The use of materials as electrical insulation

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The article describes those properties of materials which are relevant to their use as electrical insulation. It is emphasized that the mechanical, thermal, chemical and electrochemical requirements are more difficult to meet in this connection than the purely electrical ones. The physical and chemical mechanisms of failure in insulation are described, in particular the intrinsic and non-intrinsic electric strengths, the effects of discharges, thermal instability, tracking and electrochemical changes. The main types of insulation are classified in relation to the equipment for which they are appropriate, and some indication is given of their thermal and electrical limitations. Consideration of materials used primarily as dielectrics for capacitors is excluded.

Introduction

Every electric circuit must be insulated, although in a few cases, such as a transmission line, the insulation is mainly air. The number of requirements which insulation must meet, in different uses, is very great, and no really complete account can be given in a single article. An oddity of the subject is that, although the primary use of insulation is to prevent the flow of current, this is the easiest of all requirements to meet, and the choice of materials is governed much more by thermal, chemical and mechanical factors than by electrical ones. This will become very evident in the course of the article.

Insulation must meet three major needs apart from non-conduction:

(i) it must be mechanically tractable enough to be applied to conductors without excessive cost; in machine- and transformer-windings this limits possibilities mainly to impregnated paper or textile wrappings or, at much greater cost, to a composite material of mica flakes with an adhesive; in cables, it implies either impregnated paper or plastic materials such as rubber, PVC or polythene which can be extruded over the conductor;

(ii) it must be strong and tough enough to maintain the correct separation between conductors and earthed parts, without damage under vibration and short-circuit forces, and without burning or softening under the heat of short-circuit currents; the force on a conductor in a large generator may exceed 100 kg per metre of length, alternating at 50 c/s, and ten times this force under short-circuit conditions; the total force on the windings of a large transformer during a short-circuit is many tons, while at the same time the conductor temperature is increasing by some tens of degrees per second;

(iii) it must be not too much affected, during a life of perhaps 20 years, by a great variety of slow deteriorating influences; the more important of these are described later.

With so many considerations applying in different degree to a large number of materials in various environments, it is impossible in a short article to give any systematic account of the insulating systems used, with reasons for the choice. Table 1, however, states the main facts, and the reader may be able to deduce the reasons for most of them from the discussion of failure mechanisms which follows.

Mechanisms of electrical failure

The designer of insulation needs to know, apart from the large number of non-electrical properties already mentioned, primarily two electrical ones: the stress (v cm^{-1}) at which he may safely operate the insulation and the 'breakdown stress' at which rapid failure can be expected. The latter is important because almost all insulation must withstand 'impulse' conditions arising from electrical oscillations in the circuit, during which the voltage may exceed the nominal value by a factor up to three or four times, for periods between 10^{-7} and 10^{-2} sec. The concept of 'breakdown strength' is, however, a very complicated one. Except for certain special conditions described later, it is by no means an

Table 1 Some main types of equipment and the insulating systems used

Equipment		Typical main insulation
High-voltage generator and motor windings (typically 6·6–22 kv)		Almost exclusively mica flakes or splittings, bonded with shellac, bitumen or a flexible synthetic resin
Lower voltage generator and motor windings (typically 440 v–3·3 kv)		Dependent on the maximum operating temperature
	180 °c	Asbestos or glass-fibre fabric with a silicone resin impregnant
	130 °c	Asbestos, glass or synthetic fibre fabric with a synthetic resin impregnant; typical combination: Terylene fabric with polyurethane or epoxide resin impregnant
	100 °c	Cotton or synthetic fibre fabric with phenolic or other synthetic resin impregnant
Small low-voltage motors		Wires coated with a synthetic resin 'enamel'; coils protected by cellulose press-board 'slot-liners'
Large high-voltage power transformers		Oil-impregnated paper and press-board
Medium power air-cooled transformers		Glass-fibre fabric impregnated with a silicone resin
Small transformers		Enamel covered wire with paper interlayer insulation impregnated with phenolic or epoxide resin
High-voltage cables (typically 33–275 kv)		Exclusively paper impregnated with a hydrocarbon oil under pressure
Medium-voltage cables (typically 3·3–33 kv)		Paper impregnated with a viscous oil, not under pressure Extruded low-loss plastics, e.g. polythene
Low-voltage cables (typically 220 v–3·3 kv)		Extruded rubber, synthetic rubber or PVC For temperatures above 100 °c silicone rubber
Very high frequency cables		Exclusively extruded low-loss plastics, e.g. polythene or polytetrafluorethylene
High-voltage bushings (i.e. terminals) for transformers, switches, cables, etc.		Indoor: Paper impregnated with phenolic resin Mineral-filled cast epoxide resin Outdoor: Paper impregnated with oil and sheathed in porcelain
Outdoor supporting and suspension insulators		Glass or porcelain
Structural parts combining high mechanical strength with insulation		Dependent on operating temperature
	> 500 °c	(e.g. heater elements) alumina ceramics
	500 °c	Mica; asbestos with inorganic binders
	300 °c	Glass-bonded mica dust (Mycalex, Mycalon)
	180 °c 130 °c	Asbestos or glass-fibre fabrics bonded with silicone or epoxide resin
	100 °c	Wood impregnated with oil Wood impregnated with a phenolic resin and compressed ('Compreg') Paper impregnated with a phenolic resin (S.R.B.P.) Cloth similarly impregnated

intrinsic property of the material, but depends greatly upon the conditions of test. Some of the more important factors are: frequency; duration of the test; temperature; presence or otherwise of ionic discharges in the surrounding medium; the thickness of the specimen, since, under ordinary conditions, the voltage withstood is more nearly proportional to (thickness)$^{1/2}$ than to the thickness itself. A value of 'breakdown strength' has therefore little meaning unless the conditions of test are specified in detail. This variability arises from the fact that many secondary processes may contribute to breakdown, each with its own characteristic dependence on experimental conditions.

For a certain type of materials it is possible, in the laboratory, to exclude these secondary mechanisms, and to observe a much higher 'intrinsic electric strength' which is an inherent property of the material, although it may still vary with temperature. It is not yet possible to make practical use of more than a fraction of this intrinsic strength but since its existence sets a target which the insulation designer may aspire to reach, it is described in the next paragraph.

The intrinsic electric strength

The conditions which must be satisfied for an intrinsic strength to exist are the following: the material must be a homogeneous solid, without voids or interfaces where ionic discharges could occur; the electrode system must be such that no discharges strike the insulating surface; the energy loss in the material due to the field must be so small that heating is negligible; the material must be rigid enough that it is not seriously compressed by the electrostatic attraction between the electrodes – this force, usually negligible, may rise to 100 kg cm^{-2} at 'intrinsic' stresses. Relatively few materials meet all the essential requirements but typical intrinsic strengths for a few which do are given in table 2.

Table 2 Typical intrinsic electric strengths at room temperature (MV cm^{-1})

Muscovite mica	10
Borosilicate glass	10
Fused silica	7†
Polythene	6·5
Polystyrene	6·5
Electrical varnishes	3–5
Single-crystal alkali halides	0·5–1

† This value, although an experimental one, is possibly low.

The conditions necessary for attainment of the strengths shown in table 2 can so far be met only in the laboratory, and then only over small areas. Practical insulation is, at present, never homogeneous enough to avoid the effects of ionic discharges, at very high stresses, and often does not meet the other conditions stated. Permissible operating stresses are therefore very much lower than those in table 2. Some typical values, for various kinds of equipment, are given in table 3 and it will be noticed that the convenient unit is now kv cm^{-1} against the MV cm^{-1} of table 2.

Table 3 Typical continuous operating stresses (a.c., r.m.s., 50 c/s) (kv cm^{-1})

Average intrinsic strength of good solids, for comparison	5000
Oil-impregnated paper power capacitors	200
High-voltage oil-paper cables, pressurized	150
Medium-voltage oil-paper cables, not pressurized	30
Large motors and generators – slot insulation	30
Low-voltage wiring	5
Surfaces exposed to outdoor pollution, stress tangential to surface	0·5

Failure by discharges

All practical insulation, except when impregnated with a liquid under pressure, contains inclusions of air, either within the insulation or between it and the conductors. These are collectively known as voids. Their importance lies in the fact that they easily become sites of ionic bombardment of the solid. The latter is then disintegrated, either quickly with formation of a breakdown channel, or slowly, by erosion, according to the local stress. In either case, insulation containing discharges is in course of failure, although the rate may be so slow that a satisfactory life is obtained.

The breakdown strength of a gas is low compared with that of solids. For air at atmospheric pressure it is about 30 kv cm^{-1} for long gaps, rising to about 100 kv cm^{-1} for a gap of 0·01 cm. In practice, the average stress over the insulation at which discharges are initiated varies from 10 kv cm^{-1} for poorly consolidated insulation to 500 kv cm^{-1} for very well-impregnated oil-paper. That the average stress on the insulation may be lower than the stress required in the void arises from the fact that, in plane voids, the stress is increased by a factor equal to the permittivity of the solid.

The determination of the 'discharge inception stress' in insulation is of great industrial importance as indicating its quality. A modern design of apparatus for this purpose is shown in figure 1.

Figure 1 Apparatus for the detection and measurement of discharges in insulation.

The breakdown voltage of a gap is little affected by the material of its boundaries, whether conducting or not. However, if at least one boundary is non-conducting the charge transferred by breakdown remains on the surface and inhibits further discharges until it either leaks away by conduction or is neutralized by a discharge of opposite polarity. In an a.c. field, therefore, there are at least two discharges per cycle, if there are any at all, whereas their frequency in the d.c. case is inversely proportional to the resistivity of the material and can be very low. It is roughly of order $10^{13}/\varepsilon\rho$ where ε is the permittivity and ρ is in ohm cm. In the a.c. case there tends to be, for a given stress, a constant number of discharges per cycle, and hence a total number proportional to the frequency. There are numerous complicating factors which cannot be briefly stated but in general one may say that no discharges at all can be tolerated if either the stress or the frequency is very high.

The damage caused by discharges is of several kinds. If the stress in the solid is low the main effect is to erode pits in the solid, which decrease its effective thickness. This process is comparatively slow. As the average stress is raised the very high local stress at the ends of discharge streamers is able to disrupt the solid locally, and channels of a few micrometres diameter are formed and extended by successive discharges until puncture occurs. This process is known as 'channel propagation' and at high enough stress can be very fast, progressing at, say, 10^6 cm sec^{-1}. By careful adjustment of the voltage it can be made slow enough for visual observation, in a transparent dielectric such as Perspex, and this can form a useful lecture demonstration. It is best done with a needle–plane electrode system, with a few tens of kilovolts on a 1 cm thick sheet, under a clean insulating oil. Channels of this kind are shown in figure 2, although the dielectric in this case was not a solid but an extremely viscous liquid.

Apart from erosion and channel formation by discharges, organic materials are chemically decomposed directly by the impact of ions and indirectly by ozone and nitrous oxides formed in the discharge. The degradation products may cause failure because of the surface conductivity which they produce, but on the other hand this same conductivity sometimes suppresses the discharges themselves. This latter action, however, is very unreliable. Inorganic materials such as porcelain, glass and mica are much more resistant to erosion (not to channel formation) than organic ones. This is chiefly because such materials are already in their most stable chemical state, and a bond broken by ionic impact is likely to repair itself without change of structure. Insulation subjected to intense discharges is likely to fail in a short time through thermal instability induced simply by the heat liberated.

It is difficult to give any brief statement of the discharge intensity which may be tolerated, because this depends so greatly on the type of material and the stress to which it is subjected. However, at high enough stresses in organic materials a charge transfer of one picocoulomb per discharge (or an energy of, say, 10^{-2} erg) can be serious. This is below the limit of visual or audible detection, and it is sometimes difficult to convince non-physicists that invisibly small discharges can be important. Students might be asked to consider that any ionic discharge whatever will contain some ions with energies of 10 ev, while typical chemical bonds have a strength of about 2–4 ev. Further, the equivalent kinetic temperature of a particle is about 10^4 degK ev^{-1}, against some 500 degK needed for thermal degradation.

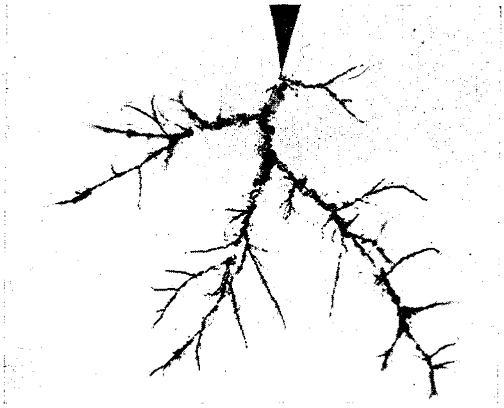

Figure 2 Breakdown by channel propagation. (*Photograph by* Z. Krasucki).

The influence of discharges upon the design of high-voltage insulation

The need to postpone the onset of discharges to the highest possible stress, and to minimize their effects when they do occur, has a major influence on the design of all high-voltage insulation.

If the insulation can be completely sheathed in metal, as in cables or large capacitors, the highest working stress can be obtained from a porous insulator, almost always paper, impregnated *in vacuo* with an insulating liquid. If the impregnation has removed all gas, no voids, and therefore no discharges, exist at the working voltage. But if a certain value, called the 'discharge inception stress' is exceeded, as possibly by a voltage surge during operation, microscopic gas bubbles are formed in the liquid. These may dissolve harmlessly, but if the insulation is overstressed they are occupied by a discharge which produces more gas, so that the bubbles and the discharges grow unstably until failure occurs. In this type of insulation, the discharge inception stress also depends on the dryness of the paper, because water can be electrolysed to form gas even in an a.c. field. About 0·1 % of residual moisture may be significant. Values of discharge inception stress exceeding 1000 kv cm^{-1} can be achieved in the laboratory, but half this value is very good in practice.

In cables for use above about 33 kv, the liquid, normally a hydrocarbon oil, is maintained under hydrostatic pressure to prevent bubble formation, and such cables may have operating stresses of up to 150 kv cm^{-1}. In lower voltage cables it is not economic to provide pressure, and these are intentionally used in a discharging condition but at so low a stress that a long life is still obtained.

If discharges are tolerated there is less reason to use paper as insulation, and many cables for the range below 30 kv are now made by extruding a sheath of some plastic, usually polythene, PVC or a synthetic rubber, around the conductor. The permissible stress in such cables depends entirely on the perfection with which voids can be kept to a minimum size.

For the windings of rotating machines, liquid impregnation is impracticable. Moreover, the temperature is often higher than the limit, about 100°C, for paper, and considerable strength against vibration and mechanical stress is also necessary. For the largest high-voltage machines, such as turbogenerators, the insulation consists of a sheet material built up from mica flakes or splittings with an adhesive, which is then wrapped and pressed on to the conductors in heated presses. The adhesive, which is normally shellac, bitumen or a synthetic resin, is in a semi-liquid state during the wrapping operation, but ultimately becomes solid by either loss of solvent or polymerization.

Machines of lower size and voltage may still have mica insulation but a much wider range of impregnated fabrics may be used instead, depending mainly on the operating temperature and the required resistance to moisture. A few examples, with some limiting characteristics are: paper or cotton fabric (105°C); Terylene fabric (130°C, but hydrolyses at this temperature if damp); asbestos or glass-fibre cloth (temperature limit set by the impregnant). In damp operating conditions asbestos is a relatively poor insulator and the glass must be a borosilicate, since soda glasses readily form sodium carbonate.

All such porous insulation must be impregnated with a varnish, applied either with a solvent which is subsequently evaporated, or, what is much better, with a solventless polymerizing varnish with which the coils are impregnated *in vacuo*. Varnishes in use include phenol-formaldehydes, polyurethanes, epoxides and silicones. Their limiting temperatures depend upon their formulation (all are complicated mixtures) but roughly the first is suitable up to 130°C and the last to 180°C. The other two fall within this range.

Neither in cables nor machine windings is it possible in practice to make good enough contact between insulation and a solid metal conductor to eliminate large voids and consequent serious discharges at the interface. All high-voltage insulation is therefore terminated, so far as possible, with a flexible semiconducting layer between it and the metal. This takes various forms, to suit the mechanical requirements. In oil-paper cables it is usually a layer of paper impregnated with carbon black, possibly backed with a layer of metallic foil or tape. In extruded plastic cables it is often an extruded layer of plastic compounded with carbon black. In machine windings, the coils may be over-wound with a semiconducting tape, or painted with a semiconducting varnish.

In large high-voltage transformers the conductor insulation is invariably paper, immersed in oil, while the main insulation between coils and to earth is either press-board (a variety of thick consolidated paper) or a synthetic-resin-bonded paper board or tube. Smaller air-cooled transformers may have glass-fibre insulation, impregnated with a silicone resin. Semiconducting shielding against discharges is mechanically impracticable for most of the insulation in a transformer, so the operating stress should be kept below the limit of discharge inception.

Failure by thermal instability

All insulation experiences a rise of temperature in an electric field, energy being converted to heat either by a conduction current in a d.c. field or by the electrical equivalent of friction in an a.c. one. This heat production increases roughly exponentially with the temperature of the insulation. On the other hand, the heat lost by cooling increases more nearly proportionally to the temperature rise. This situation necessarily involves instability, since at some high enough field and temperature the slope of an exponential curve must exceed that of any linear one and no further rise of temperature can then dissipate as much heat as is produced. Nor can this instability be prevented by cooling the exterior of the insulation, since the interior temperature will still rise unstably at some, though higher, value of the stress. If the geometry is sufficiently simple, this form of failure lends itself better to mathematical solution than any other. For example, in the case of a flat slab, in which both the field and the direction of heat flow are normal to the surfaces, the maximum d.c. voltage which can be applied without thermal failure is given by

$$V_{\max} = (8k/a\sigma_0)^{1/2}$$

where k is the thermal conductivity and a and σ_0 are the constants in the expression for the rise in conductivity with temperature, namely $\sigma = \sigma_0 \exp(a\theta)$. The surfaces are assumed to be held constant at any arbitrary temperature $\theta = 0$. It may be noted that this formula does not contain the thickness of the slab and results in a maximum voltage, not a stress, implying that even an infinite thickness of insulation will not withstand more than a finite voltage. For reasonably good insulation, at a frequency not above 50 c/s, this limiting voltage usually lies in the range 1–10 MV but it falls approximately as (frequency)$^{1/2}$.

Thermal stability tends to be a limiting factor in very high-voltage cables, say at 275 kv and higher, and also in large power-capacitors, where the heat-flow path is usually long. In poorer insulation with a high loss due to moisture or ionic impurities it may occur even at low working stresses. At radio frequencies combined with high voltage it is always a limiting factor and low-loss insulation is essential. This is usually a non-polar plastic, such as polythene, for cables, and for capacitors mica, steatite (a magnesium silicate) or a borosilicate or lead silicate glass.

Failure by tracking

When insulation is used primarily as a mechanical support, say between terminals on a board or between a transmission line and earth, the field is necessarily more or less tangential to the insulating surface. This surface, being exposed to the atmosphere, is always covered with a thin film of dirt and moisture which constitutes an electrolyte and carries a small leakage current. Whenever this film dries out, owing either to a change in humidity or to self-heating by the current, microscopic arcs occur where the current is interrupted by breakage of the film. On thermally resistant materials no damage is done but on some organic materials (notably phenolic resins) each arc leaves a minute carbonized area, which can act as a nucleus for repetition of the process when the film next dries out. Ultimately (possibly after many years of service) a carbonized track forms over the whole distance between conductors and complete failure ensues.

This trouble can occur only in materials which pyrolyse to form coherent carbon, and its severity varies greatly from one organic material to another. It is generally worst in materials containing a high proportion of aromatic carbon rings. A standard test for the property consists of determining the voltage needed to cause failure in a fixed time under standard conditions of pollution. The value of this voltage is known as the 'comparative tracking index'. It is undesirable to use any exposed organic surface to support a voltage greater than its comparative tracking index whatever the clearance allowed. The rule may sometimes have to be broken in the case of high voltage, but a certain proportion of failures may then be expected at intervals during service.

A different form of tracking occurs in the presence of voltages high enough to cause vigorous surface discharges. The formation of carbonized areas is then not necessarily dependent on the presence of pollution, but failure will be much more rapid if a moisture film is also present. The surface of organic materials out-of-doors is also contaminated through photolysis by the ultra-violet component of sunlight.

Related to tracking is the so-called 'migration' of metals across insulating surfaces. Some metals, notably silver and to a less extent copper, can form ionic solutions in the surface film of moisture and later be reduced to metallic form elsewhere on the surface, producing dendritic paths which ultimately short-circuit the gap. The effect is greatly accelerated by some impurities, for example the catalysts in phenolic resins. Silver is so prone to this action that it should not be used in contact with insulation. It can be quite cheaply replaced by gold plating, which is immune from migration.

Electrochemical failures

All insulation contains some free ions, which in general become more numerous and more mobile with increasing temperature. Insulating materials therefore behave as very weak electrolytes in which matter is constantly being transported to the electrodes. The effects are worst with a d.c. stress, but many of the reactions are not reversible and are therefore important at power frequencies also. In very good insulation, the effects are quite undetectably slow, but in practice a great variety of impurities leads to corrosion and ultimate failure. Only a few examples can be cited here: in thermosetting polymers, unreacted components and catalysts; in textiles, spinning lubricants; in mouldings, die lubricants and, sometimes, unsuitable fillers. In inorganic materials the most troublesome impurity is sodium. At high temperatures the sodium ion is quite mobile in glasses and porcelain. Figure 3 shows the result of using sodium instead of potassium felspar in porcelain used for the former of a resistor. The white incrustations consist of sodium carbonate, and the wire has been corroded through.

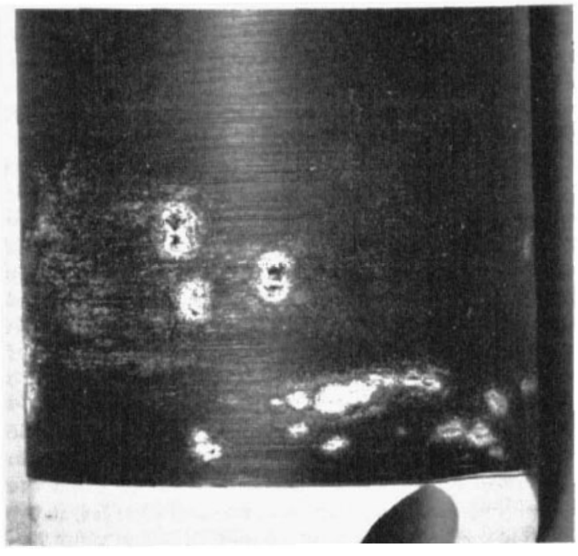

Figure 3 Electrochemical attack from sodium in a porcelain former. (*Photograph by* H. F. Church).

Since organic impurities usually electrolyse to form an organic acid at the anode, a copper electrode will be attacked, and copper ions pass into the material. One standard test for assessing the electrochemical activity of insulation is based on this effect. Pairs of thin copper wires are stretched in contact with the material to be tested and maintained for 24 hours in a hot and almost saturated atmosphere with a d.c. voltage between the wires. The degree of attack on the copper is estimated by the loss in tensile strength of the wires. The conductivity and loss angle of insulation are also measures of its ionic content, but to apply these criteria it is necessary to know the values expected from uncontaminated samples.

Moisture also must be regarded as an ionic impurity, since it will electrolyse to give nascent oxygen and hydrogen, both of which are powerful corrosive agents under suitable conditions.

Very occasionally a purely chemical trouble is encountered. For example, Neoprene (a chlorine-containing synthetic rubber) has been compounded with antimony sulphide (a filler often used with natural rubber). However, Neoprene and the sulphide react in the presence of light to give antimony chloride, with production of a very conductive solution of the chloride on the surface.

Conclusion

This article should impress upon the student the great variety of considerations which enter into the design of insulation.

Overriding considerations are mechanical tractability, to allow the insulation to be applied, and stability against thermal deterioration.

The most important electrical considerations depend upon the nature of the field. At high a.c. stresses, avoidance of discharges is of prime importance. At high frequencies, a low loss angle is essential to avoid thermal instability, with avoidance of discharges equally important if the voltage also is high. In d.c. fields, chemical purity becomes predominant.

These divisions are, however, only rough indications. All the mechanisms of failure are operative at some rate under most conditions, and progress toward the industrial use of the high intrinsic electric strength of materials depends upon progress toward elimination of all the causes of failure simultaneously.

Exhibition reports

Manufacturers' exhibition at the ASE annual meeting

Imperial College London, 2nd–5th January 1968

Although more than 80 manufacturers were represented their displays did not suffer from lack of space. The difficulty lay in finding the 16 or more rooms in three buildings and the elusive manufacturer who did not seem to be listed in the catalogue. This report cannot hope to do more than mention some of the equipment which has appeared since the last annual meeting.

Advance Electronics showed their SC 3 four decade digital timer/counter which uses the mains frequency as a reference standard and costs £95. This can also be used as a frequency meter or tachometer with remote control of start and stop via the terminals (not 4 mm) at the rear. Both this firm and Venner Electronics also showed more expensive crystal-controlled models.

New scalers suitable for school use were the 905 C from Research Electronics and one from Griffin and George which enables resetting by operation of only one push button. Griffin and George had its own 3 cm electromagnetic wave apparatus and, at about £30, a simple x-ray source which will enable a limited range of safe experimentation.

The much more versatile and expensive Teltron x-ray set TEL 560 has now started production. Teltron also showed their double beam (fine beam) tube and a very versatile photocell tube for measurements of Planck's constant, which shows the principle of a photomultiplier and also, if our notes are correct, a determination of e/m.

Overseas firms may well find increased difficulties due to devaluation, but Russian measuring instruments imported by Derritron, who promise servicing in the U.K., were at competitive prices. Their P 4002–1