and they move about more freely. As a result a solid often softens when heated and then melts to a liquid. When a liquid is heated, the molecules move about at an even greater speed, and some may escape in the form of a gas.

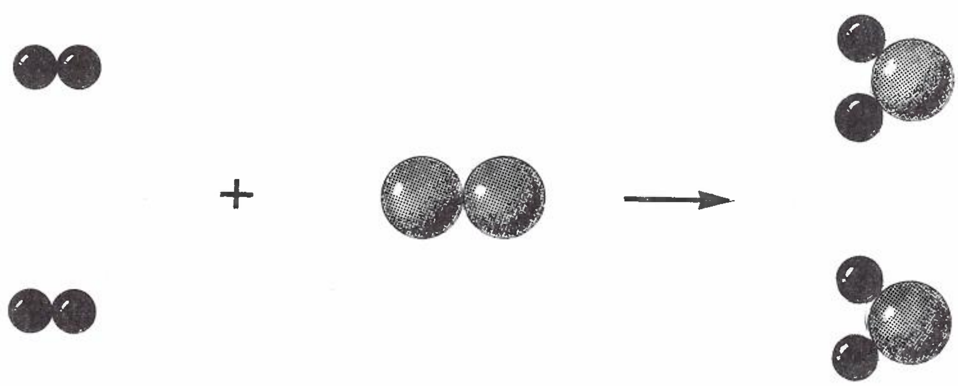
The molecule, however, is not the fundamental particle of matter, as most molecules can be subdivided further into smaller particles called atoms.

An atom is the smallest particle of matter that can enter into a chemical combination.

Sometimes a molecule consists of a single atom, as happens with the inert gases such as neon and argon. In most cases however, the molecule contains two or more atoms which may be similar, or of different types, depending upon the substance. On this basis, substances can be divided into two groups. These are:

- ELEMENTS, in which the molecules are composed of atoms of the same type.
- COMPOUNDS, in which the molecules are combinations of different types of atoms.

Fig. 1 shows how two molecules of the element hydrogen (H_2) combine with one molecule of the element oxygen (O_2), to form two molecules of the compound substance, water (H_2O).



$$2H_2 \quad + \quad O_2 \quad \longrightarrow \quad 2H_2O$$

FIG. 1. ELEMENTS COMBINE TO FORM COMPOUNDS.

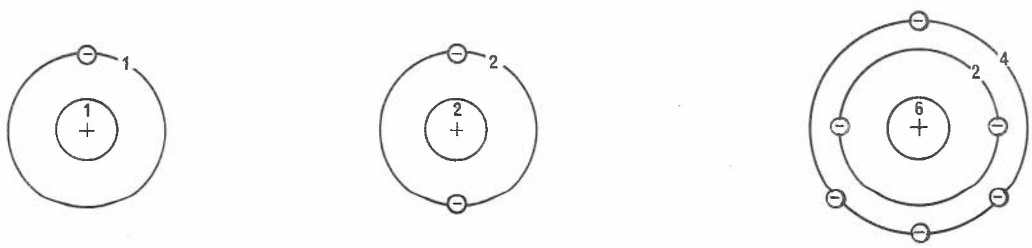
The molecules of many other compound substances are usually more complex. For example, the molecules of the human body consist of combinations of fifteen kinds of atoms, the main ones being oxygen, carbon, hydrogen, nitrogen, calcium and phosphorus.

2.3 ATOMIC STRUCTURE. In all atoms, there is a very small central nucleus, which contains most of the mass of the atom. It is generally accepted that the nucleus contains particles called protons and neutrons. The nucleus as a whole exhibits a positive electric charge, due to the combined effects of the individual positive charges of the protons. The neutron is uncharged, and as it does not seem to contribute to the electrical behaviour of the atom, we shall not consider it further.

Surrounding the nucleus is a cloud of negative charge, thought to be due to orbiting electrons. Each electron has a charge of the same strength but of the opposite type to that of a proton. All normal atoms have equal numbers of protons and electrons, and therefore an atom as a whole is electrically neutral.

The structure of the simplest atom, that of the element hydrogen, is shown in Fig. 2a. The nucleus contains one proton, and a single electron is shown in orbit around it. A strong force of attraction exists between the positively charged nucleus and the negatively charged electron. This force exactly balances the tangential velocity of the orbiting electron to hold it in a stable path in space. The electron's path is called an orbital.

Also represented in Fig. 2 are the helium atom, which has two protons, two neutrons and two electrons, and the carbon atom with six protons, six neutrons, and six electrons. There are more than one hundred different elements, and consequently, more than one hundred different types of atoms.



(a) Hydrogen Atom. (b) Helium Aton. (c) Carbon Atom.

FIG. 2. SIMPLIFIED ATOMIC STRUCTURES.

2.4 ENERGY LEVELS. An orbiting electron possesses a certain amount of energy. This is due to:

- the kinetic energy due to its motion;
- the potential energy due to its position in relation to the nucleus.

The total energy of an electron determines the shape of its orbital, and for an electron to remain in a particular orbital, it can neither gain nor lose energy.

If, by some means, the energy of an electron is increased sufficiently, it will move to a new orbital, and further away from the nucleus than before. However, it has been found that electrons can orbit the nucleus only in certain definite patterns; it is not possible for an electron to exist anywhere else in an atom, other than in one of these "allowed" orbitals. This means that an electron can accept energy, only in "bundles" or "packets" of the exact quantity required to allow it to move or jump from one allowed orbital to another.

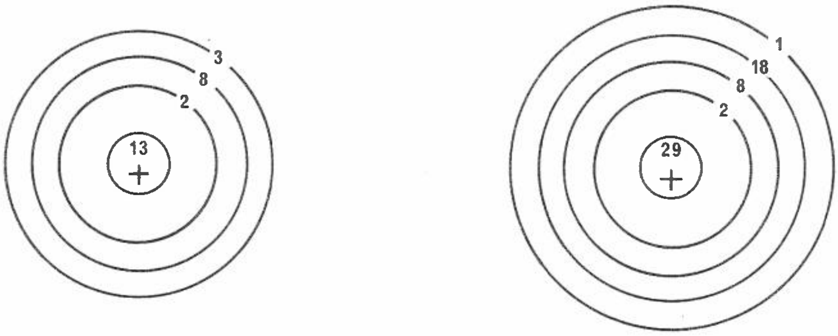
Each allowed orbital therefore represents a level of energy which an electron must possess in order to be able to ocupy it. An electron will remain at its lowest possible energy level until sufficient energy is available, at which time it accepts the energy and jumps to a higher level.

Once an electron has been raised to an energy level higher than its lowest possible energy level, the atom to which it belongs is said to be in an "excited" state. It remains in this condition for no more than a fraction of a second however, before it radiates the acquired energy and returns to its normal energy level. When each electron is at its lowest possible energy level, the atom is said to be in the "ground state".

2.5 ELECTRON SHELLS. In all but the simplest atoms, the electrons are arranged in groups of orbitals called shells, each of which corresponds to a different range of energy levels. The shells in an atom are sometimes pictured as a series of elliptically shaped surfaces, spaced at fixed intervals from the nucleus. They are numbered for identification, with the lowest numbered shell being closest to the nucleus. The letters K, L, M, N, etc. are also used to identify the shells, with the K shell being the innermost.

The maximum number of electrons that a shell can contain, varies according to the number of the shell. The shell closest to the nucleus can hold only two electrons, while the next three shells can accommodate eight, eighteen and thirty-two electrons respectively. The capacities of the remaining shells have not yet been determined.

Fig. 3a shows, in simplified form, how the thirteen electrons in the aluminium atom are accommodated in three shells around the nucleus. The arrangement of the twenty-nine electrons in the copper atom is shown in Fig. 3b.



(a) Aluminium Atom. (b) Cooper Atom.

FIG. 3. SIMPLIFIED ATOMIC STRUCTURES.

When an electron shell is the outer shell of an atom, the maximum number of electrons it can contain is eight, even though the normal capacity of the shell may be more than eight. When an outer shell contains eight electrons, it is effectively filled, and the atom is said to be in the stable state. Elements in which this condition occurs naturally include the inert gases neon, argon and krypton, which do not react chemically with atoms of other elements. Most atoms show a tendency to achieve the stable state, and they accomplish this by combining with other atoms, so that by a process of sharing electrons, they effectively attain a complete outer shell.

2.6 VALENCE. In chemistry, the term "valence" refers to the combining power of an atom, when it takes part in a chemical combination. The valence of an atom determines its ability to gain or lose electrons, which in turn, determines its chemical properties.

In most atoms the valence is determined by the number of electrons contained in the outer shell. The outer shell is therefore called the valence shell and the electrons it contains are called the valence electrons.

It is now believed that only the valence electrons contribute to the electrical behaviour of atoms, and that the differing electrical properties of various substances are due to the differences in the numbers and locations of their valence electrons. The electrons in the inner shells are at all times tightly bound to the nucleus, and for our purposes, can be considered as part of the "core" of the atom.

2.7 ATOMIC NUMBERS. The atomic number of an element is the number of protons contained in the nucleus of its atom. As a normal atom has equal numbers of protons and electrons, the atomic number also indicates the number of electrons contained in the atom.

A partial list of the elements in the order of their atomic numbers is given in Table 1. The table also shows the distribution of electrons amongst the shells for each atom in the unexcited or ground state.

ATOMIC NUMBER	ELEMENT	ELECTRON DISTRIBUTION						ATOMIC NUMBER	ELEMENT	ELECTRON DISTRIBUTION					
		K	L	M	N	O	P			K	L	M	N	O	P
1	Hydrogen	1						26	Iron	2	8	14	2		
2	Helium	2						27	Cobalt	2	8	15	2		
3	Lithium	2	1					28	Nickel	2	8	16	2		
4	Beryllium	2	2					29	Copper	2	8	18	1		
5	Boron	2	3					30	Zinc	2	8	18	2		
6	Carbon	2	4					31	Gallium	2	8	18	3		
7	Nitrogen	2	5					32	Germanium	2	8	18	4		
8	Oxygen	2	6					33	Arsenic	2	8	18	5		
9	Fluorine	2	7					34	Selenium	2	8	18	6		
10	Neon	2	8					35	Bromine	2	8	18	7		
11	Sodium	2	8	1				36	Krypton	2	8	18	8		
12	Magnesium	2	8	2				37	Rubidium	2	8	18	8	1	
13	Aluminium	2	8	3				38	Strontium	2	8	18	8	2	
14	Silicon	2	8	4				39	Yttrium	2	8	18	9	2	
15	Phosphorus	2	8	5				40	Zirconium	2	8	18	10	2	
16	Sulphur	2	8	6				41	Niobium	2	8	18	12	1	
17	Chlorine	2	8	7				42	Molybdenum	2	8	18	13	1	
18	Argon	2	8	8				43	Technetium	2	8	18	14	1	
19	Potassium	2	8	8	1			44	Ruthenium	2	8	18	15	1	
20	Calcium	2	8	8	2			45	Rhodium	2	8	18	16	1	
21	Scandium	2	8	9	2			46	Palladium	2	8	18	18		
22	Titanium	2	8	10	2			47	Silver	2	8	18	18	1	
23	Vanadium	2	8	11	2			48	Cadmium	2	8	18	18	2	
24	Chromium	2	8	13	1			49	Indium	2	8	18	18	3	
25	Manganese	2	8	13	2			50	Tin	2	8	18	18	4	

TABLE 1. PARTIAL LIST OF ELEMENTS.

The table of elements and their atomic structure is provided as a point of reference only. Although it is not complete, most of the elements which have significance from a telecom point of view are listed.

2.8 IONISATION. In a normal atom, there are equal numbers of positive and negative charges, so that the atom as a whole is electrically neutral. It is possible, however, to remove one or more electrons from any of the shells of an atom, and where an atom has incomplete shells, it is also possible to cause one or more electrons to become attached to it.

Whenever an atom gains or loses an electron, its electrical balance is upset and it is said to be ionised. Therefore:

- A NEGATIVE ION is an atom which has gained an electron and consequently has a negative charge.
- A POSITIVE ION is an atom which has lost an electron and has a positive charge.

In order to remove an electron from an atom to produce a positive ion, it is necessary to increase the energy level of the electrons to the point where one or more can become free of the nucleus. The energy required to accomplish this can be supplied in a number of ways, such as by bombarding the atom with high velocity atomic particles, by subjecting it to electric fields, or by exposing it to heat, light or other forms of energy radiation.

The earth's atmosphere contains a percentage of ionised gas as a result of the continual bombardment it receives from cosmic particles.

3. STATIC ELECTRICITY

3.1 Electricity was first produced by friction. At about the year 600 B.C., the ancient Greeks found that amber, when rubbed with fur or wool, attracted small particles such as leaves and hair. At about 1600 A.D., other substances such as glass, ebony, sealing-wax, resin and sulphur were found to possess similar properties.

This effect was called electrification, and the substances were said to be electrified. This term was derived from the Greek work "elekton" meaning amber, and from this, the word electricity subsequently envolved.

3.2 ELECTRIC CHARGE. In the natural state, all atoms are electrically neutral. We have seen however, that when the internal energy of an atom is raised sufficiently, one or more electrons can become free, leaving the atom as a positive ion. Also, an atom can gain an electron to become a negative ion.

If a body could be composed entirely of neutral atoms, its net charge would be zero. However, all matter is subjected to various forms of energy radiation, so that all bodies contain a certain number of ionised atoms. When a body has equal numbers of positive and negative ions, it is electrically neutral or uncharged. When a body contains more positive ions than negative ions, it is positively charged, but when the negative ions outnumber the positive ions, the body has a negative charge.

Since ions are actually atoms without their normal number of electrons, it is ultimately the number of electrons possessed by a body in relation to its number of protons, which determines its state of charge. Therefore:

- a body with a negative charge has a surplus of electrons;
- a body with a positive charge has a deficiency of electrons.

The unit used for measuring charge is the COULOMB, which is equal to the combined charge of 6.25×10^{18} electrons.

3.3 LAWS OF CHARGED BODIES. It has been found experimentally that when two charged bodies are brought together, a force exists between them.

When the bodies have similar charges, that is, either both positive or both negative, the force is one of repulsion. When the bodies have opposite charges, that is, one positive and one negative, the bodies attract each other.

In both cases, the force of attraction or repulsion depends on the strengths of the charges and the distance between them.

These results are summarised in the following laws:

- *like charges repel; unlike charges attract;*
- *the force of attraction or repulsion between two charged bodies is directly proportional to the product of the charges, and inversely proportional to the square of the distance between them.*

The second law is often referred to as Coulomb's Law, and it can be expressed mathematically as follows:

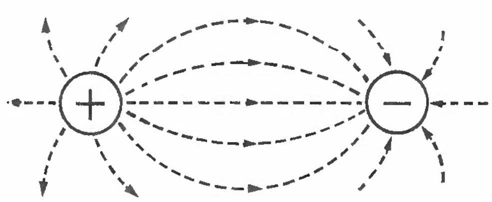
$$F \propto \frac{Q1 \times Q2}{d^2}$$

F = *Force of attraction or repulsion;*
Q1 = *Strength of Charge 1;*
Q2 = *Strength of Charge 2;*
d = *Distance separating the charges.*

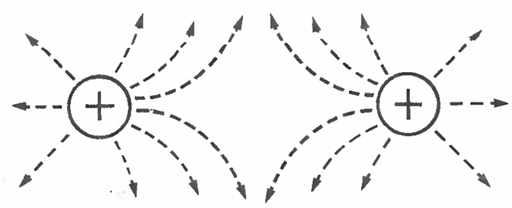
The symbol $\propto$ as used above, means "varies as". While this type of expression is incomplete for the purpose of calculating the magnitude of the force, it is useful in that it describes the significance of the physical factors involved.

3.4 ELECTRIC FIELDS. The area surrounding a charged body, where attracting or repelling forces are evident, is known as an electric field. This field exists in a definite pattern, and is often represented by lines radiating in all directions from a charged body. These lines, known as electrostatic lines of force, are imaginary, but they help to illustrate the area of influence of charged bodies.

By convention, the lines are shown starting from a positive charge, and ending at a negative charge. The arrows show the direction of the force that would be exerted on a positive test charge if it was placed in the field. Fig. 4a represents the electric field produced by two unlike charges, while that produced by two like charges is shown in Fig. 4b.



(a) Unlike charges.



(b) Like charges.

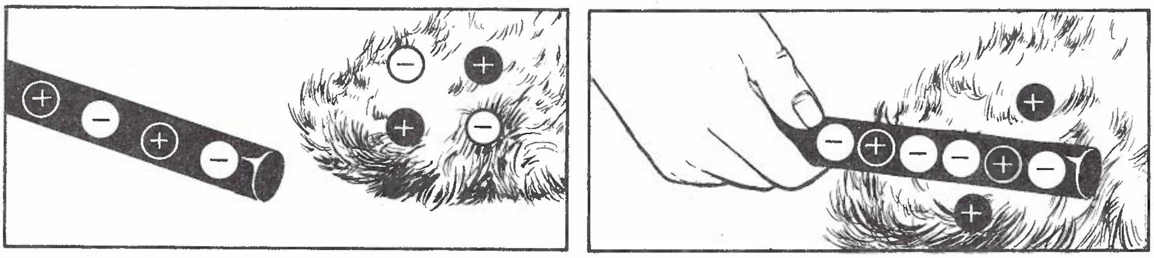
FIG. 4. ELECTRIC FIELDS.

3.5 CHARGING BY FRICTION. When two substances are rubbed together, the energy levels of the electrons in both substances are raised to the point where some electrons could become free of their parent atoms. When the substances are different, their different atomic structures allow electrons in one substance to become free before the electrons in the other do so, and a transfer of electrons occurs between them. When this happens, the substance losing the electrons assumes a positive charge., while the substance gaining the electrons assumes a negative charge.

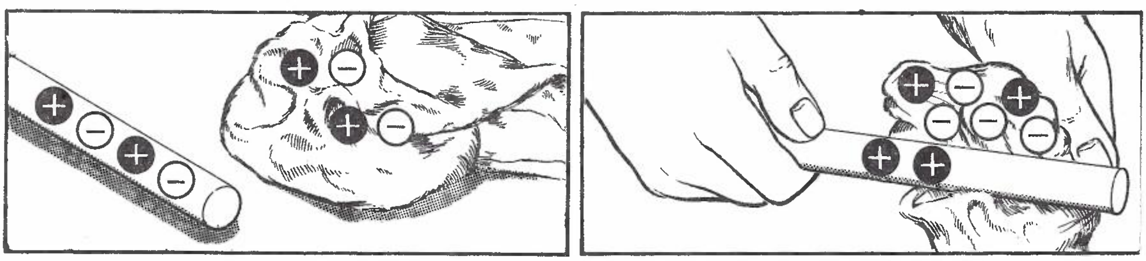
The degree and type of charge produced depends on the substances used. As the result of experiments, substances can be arranged in a list so that any one has a positive charge when rubbed by a substance which follows it, and a negative charge when rubbed by a substance ahead of it. Some common items are:

(+) fur, flannel, glass, silk, metals, rubber, sealing-wax, resin, ebonite, amber (-).

For example, when an ebonite rod is rubbed with fur, the fur loses electrons to the rod. As a result, the rod becomes negatively charged and the fur becomes positively charged, as in Fig. 5a. Similarly, when a glass rod is rubbed with a silk cloth, the glass loses electrons to the silk so that the silk acquires a negative charge while the glass receives a positive charge (Fig. 5b).



(a) Ebonite and fur.



(b) Glass and silk.

FIG. 5. PRODUCING STATIC CHARGES BY FRICTION.

3.6 CHARGING BY CONTACT. A charged body can transfer some of its charge to other bodies by coming into contact with these bodies.

For example, when a negatively charged ebonite rod is brought into contact with a neutral body, some of the excess electrons on the rod are transferred to the body, leaving it with a negative charge. In the same way, a body can be charged positively by contact with a positively charged glass rod. In this case the rod has a deficiency of electrons, and it attracts some of the electrons from the body, leaving the latter with a positive charge.

3.7 CONDUCTORS AND INSULATORS. When a metallic substance such as copper, brass or aluminium is charged, the charge spreads uniformly over its surface. Electrons can move readily through these materials, and they are called electrical conductors.

When most non-metallic substances are charged, the charge is localised, and does not spread beyond the area in which it was produced. These substances do not conduct electricity and are called insulators.

Most metals are good conductors, and materials used for this purpose in telecom include copper, silver, aluminium, brass, iron, and lead. Most chemical solutions and ionised gases conduct electricity, but these rely on a migration of ions as well as a flow of electrons to conduct charges.

The materials most commonly used as insulators in telecom equipment are the plastics, polyvinyl chloride (P.V.C.) and polystryene. Other substances used as insulators include glass, paper, rubber, ebonite, cotton, silk and porcelain.

3.8 ELECTRON FLOW BETWEEN CHARGED CONDUCTORS. When two oppositely charged conducting bodies are brought into contact, the excess electrons on the negatively charged body are transferred to the other body, where they neutralise its positive charge. The same effect can be achieved by connecting a conductor, such as a piece of copper wire, between the two oppositely charged bodies, as shown in Fig. 6.

The negatively charged body repels electrons in the copper wire, while, at the other end of the wire, the positively charged body attracts them. Electrons therefore, move along the wire towards the positively charged body where they neutralise its charge. These electrons are replaced by an equal number of electrons which enter the wire from the negatively charged body. The result is an general drift of electrons along the conductor, from the negatively charged body to the body with the positive charge.

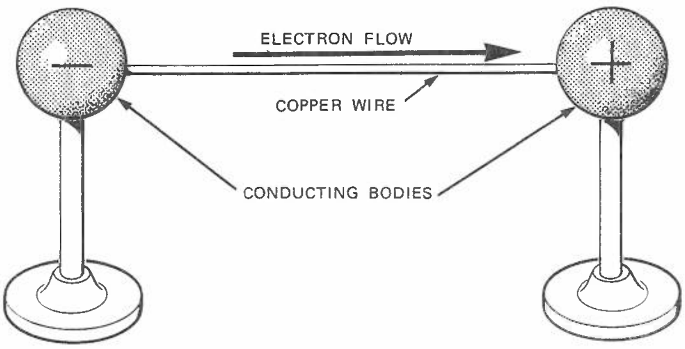


FIG. 6. ELECTRON FLOW IN A CONDUCTOR.

This flow of electrons in the wire will continue until the charges on the bodies are neutralised. If the charges on the bodies are static, for example produced by friction, the flow of electrons will be momentary only.

If, however, the bodies are connected to some device which continually supplies electrons to the negatively charged body and removes electrons from the body with the positive charge, the flow of electrons will be maintained.

The result is a continuous flow of charges from negative to positive, and this constitutes an electric current with electrons as the *current carriers*.

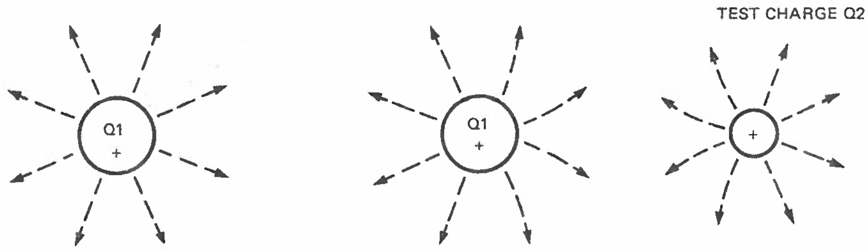
4. ELECTRICAL POTENTIAL AND E.M.F.

4.1 In physics, the term "potential" refers to the type of energy possessed by a body due to its position. For example, an object suspended above ground level possesses potential energy which can be converted into kinetic energy when it is released. In electricity, "potential" refers to the energy stored in an electric charge, because of its position in an electric field.

4.2 WORK. Work is done whenever a force causes movement. When an object is lifted above ground level, work is done in overcoming the force of gravity. In the same way, work is done whenever an electric charge is moved against the force exerted by an electric field. In all cases, the amount of work done depends upon the magnitude of the force and the distance through which the force causes movement.

The unit used to measure work is the JOULE which is the work done when a force of one unit acts over a distance of one metre. (The unit of force is the Newton which is that force which gives a mass of one kilogramme an acceleration of one metre per second per second).

4.3 ELECTRIC POTENTIAL ENERGY. Fig. 7a shows the electric field radiating in all directions from a positively charged fixed body Q1. When a positive test charge Q2 is introduced into the field from a distant point (Fig. 7b), energy is expended in overcoming the repelling force caused by the interaction of the two fields. This energy is converted into electrical potential energy which is stored in the test charge. Each time the test charge is moved closer to Q1, more work is done and additional energy is stored in the charge, increasing its potential.



(a) Electric Field (b) Fields Interact.

FIG. 7. ELECTRIC POTENTIAL.

4.4 DIFFERENCE OF POTENTIAL. Electric potential is also produced whenever substances are electrically charged. For example, when two substances are charged by friction, work is done as charge is transferred between them. As charge is moved from one substance to the other against the opposition of the resulting electric field, the electrical potential of one substance is raised with respect to that of the other, so that a difference of potential exists between them.

It is not necessary for the substances to be oppositely charged to establish a difference of potential. A potential difference exists between two similarly charged substances when the charges are of unequal strength. Fig. 8 illustrates three ways in which a potential difference or p.d. can exist between two charged bodies. In all cases, the polarity of the p.d. is the same, that is, A is positive with respect to B.

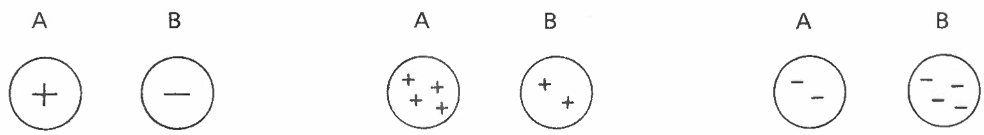


FIG. 8. DIFFERENCE OF POTENTIAL.

Whenever a difference of potential exists between two points, the energy stored in the charge can be recovered when an electrical conductor is connected between the two points. As the charges move through the conductor from the point of high potential to the point of low potential, they do work equal to the work performed in creating the difference of potential. All electric currents originate from a difference of potential. It is not possible to establish a current between points of equal potential.

4.5 UNIT OF POTENTIAL DIFFERENCE. The unit of potential difference is the VOLT, named in honour of Alessandro Volta, who discovered one of the first practical methods of generating a continuous difference of potential.

A potential difference of one volt exists between two points, when one joule of work is done by each coulomb of charge in moving from the point of higher potential to the point of lower potential.

The symbol for a difference of potential is V. The magnitude of a difference of potential is often called its "voltage", and this can be found from:

$$V = \frac{W}{Q}$$

where V = *Potential Difference in volts;*
W = *Work in joules;*
Q = *Charge in coulombs.*

The abbreviation for the Volt is also V. The potential differences encountered in telecom equipment range from a small fraction of a volt to many thousands of volts, so that the more common multiple and submultiple units are:

- the kilovolt (abbreviated kV), $1\text{kV} = 1\text{V} \times 10^{3}$;
- the millivolt (abbreviated mV), $1\text{mV} = 1\text{V} \times 10^{-3}$;
- the microvolt (abbreviated µV), $1\mu\text{V} = 1\text{V} \times 10^{-6}$

4.6 ELECTROMOTIVE FORCE. For a difference of potential to become a practical source of voltage, it is essential that the accumulation of charge is maintained, even though the source is supplying current to some external device. A practical voltage source requires an internal action which continually removes electrons from the positive terminal and simultaneously supplies them to the negative terminal.

The force which maintains the state of charge within a source of voltage, and thereby causes the movement of electrons in an electric circuit is called the Electromotive Force.

The abbreviation for electromotive force is e.m.f.; the symbol for e.m.f. is E. Like potential difference, e.m.f. is measured in volts.

4.7 DIFFERENCE BETWEEN P.D. AND E.M.F. Although the same basic unit is used to measure p.d. and e.m.f., the terms are not completely interchangeable.

Potential difference is a term used to compare the electrical potential existing between two points. A p.d. exists wherever a voltage can be detected.

On the other hand, electromotive force refers to the rate at which energy is exchanged within a voltage source. In some cases this can be quite different from the p.d. available at its terminals. For example, when current is being taken from a practical source of voltage, internal losses usually reduce the p.d. measured at its terminals to a value less than the e.m.f.

Therefore, the term "e.m.f." is not a direct alternative for "p.d." or "voltage," and it should only be used when referring to:

- the force within a device which generates a p.d. at its terminals;
- the p.d. between the terminals of a source of voltage when it is not delivering current.

4.8 SOURCES OF VOLTAGE. A practical source of voltage is a device which is capable of establishing and maintaining a difference of potential, while some type of electrical apparatus is connected across its terminals. All practical methods of producing a difference of potential rely on the conversion of some form of energy to electrical potential, which can be converted into work when the source delivers current.

Practical methods of generating a potential difference make use of magnetism, chemical action, heat, light or pressure. Briefly, the principles involved in each of these methods are as follows:

- MAGNETISM. Whenever relative motion exists between a conductor and a magnetic field, an e.m.f. is generated within the conductor. This principle is used in electric generators, which consist essentially of a means of moving conductors in a magnetic field. As the principle has important applications in telecom equipment, it is treated in more detail in other publications.

- CHEMICAL ACTION. An e.m.f. is produced when two dissimilar conductors are immersed in a chemical solution called an electrolyte. This arrangement constitutes a simple electric cell, and is a means of converting chemical energy into electric energy. The many types of cells and batteries used to energise telecom equipment are applications of this principle.

- HEAT. A small p.d. is produced when the junction of two dissimilar metals is heated. The value of the p.d. depends upon the metals used and the difference in temperature between the heated and non-heated junctions. This principle is called the "thermo-electric effect", and devices using it are called thermo-couples. Thermo-couples are not widely used for producing large amounts of electrical energy, but they are used in some types of electrical measuring instruments and as small power supplies.

- LIGHT. When light falls on certain materials such as selenium, sufficient energy can be transferred to the material to permit electrons to be emitted. This leaves the material with a positive charge, while the surface which collects the electrons acquires a negative charge. This effect is called the "photo-electric effect", and is used in devices called photo-electric cells. The principle is also used in solar cells, which convert solar energy into electrical energy.

- PRESSURE. If a crystal of quartz is compressed, charges of opposite polarity appear on opposite faces of the crystal. If the force is reversed so that the crystal is stretched, the polarity of the charge reverses. This effect, known as the "piezo-electric effect", is used in certain types of microphones, and in the crystal pick-ups associated with some types of record players.

A difference of potential can also be produced by friction, but because of the nature of the materials used, and the difficulty of maintaining the charge, this method has very limited practical application.

4.9 TYPES OF VOLTAGES. With some methods of producing a difference of potential, the process is continuous and the polarity of the voltage does not change. With other methods, a voltage is produced only when a change is taking place, and its polarity reverses each time the direction of the change reverses.

Voltages can therefore be grouped into two types. These are:

- DIRECT VOLTAGES, where the polarity of the difference of potential does not change. This type of voltage is produced by chemical action, light and heat, and by special types of electromagnetic generators.

- ALTERNATING VOLTAGES, where the polarity reverses, usually in a periodic manner. These voltages are commonly derived by electromagnetic means, and from applications of the piezo-electric effect.

4.10 VOLTAGE RATING OF ELECTRICAL EQUIPMENT. Many items of electrical apparatus are designed to operate with a certain applied voltage. If this value is exceeded, damage may result; if the voltage is less than the designed value, the current may be insufficient for the correct operation of the equipment.

The voltage required for the correct operation of electrical apparatus is called voltage rating. This value is usually marked on the apparatus; it should not be exceeded.

5. ELECTRIC CURRENT

5.1 An electric current is an ordered movement of charges under the influence of some external force. The symbol for current is I, and current is found from:

$$I = \frac{Q}{t} \qquad \text{where } \begin{aligned} I &= \textit{Current in amperes,} \\ Q &= \textit{Charge in coulombs,} \\ t &= \textit{Time in seconds.} \end{aligned}$$

5.2 UNIT OF ELECTRIC CURRENT. The basic unit used to measure electric current is the AMPERE. The ampere is defined as the magnitude of the current which, when maintained in each of two long parallel wires separated by one metre in free space, produces a force between the two wires of 2×10^{-7} newton for each metre of length.

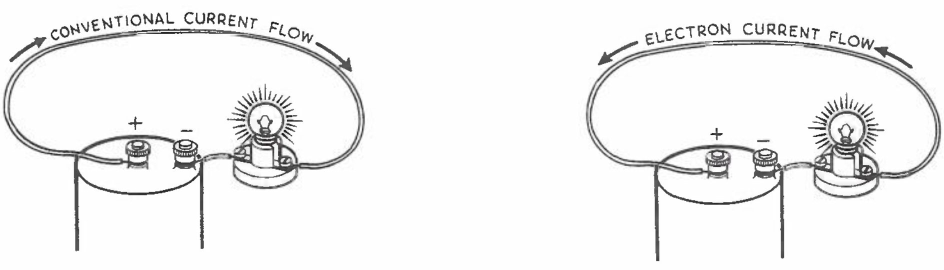
The abbreviation for ampere is A. As currents in excess of 1000A are comparatively rare, the ampere is quite satisfactory as a major unit. In telecom however, currents of less than one ampere are very commonly encountered and two sub-multiple units are used. These are:

- the milliampere (abbreviated mA), $1\text{mA} = 1\text{A} \times 10^{-3}$;
- the microampere (abbreviated µA), $1\mu\text{A} = 1\text{A} \times 10^{-6}$.

It is important to remember the difference between the coulomb and the ampere. The coulomb represents the quantity or number of electrons in a charge; the ampere represents the rate at which they flow.

5.3 DIRECTION OF CURRENT. It has been shown in previous sections of this paper that current in a conductor is due to a movement of electrons. However, for many years before this was known, it was assumed that the current was due to a movement of positive charges, and the direction of flow was from positive to negative. As this assumption of current, now called *Conventional Current,* was the one used to develop many useful rules which assisted in the understanding of electrical effects, most people continued to think of these rules in terms of conventional current.

Consequently, although text books teach that current flow is the result of a movement of electrons, most still base their rules on conventional current. This method will be used in future Technical Training Publications. However, some publications, including Technical Training Publications, use rules based on electron flow. These rules are, naturally, opposite in sense to those based on conventional current. It is important to realise that *either method of expressing current flow and the associated rules may be used,* but, irrespective of what direction of current flow is considered, the results remain unaltered. For example, the globes in Fig. 9 will light for both assumed directions of current flow.



(a) Positive to Negative (b) Negative to positive

FIG. 9. RESULTS ARE INDEPENDENT OF ASSUMED DIRECTION.

5.4 EFFECTS OF ELECTRIC CURRENT. When an electric current flows in a conductor, it produces effects which can be detected externally.

The four principal effects of electric current are:

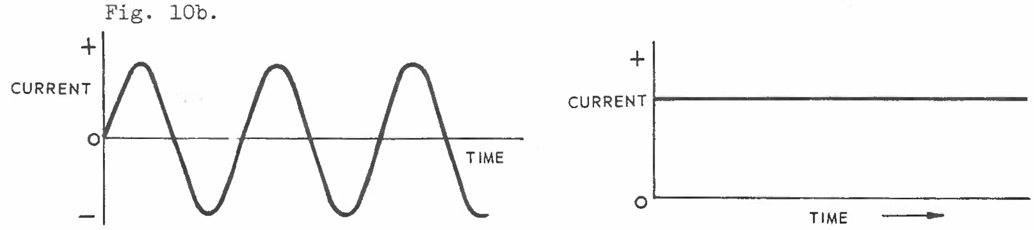
- HEATING EFFECT. An electric current heats the conductor through which it flows. This effect is made use of in items such as electric radiators, stoves and soldering irons, and in electric lamps where the temperature is raised to white heat to give light.
- CHEMICAL EFFECT. When an electric current flows through a conducting liquid, such as an acid or a metallic salt solution, the fluid undergoes a chemical change. This effect is called "electrolysis", and has application in the action of some types of electric cells, and in electroplating.
- MAGNETIC EFFECT. An electric current sets up a magnetic field about the conductor through which it flows. This effect is put to use in the electric bell, the telephone receiver, the loudspeaker and in almost all electric machinery.
- PHYSIOLOGICAL EFFECT. An electric current causes the muscles to contract when it passes through the human body. In certain instances, this effect can cause death. Provided that normal safety precautions are observed however, there is little danger when working with electricity.

These effects are treated in greater detail in other publications.

5.5 CLASSIFICATION OF ELECTRIC CURRENTS. We have seen that although electric currents can originate from a number of different voltage sources, all electric currents in conductors are similar, in that they consist of flows of electrons. However, the rate of flow is not the same in all cases, and even in the same conductor the current can vary in value from instant to instant. In addition, the direction of flow can reverse, if the polarity of the applied voltage reverses.

Electric currents can be classified into two basic types. These are:

- ALTERNATING CURRENT or A.C., which regularly alters its direction of flow, first flowing in one direction, then reversing and flowing in the opposite direction as shown graphically in Fig. 10a;
- DIRECT CURRENT or D.C., which flows in one direction only, as shown in Fig. 10b.



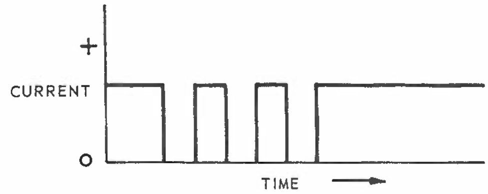
(a) Alternating Current. (b) Direct Current.

FIG. 10. TYPES OF CURRENT.

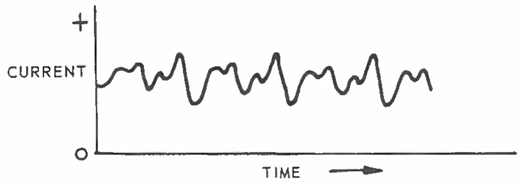
Alternating currents are used extensively in all branches of electrical engineering. For example, the commercial power supply provides A.C. for lighting and power. In telecom, alternating currents are used for many purposes, ranging from transmitting T.V. programmes to ringing telephone bells. Although many alternating currents have a waveform which corresponds with the "sine-wave" shown in Fig. 10a, this is not an essential characteristic of A.C., and in many telecom applications, non sine-waves are used.

The D.C. shown in Fig. 10b maintains a constant value, and is sometimes called a steady direct current. In telecom, this type of current is comparatively rare, as in most cases the currents are constantly changing in value. There are two types of fluctuating direct currents. These are:

- PULSATING CURRENT, which is a form of D.C. which flows in pulses, having complete periods of no current, as shown in Fig. 11a.
- VARYING CURRENT, which is also unidirectional, but which varies in value from instant to instant as shown in Fig. 11b.



(a) Pulsating Current.



(b) Varying Current.

FIG. 11. FLUCTUATING CURRENTS.

Pulsating currents are commonly used in telegraph working. The current shown in Fig. 11a is a graphical representation of the current sent to line from a modern telegraph machine when the key for letter "Y" is depressed. Pulsating current is usually derived by periodically interrupting steady direct current.

Varying currents are often employed in telephone working. For example, the process of the electrical transmission of speech starts with a varying current similar to that shown in Fig. 11b, flowing in a telephone transmitter. Varying currents are sometimes derived from varying direct voltages, but more often, they are the result of applying steady direct voltages to items of equipment which offer varying amounts of opposition to current.

6. RESISTANCE

6.1 Many different substances allow the passage of electric current, but not all substances conduct to the same degree. Some conductors offer very little opposition to current flow; others oppose it to a great extent.

The amount of opposition offered by a body to the flow of electric current is called its resistance. The symbol used to indicate resistance is R.

6.2 UNIT OF RESISTANCE. The unit of resistance is the OHM. A conductor has a resistance of one ohm when a p.d. of one volt applied across its ends causes a current of one ampere.

The abbreviation for ohm is the Greek Letter Ω (omega). Other multiple and submultiple units in common use are:

- the megohm (abbreviated MΩ), $1M\Omega = 1\Omega \times 10^6$;
- the kilohm (abbreviated kΩ), $1k\Omega = 1\Omega \times 10^3$;
- the microhm (abbreviated μΩ), $1\mu\Omega = 1\Omega \times 10^{-6}$.

6.3 RESISTIVITY. One of the factors which determine the resistance of a body is the material from which it is made. The degree of opposition the material offers to the passage of electric current is determined by the material's atomic structure. This opposition is a characteristic property of the material, and is called resistivity.

The resistivity of a solid material depends essentially upon the number of current carriers present in its atomic structure, and upon the degree of ease with which they are able to move through the material. Substances which have relatively few current carriers, or those in which the current carriers can travel only short distances before colliding with ions of the substance, have higher values of resistivity than those whose atomic structures provide many current carriers which can move relatively unimpeded.

The resistivity of a material is the resistance measured between opposite faces of a metre cube of the substance (Fig. 12) at a given temperature.

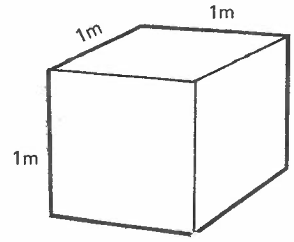


FIG. 12. ONE METRE CUBE.

The symbol for resistivity is the Greek letter ρ (rho). Resistivity is sometimes expressed in ohms per metre cube, but in the S.I. system, the unit is the OHM-METRE, which represents the same value. Some typical values of resistivity (at 20°C) are shown in Table 2.

Material	Resistivity in ohm-metres	Material	Resistivity in ohm-metres
Silver	1.59×10^{-8}	Iron	10×10^{-8}
Copper	1.72×10^{-8}	Platinum	10×10^{-8}
Aluminium	2.81×10^{-8}	Lead	22×10^{-8}

TABLE 2. TYPICAL RESISTIVITY VALUES.

6.4 CONDUCTANCE. Conductance is a measure of the ability of a body to conduct an electric current; it is the reciprocal of resistance. When the resistance is considered as a measure of the difficulty with which an electric current flows in a body, conductance expresses the ease with which it flows. A good conductor has high conductance and low resistance, while a poor conductor has low conductance and high resistance.

The term conductivity is often used when describing the conducting ability of a substance. The conductivity of a material is the conductance measured between opposite faces of a metre cube of the material at a given temperature. Conductivity is the reciprocal of resistivity.

6.5 UNIT OF CONDUCTANCE. The unit of conductance is the siemens, the abbreviation for which is S. The symbol for conductance is G, and conductance can be found from:

$$G = \frac{1}{R}$$

where G = *Conductance in siemens;*
R = *Resistance in ohms.*

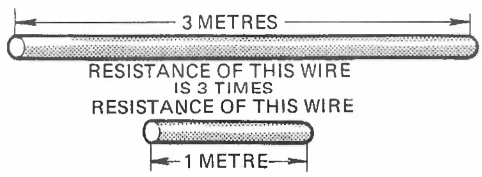
A submultiple unit is sometimes used to express the conductance of poor conductors. This is the microsiemens, (abbreviated μS) which equals $1S \times 10^{-6}$ and is the conductance of a body which has a resistance of $1M\Omega$.

6.6 FACTORS WHICH AFFECT CONDUCTOR RESISTANCE. The resistance of an electrical conductor depends upon its physical dimensions and upon the material from which it is made. The individual factors which determine the resistance of a conductor are:

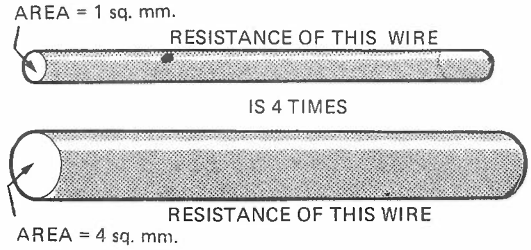
- THE LENGTH. As electrons move along a conductor, they are continually colliding with ions in the conductor. The longer the conductor, the greater the number of collisions, and the greater is the opposition to current. Provided that all other factors are the same, a conductor twice the length of another has twice its resistance, while a conductor three times the length of another (Fig. 13a) has a resistance value three times that of the shorter wire. Resistance is therefore directly proportional to length.

- THE CROSS-SECTIONAL AREA. For a given type of material, there are more current carriers available in a conductor of large cross-section than there are in a conductor of smaller cross-section. Therefore the conductor with the larger area has the lower resistance. When the cross-sectional area of one conductor is double that of another, its resistance is half that of the smaller conductor. Similarly, a conductor with four times the cross-sectional area of another (Fig. 13b), has one quarter of its resistance. Therefore, resistance is inversely proportional to cross-sectional area.

- THE RESISTIVITY. We saw that the electrical properties of a material are indicated by its resistivity, which is the actual resistance of a sample of the material of a standard size. Provided that the length and cross-sectional area are the same, a conductor made from a material with a high resistivity has more resistance than a conductor made from a material with a low resistivity. The resistance of a conductor is therefore directly proportional to its resistivity.



(a) Resistance Depends Upon Length.



(b) Resistance Depends upon Cross-sectional Area.

FIG. 13. FACTORS DETERMINING RESISTANCE.

6.7 RESISTANCE FORMULA. The factors which determine the resistance of a conductor can be combined into a formula which, for most practical purposes, allows the resistance of a particular conductor to be calculated.

The formula is:

$$R = \frac{\rho \ell}{a}$$

where
R = *Resistance in ohms;*
ρ = *Resistivity in ohm-metres;*
ℓ = *Length in metres;*
a = *Cross-sectional area in square metres.*

Where greater accuracy is required in determining the resistance, it is necessary to make allowances for the temperature.

6.8 EFFECT OF TEMPERATURE ON RESISTANCE. We saw earlier that current flow in a solid is due to a drift of current carriers through the material under the influence of an electric field.

In a conductor, increases in temperature do not significantly change the number of current carriers present in the structure. However, increasing the temperature causes the atomic structure to quiver or vibrate, so that the movement of current carrying electrons through the material is impeded. With most metallic conductors therefore, the resistivity increases when the temperature increases, which causes the resistance to increase.

In a semiconductor, the increase in temperature also causes the atomic structure to vibrate, but the impeding effect of this vibration is off-set by an increase in the number of current carriers available, so that with semiconductors, the resistance decreases when the temperature is increased.

6.9 TEMPERATURE COEFFICIENT OF RESISTANCE. The amount by which the measured resistance of a material changes, for each degree change in temperature, is called its temperature coefficient of resistance.

- A POSITIVE TEMPERATURE COEFFICIENT indicates that the resistance increases when the temperature is increased. Most pure metals and many alloys have positive temperature coefficients of resistance.
- A NEGATIVE TEMPERATURE COEFFICIENT indicates that the resistance decreases when the temperature is increased. Germanium, silicon and carbon are examples of materials having negative temperature coefficients of resistance.

The temperature coefficients of resistance for some typical materials are given in Table 3.

Material	Temperature Coefficient of Resistance per $^{\circ}C$	Material	Temperature Coefficient of Resistance per $^{\circ}C$
Silver	+ 0.0038	Iron	+ 0.005
Copper	+ 0.0039	Platinum	+ 0.0039
Aluminium	+ 0.0039	Lead	+ 0.0039

TABLE 3. EXAMPLES OF TEMPERATURE COEFFICIENT OF RESISTANCE.

6.10 RESISTANCE ALLOYS. It has been found that the resistance of a conductor can be increased by adding impurities to it, even though the impurities themselves are good conductors. Practical advantage is taken of this fact in the manufacture of resistance alloys, which provide high resistance for a short length, often with a negligible temperature coefficient. The characteristics of some typical resistance alloys are shown in Table 4.

Material	Composition	Resistivity in ohm-meters at $20^{\circ}C$	Temperature Coefficient of Resistance per $^{\circ}C$
Manganin	Copper-Maganese-Nickel	44×10^{-8}	0.00001
Eureka	Nickel-Copper	49×10^{-8}	0.00001
Nichrome	Nickel-Chromium	110×10^{-8}	0.0004

TABLE 4. TYPICAL RESISTANCE ALLOYS.

6.11 RESISTORS. Resistance is inherent in all electrical equipment. In some cases, the effects of this resistance are undesirable, and special techniques are adopted to keep resistance to a minimum value. In other instances, the natural resistance of a wire or component is insufficient for a particular application, and additional resistance is intentionally added.

Components designed specifically to offer resistance to electric current are called resistors. Many different types of resistors are used in telecom equipment, and these can be of the fixed value or of the variable resistance type.

6.12 FIXED RESISTORS. Fixed resistors provide a resistance value which cannot be changed. These resistors can be broadly classified according to the materials from which the resistance elements are made. These are:

- WIRE WOUND RESISTORS, which usually consist of a suitable length of resistance wire wound on an insulating bobbin or former. This type of resistor is generally used in high current applications, or where extreme accuracy and stability of resistance value are required. They are available in resistance values ranging from a fraction of an ohm up to about 100 kilohms.

- CARBON RESISTORS, which are made from carbon or carbon composition rod, or by depositing a thin layer of pure carbon on an insulating tube. These resistors are the most commonly used type for most general purposes, and are available in a range of resistance values from about 10 ohms to about 22 megohms A disadvantage of carbon resistors is their temperature coefficient of resistance, which is much higher than that for wire wound resistors.

- METAL OXIDE RESISTORS, which consist of a thin film of metal oxide on a ceramic rod. Generally, these resistors offer closer tolerances and higher stability than ordinary carbon resistors. The range of values available is typically from a few ohms to about 100 kilohms.

Some typical fixed resistors are shown in Fig. 14.

FIG. 14. TYPICAL FIXED RESISTORS.

6.13 VARIABLE RESISTORS. Variable resistors are specially constructed so that their resistance can be varied or adjusted to any value within the range of resistance provided. The resistance element can be wire wound or made from a carbon composition, and the variation in resistance is derived by moving a wiper arm or adjustable clamp along the resistance element.

Variable resistors usually have three terminals or connection points. The two outside terminals connect to the ends of the resistance element, while the middle terminal connects to the wiper arm or its equivalent. Some typical variable resistors as used in telecom equipment are shown in Fig. 15.

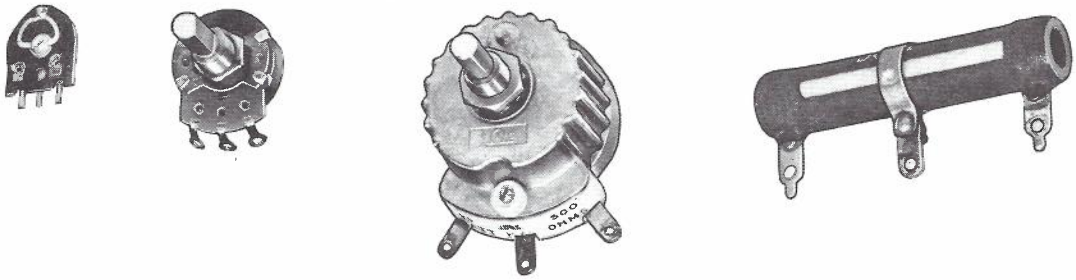


FIG. 15. TYPICAL VARIABLE RESISTORS.

6.14 RESISTOR TOLERANCE. To allow for variations in resistance value due to the manufacturing process, resistors are supplied in certain tolerance ranges. The tolerance of a resistor is the allowable percentage variation above or below its nominal value.

Resistors are available with tolerances which range from ±20% to less than ±1% of the stated value.

6.15 PREFERRED RESISTANCE VALUES. Standard resistors are manufactured with values selected so that the highest value allowed by the tolerance does not greatly overlap the lowest value of the next higher range. For instance, the highest allowable value of a 100 ohm resistor marked ±10% is 110 Ω, and the lowest allowable value of the next higher value, a 120 Ω ±10% tolerance resistor, is 108 ohms.

These values are termed Standard Preferred Resistance Values, and values from 10 Ω to 91 Ω are given in Table 5. Values outside this range are obtained by multiplying or dividing by a power of 10.

E24	10	11	12	13	15	16	18	20	22	24	27	30	33	36	39	43	47	51	56	62	68	75	82	91	5%
E12	10		12		15		18		22		27		33		39		47		56		68		82		10%
E 6	10				15				22				33				47				68				20%

TABLE 5. STANDARD PREFERRED RESISTANCE TABLE

FOR TWO SIGNIFICANT FIGURE VALUES

With advancing technology a need arose for a finer range of resistance values. By introducing a third significant figure to the value of each resistor a widely increased range was made available, effectively filling out the original range.

This closer range of values required a more stringent set of tolerances to prevent any overlap. For example, in Table 6 the tolerance of the E48 range is 2% and of the E192 range is 0.5%.

Because the E 6 to E 24 range (Table 5) does not coincide with the newer E 48 to E 192 range of values, difficulty is experienced by anyone stocking resistors for maintenance purposes. To overcome the incompatibility of the two ranges, the E 48 range, which is ideal for precise requirements, has every forth value extracted to form a new E 12 series called E48/4. A study of Tables 5 and 6 shows how close this is for most purposes. By stocking the E48/4 values all maintenance requirements are covered.

The values given in Table 6 and their decimal multiples or sub-multiples are a series of preferred values for components with tolerances closer than 5% and for those cases where the E-24 series (Table 5) is not acceptable because of special requirements.

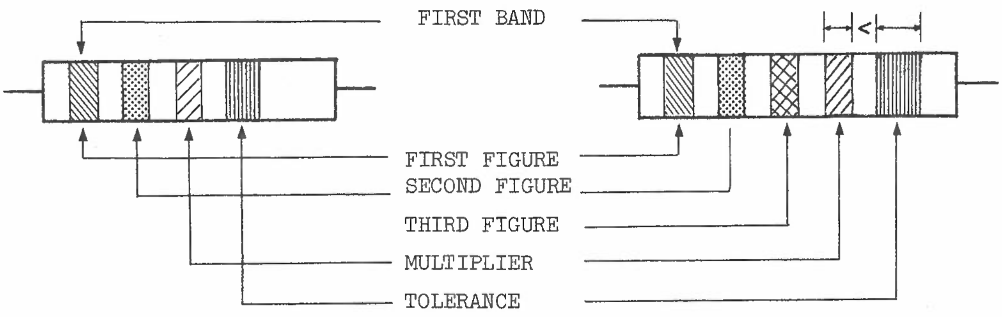
E192	E96	E48	E48/4	E192	E96	E48	E48/4	E192	E96	E48	E48/4	E192	E96	E48	E48/4
100	100	100	100	182	182			332	332	332		604	604		
101				184				336				612			
102	102			187	187	187		340	340			619	619	619	
104				189				344				626			
105	105	105		191	191			348	348	348		634	634		
106				193				352				642			
107	107			196	196	196		357	357			649	649	649	
109				198				361				657			
110	110	110		200	200			365	365	365		665	665		
111				203				370				673			
113				205	205	205		374	374			681	681	681	681
114				208				379				690			
115	115	115		210	210			383	383	383	383	698	698		
117				213				388				706			
118	118			215	215	215	215	392	392			715	715	715	
120				218				397				723			
121	121	121	121	221	221			402	402	402		732	732		
123				223				407				741			
124	124			226	226	226		412	412			750	750	750	
126				229				417				759			
127	127	127		232	232			422	422	422		768	768		
129				234				427				777			
130	130			237	237	237		432	432			787	787	787	
132				240				437				796			
133	133	133		243	243			442	442	442		806	806		
135				246				448				816			
137	137			249	249	249		453	453			825	825	825	825
138				252				459				835			
140	140	140		255	255			464	464	464	464	845	845		
142				258				470				856			
143	143			261	261	261	261	475	475			866	866	866	
145				264				481				876			
147	147	147	147	267	267			487	487	487		887	887		
149				271				493				898			
150	150			274	274	274		499	499			909	909	909	
152				277				505				920			
154	154	154		280	280			511	511	511		931	931		
156				284				517				942			
158	158			287	287	287		523	523			953	953	953	
160				291				530				965			
162	162	162		294	294			536	536	536		976	976		
164				298				542				988			
165	165			301	301	301		549	549						
167				305				556							
169	169	169		309	309			562	562	562	562				
172				312				569							
174	174			316	316	316	316	576	576			0.5%	1%	2%	2%
176				320				583							
178	178	178	178	324	324			590	590	590					
180				328				597							

TABLE 6 STANDARD PREFERRED RESISTANCE TABLE FOR THREE SIGNIFICANT FIGURE VALUES

6.16 RESISTOR COLOUR CODES. With most wire wound resistors and some special carbon resistors the nominal resistance value is printed on the body of the resistor together with the tolerance.

With most general purpose carbon and metal oxide resistors, and with some low-value types of wire wound resistors, however, this information is indicated by a series of coloured bands painted on the resistor body as shown in Fig 16 (a) and (b).

The colours used, and their significance, are shown in Table 7.



COLOUR CODE MARKING FOR VALUES WITH TWO SIGNIFICANT FIGURES

(a)

COLOUR CODE MARKING FOR VALUES WITH THREE SIGNIFICANT FIGURES

(b)

Fig. 16

COLOUR	FIGURE	MULTIPLIER		TOLERANCE ±%
SILVER	-	10^{-2}	0.01	10
GOLD	-	10^{-1}	0.1	5
BLACK	0	10^{0}	1	-
BROWN	1	10^{1}	10	1
RED	2	10^{2}	100	2
ORANGE	3	10^{3}	1 000	-
YELLOW	4	10^{4}	10 000	-
GREEN	5	10^{5}	100 000	0.5
BLUE	6	10^{6}	1 000 000	0.25
VIOLET	7	10^{7}	10 000 000	0.1
GREY	8	10^{8}	100 000 000	-
WHITE	9	10^{9}	1 000 000 000	-
NONE	-	-	-	20

TABLE 7 IEC STANDARD COLOUR CODE

The following are examples of applications of the colour code:

4.7 Ω ±10%	:	Yellow	Violet	Gold	Silver	
68 Ω ±1%	:	Blue	Grey	Black	Brown	
1500 Ω ±20%	:	Brown	Green	Red		
56.2K Ω ±2%	:	Green	Blue	Red	Red	Red

7. TEST QUESTIONS

1. *State the three forms in which matter can exist.*

2. *What is the essential difference between an element and a compound?*

3. *The central part of an atom is called the .... ; it contains particles called .... and ....; it exhibits a .... charge.*

4. *Surrounding the central part of the atom is a cloud of electrons, each of which has a .... charge. The electrons are accommodated in groups of orbits called .... Each allowed orbit corresponds to a particular .... level.*

5. *Where are the valence electrons in an atom?*

6. *An atom which has an excess of electrons is called a ....*
   An atom with a deficiency of electrons is called a ....

7. *State the laws which relate to charged bodies.*

8. *Name the unit used to measure electric charge.*

9. *What is an electric current?*

10. *The unit used to measure electrical potential difference is the ...... ; a multiple unit one thousand times greater than the basic unit is the ....*

11. *Name five practical sources of electrical potential difference.*

12. *What is meant by the term "electromotive force"?*

13. *The unit used to measure electric current is the .... ; a submultiple unit, one millionth of the basic unit is the ....*

14. *Draw simple graphs to show the nature of (a) direct current; (b) alternating current; (c) varying current; (d) pulsating current.*

15. *Name the four principal effects of electric current.*

16. *Write the formula for determining the resistance of a piece of wire.*

17. *What two factors determine the resistivity of a substance?*

18. *Substance in which the resistance increases with increases in temperature have a .... of resistance.*

19. *The unit of resistance is the .... ; a multiple unit equal to one million times the basic unit is the ....*

20. *State the resistance values and percentage tolerance for the following colour coded resistors.*
    (a) red-violet-yellow-silver .....; *(b) grey-blue-green-brown-red ..... ;*
    (c) brown-black-green ...... ; *(d) yellow-violet-silver-gold ......*

END OF PAPER.

NOTES