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ELECTROLUMINESCENT PANELS

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Through continual research in the field of electroluminescence, considerable improvement has been obtained in the emittance, efficiency and life of electroluminescent devices. This improvement is reflected in their increasing use in industry and commerce in the form of mimic diagrams, illuminated boards and signs, 'light-operated' relays and alpha-numerical display. The article describes in some detail the fabrication, function and characteristics of some simple a.c.-powered luminous panels called 'Phospholites' and briefly outlines the construction and operation of one of a group of more complex panels to which the Company has applied the generic title of 'Phosphotrons'. The author concludes with future possibilities in electroluminescence research, particularly in regard to d.c. and low-voltage application in the telephone industry.

IN 1936 Destriau described experiments in which he had observed that certain materials emitted light when placed in an electric field. Since this time, these materials, called electroluminescent phosphors, have been improved to such an extent that this new light source is now becoming technically important. Because the Company has a keen interest in methods of data display, whether it be a simple switchboard lamp or a complete totalisator, the Laboratories have pioneered a number of electroluminescent devices.

The manufacture of a simple electroluminescent panel, known as a Phospholite, can be divided into four stages.

(*a*) Preparing the phosphor.

(*b*) Sandwiching the phosphor in a suitable binder between the plates of a capacitor; one plate must be transparent, so that light can escape from the device.

(*c*) Assembling the lamp unit made in stage (*b*) into a suitable frame to allow easy fixing.

(*d*) Testing and life-testing.

Phosphors

Preparation

All phosphors made at the Works are prepared from zinc sulphide and zinc selenide. Neither of these substances is a phosphor in the pure state, and it is necessary to incorporate traces of certain metallic impurities, known as activators, into the crystals in order to produce phosphors. A typical addition is about 1 part in 10,000 of a copper salt to pure zinc sulphide. After intimate mixing, the material is fired in a high temperature furnace, and the copper actually penetrates into the zinc sulphide crystals, so that every ten thousandth zinc atom is replaced by a copper atom. The material is removed from the furnace and crushed into a fine microcrystalline powder, which glows brilliantly when placed under an ultraviolet lamp. Nevertheless, such a powder is still not an electroluminescent phosphor, and a further chemical process involving washing the powder to form the correct surface on the individual crystals is necessary before the phosphor is useful.

Colour

The zinc sulphide phosphors tend to give a blue luminescence. When other colours are required, the desired shift towards the red end of the spectrum is obtained by the addition of increasing amounts of zinc selenide. Colour is also affected by the firing conditions in the furnace and by the kind of impurities added. Any colour, from the deepest blue through green and yellow to deep orange can be produced, but red phosphors tend to be inefficient.

Luminescence in a.c. Field

The reasons why crystals prepared in this way light up when placed in an electric field are not precisely known, but a general picture of the phenomenon has been built up which explains most of the observed facts.

When the electric field is applied across the crystal, electrons are attracted to the positive side of the crystal. Some of these electrons come from the copper impurity atoms. When the electric field is reversed, the electrons travel back towards the side from which they came, and some will recombine with the empty copper atoms. It is when this recombination occurs that a flash of light is emitted. By applying an a.c. field across the crystals, electrons are continually switched from one side of the crystal to the other, and recombination occurs at the copper atoms on alternate sides of the crystal each time the field changes. At 50 c/s there will be 50 flashes from each side of the crystal, making 100 flashes per second, but the eye cannot respond to such rapid variations and simply sees a continuous glowing light.

The necessity for the copper impurities is explained by these arguments, but the reason for the special surface treatment is not intuitively obvious. It has been shown that this treatment increases the number of electrons which are extracted from the impurity atoms, this extraction mainly occurring close to the surface.

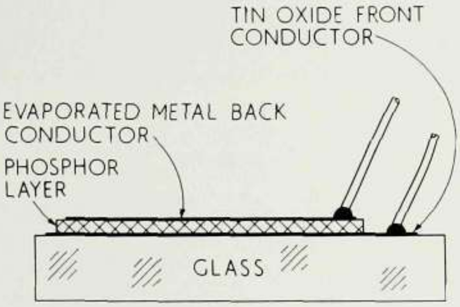

Figure 1—Cross-section of lamp unit

Lamp Unit Construction

There are several methods of embedding the phosphor between the plates of a capacitor, depending on the type of binder used to hold the loose powder together. The Phospholite is made by spraying on the phosphor as a paint in which the phosphor acts as a filler and the binding material is an epoxy resin. Thinners are used and the technique of applying the phosphor is very similar to ordinary spraying except that the thickness has to be controlled very accurately.

A diagrammatic cross-section of the complete lamp unit is shown in Fig. 1. The starting point is a sheet of glass which has a very thin film of tin oxide on its surface. This material has the remarkable property of being a good electrical conductor whilst being substantially transparent. The tin oxide forms the front conductor of the capacitor and the phosphor paint is sprayed on to it and allowed to dry and harden. The back conductor is applied as a thin metal film by means of a vacuum evaporation technique similar to that used for making mirrors, and wires are joined to the tin oxide front conductor and the metal back conductor. At this stage, the essential part of the panel is finished, and on applying the 240-volt 50 c/s a.c. mains to the lead-wires, the phosphor lights up. Viewed from the front, through the transparent tin oxide, the whole of the phosphor layer can be seen to be glowing with a soft and velvety light.

Although the lamp unit will work at this stage, it is too vulnerable to atmospheric attack to be allowed to stay long in this condition, and a backing glass is sealed by use of a special adhesive. The glass completely covers the working area of the Phospholite and protects the phosphor from the atmosphere. Once protected in this way, the storage life of the Phospholite is excellent, and the panels can be run under water without deterioration.

Framing

The lamp unit, although technically a complete device, is awkward to handle and fix. For these reasons, all Phospholites have a frame which not only permits the provision of fixing holes but also gives an attractive finish to the complete device. Fig. 2 shows a group of electroluminescent devices made by the Company. The PS2 and the PS6 are typical Phospholites used for illuminated indicator boards and they are also finding applications as illuminated signs. In these types, the lamp unit is placed in a vacuum-formed p.v.c. frame, and epoxy resin is poured into the back of the frame to make a weatherproof seal. In front of the lamp unit is a perspex plate which can be engraved, or silk-screen printed if desired. Also shown in Fig. 2 is a more complex type, the Phosphotron[1] Type P40 alpha-numerical display. This differs from the simple Phospholites in having the back conductor broken up into a pattern of segments. By selecting groups of conductors, any letter or number can be lit up and the figures changed by simply altering the electrical connections. The devices are not framed in p.v.c., but are cast directly on an epoxy resin moulding in metal moulds. Once again a sealed finish, which is easy to fix, is obtained.

Testing and Life Testing

The most attractive feature of the Phospholite is its inherent reliability and robustness. Rigorous test specifications have been laid down in order to detect any faults. The initial test specification of the Phospholite is primarily concerned with:—

[1] 'Phosphotron' is the Company's registered Trade Mark for more complicated electroluminescent devices.

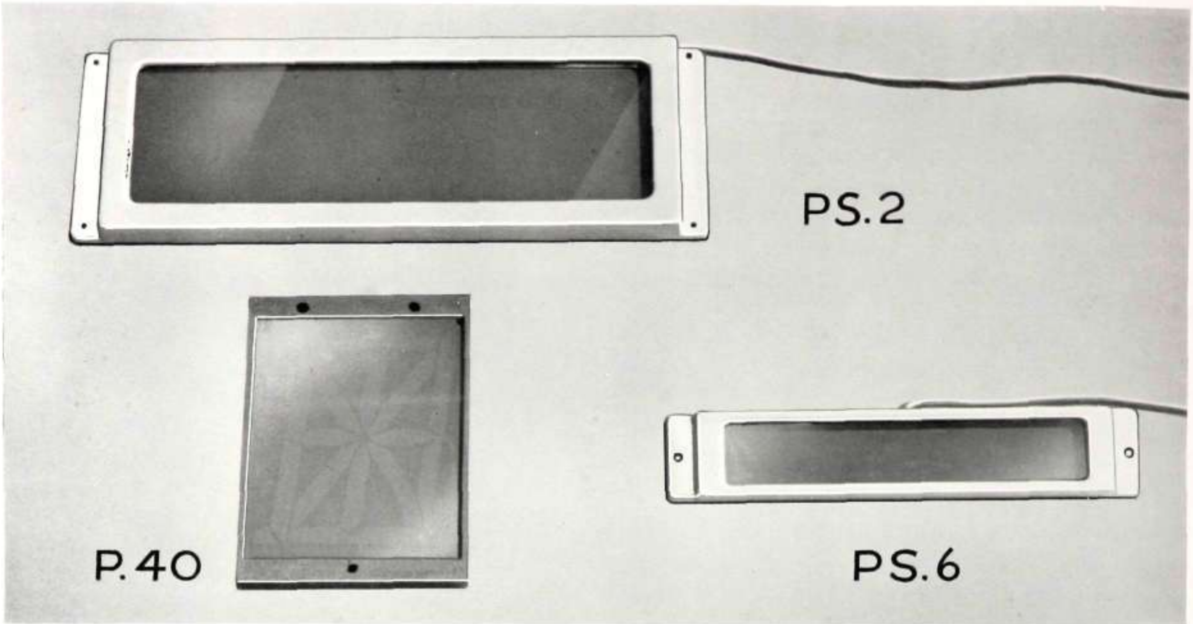

Figure 2—General view of group of electroluminescent devices
(*a*) **PS2 Phospholite** (*b*) **PS6 Phospholite** (*c*) **P40 Phosphotron**

(*a*) Surface Brightness
(*b*) Breakdown Voltage
(*c*) Visual appearance

Surface brightness is measured with calibrated selenium photocells, which have a relatively slow response and, like the eye, average out the pulses of light to give a steady measurement. Brightness of the panels is allowed to vary by no more than $\pm 10\%$ of a nominal figure, and this variation is about the limit which can be detected by the eye when two panels are placed side by side. To secure this close tolerance on brightness, it is necessary to control the thickness of the phosphor layer to

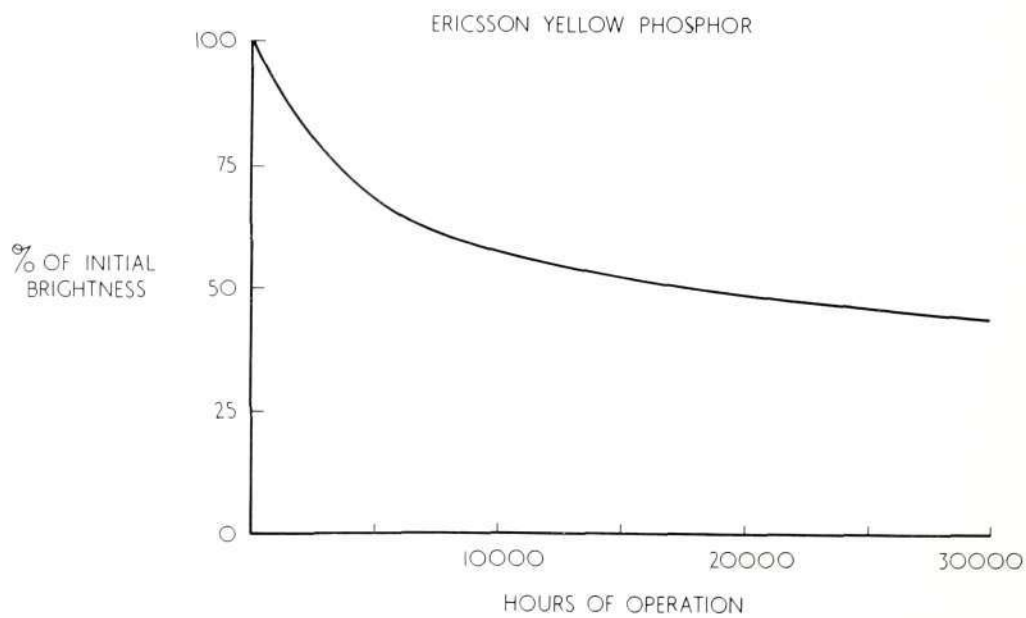

Figure 3—Luminescence decay in yellow phosphor

better than ±5%. Thus the spraying operation has to be very tightly controlled.

All panels are tested to ensure that they will withstand a substantial over-voltage for a period of time. One such test done on every panel is an 80% over-voltage test for half an hour. All panels are also switched on and off once per second for half an hour to ensure that there are no internal contact troubles.

Visual inspection of the panels is partly directed to ensuring that the external finish is of high quality, but is also concerned with the appearance of the glowing surface. Any black spots that are plainly visible from a distance of five feet cause rejection of the panel.

Life testing follows the initial tests in that it is concerned with surface brightness and breakdown, and in any visual changes in the glowing surface. The only change which actually occurs during the life of Phospholites is a slow decay of luminescence. Fig. 3 shows the way in which this occurs for a yellow phosphor panel. Even after two years of continuous running, the panel has still not decayed to half its initial brightness, and the rate of decay thereafter is extremely small. Catastrophic failures are unknown, and this is the outstanding difference between the Phospholite and, for instance, the filamentary lamp.

Phospholite, Characteristics and Applications

The surface brightness of the Phospholite depends upon the voltage and frequency of the applied a.c. The peak voltage determines the peak field applied to the phosphor, and the greater this field the more electrons are extracted from the copper activator atoms. Fig. 4 shows how the brightness increases rapidly with voltage. The dotted curve in the figure shows the effect of spraying the phosphor layer to half the normal thickness. The brightness is greatly increased but the mean breakdown voltage has been reduced from 1000 to 400. This is the voltage at which the phosphor layer punctures and a black patch appears on the Phospholite, spoiling the smooth appearance of the glow. Obviously it is possible to obtain high brightnesses by using thin layers, but only by running a greatly increased risk of dielectric breakdown. Since reliability is one of the great assets of electroluminescence, the designers of the Phospholite have chosen a phosphor layer thickness which is absolutely safe from this risk.

A surface brightness of 1 lumen/sq. ft. can be pictured by thinking of a white card in twilight. Thus, Phospholites worked from the 50-c/s 240 V mains appear bright in the dark, are visible in twilight, but are not visibly lit in full daylight. It is of interest to note that the standard PS2, which has an illuminated area of 10″ x 3″ (25.4 x 7.6 cm) consumes only about ¼ watt of electric power, and for many purposes this saving in power consumption more than compensates for the modest brightness. One way of making Phospholites brighter is to run them from a higher frequency, keeping the voltage at 240 volts. As the light is actually made up of pulses at a repetitive rate of twice the frequency, increasing the frequency increases the number of light pulses per second. The eye smooths out the individual pulses, but if the pulse rate is increased, the total light energy emitted per second increases, and the visual effect is a proportional increase in brightness. Increasing the frequency to 400 c/s therefore produces an eight-fold increase in brightness.

Whilst this technique is now commonplace in technical applications, it requires special power supplies, such as transistor oscillators, and would be too expensive for domestic applications. For this reason, the present Phospholites are being employed at 400 c/s only in special technical fields, such as mimic diagrams, data display systems and film recording. In the consumer market, for signs which

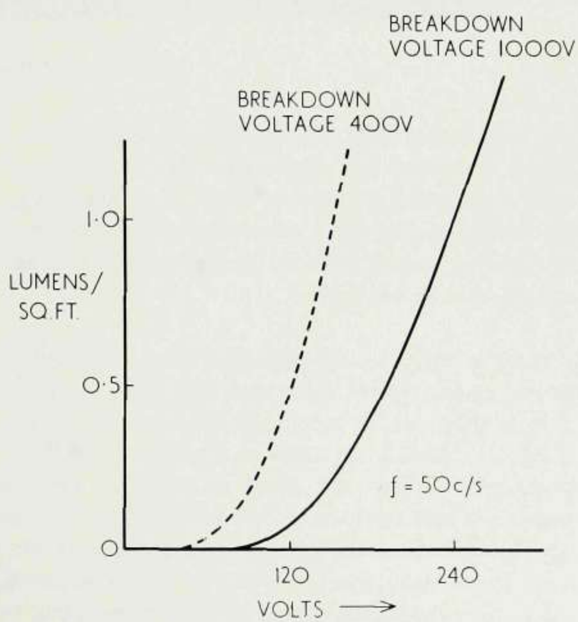

Figure 4—Increasing light intensity by voltage increase

(a)
During Daylight

(b)
In twilight

(c)
At night

Figure 5—Behaviour of Phospholite

are illuminated only at night, the ordinary 50 c/s mains is used as the supply and Fig. 5 shows how such a Phospholite becomes useful as darkness falls. By using a special 400 c/s transistor power supply, a Phospholite can be made visible in normal roomlight should this be required.

Another application of Phospholites is their use in providing one type of 'light-operated' relay. In these devices there are no moving parts, but an electroluminescent panel is arranged to illuminate a group of photocells. When the panel is switched off the photocells pass no current, but when the panel is lit up the cells become conductive and pass current. The device corresponds exactly to the conventional relay; the electroluminescent panel corresponding to the coil, and the photocells to the contacts, which close when the coil is actuated. These solid state relays would seem to have an important future in certain specialized switching fields.

Reverting to the use of Phospholites and Phosphotrons for visual display, their advantages can be summed up as follows:—

(*a*) Extreme reliability and ruggedness.
(*b*) Small thickness.
(*c*) Low power consumption.
(*d*) Range of distinctive colours without using filters.
(*e*) Wide viewing angle because the light is emitted close to the front of the device.

FUTURE POSSIBILITIES

Whilst the present phosphors are good enough for a number of useful applications, every improvement in brightness or efficiency extends these applications into new fields. Theoretically, electroluminescence can be shown to be capable of producing far higher efficiencies than are at present attained, so that research work is likely to yield rich prizes. Fundamental research into luminescence forms a big part of the physics publications of the Soviet Union, and several companies in the United States have large programmes of research and development in electroluminescence. One line which is being actively investigated is the production of electroluminescence in single crystals when d.c. is passed through them. D.C.-electroluminescence would have immediate applications to a number of problems in the telephone industry, where the present a.c.-type cannot be used on any scale because of the risk of introducing a.c. hum into the speech paths. Similarly, the use of electroluminescence in the telephone industry will be greatly encouraged when lower voltages can be used. It seems likely that all these improvements, giving low-voltage d.c.-operated lamps at high efficiency, will be effected in the next few years. The crucial problem is not, therefore, whether it can be done, but when it can be done cheaply and simply. On the answer to this question depends the future of electroluminescence; either it will remain as it is now, a technique important only in special applications, or it may become the basis of a completely new lamp industry.

U.D.C.621.395.91

A LOW-COST TIME ANNOUNCER

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The new Time Announcer described has been designed to satisfy a genuine and recurrent need for a reliable but inexpensive time service sufficiently accurate to meet all normal requirements. The machine uses a magnetic-type recording medium and gives 'time of day' announcements at 10-second intervals when a designated number is dialled. Provision is made for two types of speed control, i.e. synchronous drive for a.c. mains and d.c. pendulum drive for areas where a mains supply is unreliable or not available.

THE use of Time Announcers with telephone systems is now becoming quite common and represents a useful source of revenue to an Administration. The new Time Announcer, or Speaking Clock, has been developed for use where an economically priced equipment is required with a degree of time accuracy sufficient for normal domestic requirements. No attempt has been made to achieve higher time accuracy because of the much higher costs involved in the production of the clock and in its subsequent maintenance.

The Announcer, illustrated in Fig. 1, is simply a recording and reproducing machine with the necessary time announcements stored in it. By driving the machine at the correct speed a series of announcements are generated and, when the designated number for the system is dialled, the appropriate time announcement is amplified through distribution amplifiers and applied to the caller's line. Special anti-crosstalk circuits are included in the connections between subscribers and the amplifier output to prevent conversation across the clock circuit.

The machine is designed primarily for 12-hour repetition but, as will be seen later, provision can be made for 24-hour time with very little change to the mechanism. Time-of-day announcements are recorded and reproduced by standard magnetic recording techniques on a neoprene-surfaced drum, the neoprene being loaded with a magnetic oxide which acts as the recording medium. The time is given at 10-second intervals, since to provide a higher rate of announcement would result in loss of intelligibility and a lower rate would give long silent periods between signals.

Considerations of Accuracy

If a number of messages are recorded on a drum of the type mentioned, and means are provided to reproduce these messages in the order in which they were recorded, it is possible to provide an accurate clock simply by rotating the drum at the required speed. Accuracy of the clock would be determined solely by the drive speed of the drum, the drive being essentially of the non-slip type. To obtain high accuracy of drive as provided by T.I.M. in the B.P.O. system a phonic motor could be used, driven from a stable high frequency oscillator through a series of frequency dividers, but this arrangement would be much too expensive for the type of machine now under discussion and would in any case provide for greater accuracy than is required.

Fortunately, there is a readily available form of stable frequency supply in the a.c. mains. This supply, although subject to short term inaccuracies, is corrected daily during off-peak periods so that the correct number of cycles is supplied in a twenty-four hour period. Thus, by using a synchronous drive, an Announcer will keep correct time for very long periods and be subject only during periods of heavy load to small errors which will be automatically corrected.

This simple and economic arrangement, which ensures a degree of accuracy more than adequate for all practical timekeeping requirements, is used in the a.c. version of the new Time Announcer.

In areas where the mains supply is not so well regulated, another system of speed control is necessary. This is obtained by utilizing the pendulum master clock in the main exchange in conjunction with suitable circuits to provide precise timing pulses to the drive motor. For these installations a d.c. motor is used, powered from the exchange battery.

Both a.c. and d.c. versions of the Announcer are identical except for the driving motors used and the need for the inclusion of a relay-set and timing shaft in the d.c. machine.

The Announcer is a self-contained free-standing unit with approximate overall dimensions 11½″ x 12″ x 13½″ (29 x 30 x 34 cm), and may be placed on a table or wall shelf, or accommodated on a standard equipment rack 19″ or 30″ (48 or 76 cms) wide. The equipment is protected by a dust cover.

THE A.C. TIME ANNOUNCER

FORM OF ANNOUNCEMENT

Announcements are made every ten seconds in the form:

" The time is ten twenty-seven and ten seconds ".

To cover the full twelve-hour period, a total of 4320 messages is required if each announcement is regarded as separate from every other. This recording problem is minimized by sub-dividing the message into four parts as indicated below:

"The time is ——	(Preamble)
——— ten ———	(Hours)
—— twenty-seven ——	(Minutes)
—— and ten seconds."	(Seconds)

Synthesizing the announcement in this manner reduces the number of recorded messages required to 79, this total being composed of the standard preamble, together with 12, 60 and 6 messages for the appropriate hour, minute, and 10-second periods. The word ' o'clock ' is used in the minutes message instead of ' sixty ', and the word ' precisely ' instead of ' and sixty seconds ' in the seconds messages. Announcements at the exact hour and completed minute are then given in the following form:

" The time is ten o'clock precisely."

" The time is ten o'clock and ten seconds."

" The time is ten seventeen precisely."

Each 10-second cycle also includes a silent period during which the stepping and releasing of the heads occurs.

The cycle is divided as follows:—

Preamble	0 to 1·95 secs.
Hours	1·95 to 2·95 secs.
Minutes	2·95 to 4·49 secs.
Seconds	4·49 to 7·19 secs.
Stepping Period	7·19 to 10 secs.

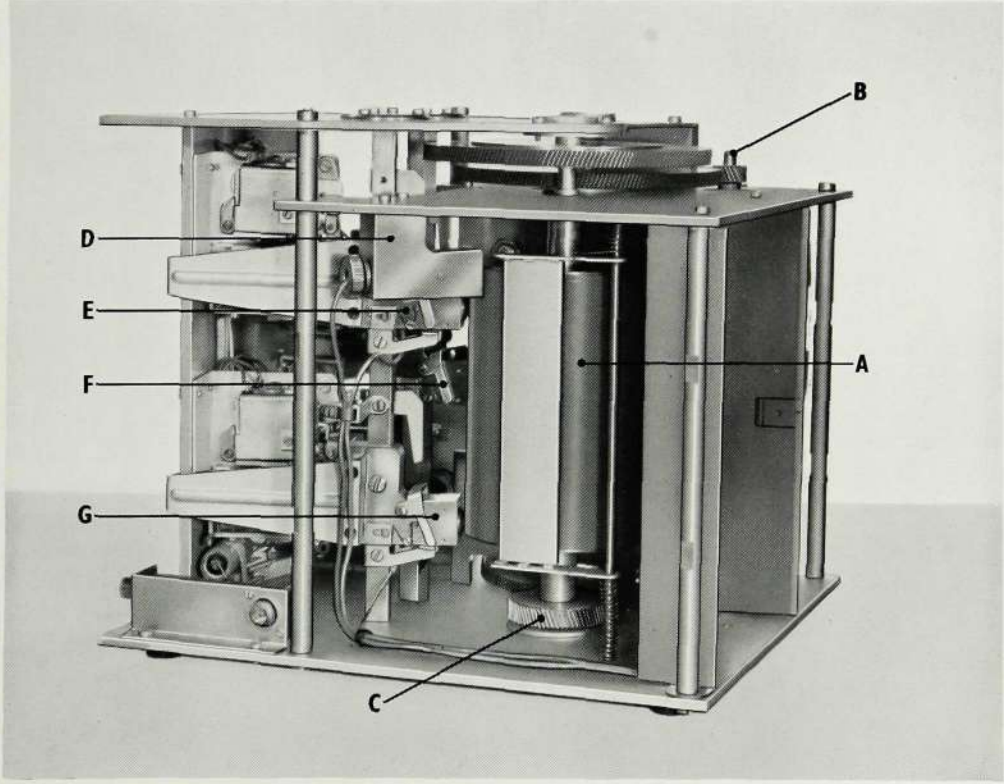


Figure 1—General View of a.c. Time Announcer with dust cover removed

A = Neoprene-surfaced drum.
B = 83⅓: 1 reduction gear train.
C = 3: 1 reduction gear train.
D = Preamble Head.
E = Hours Head.
F = Minutes Head.
G = Seconds Head.

The figures quoted are for an Announcer with recordings in English; some change in the values is usually necessary for recordings in other languages.

Each of these periods is maintained below $3\frac{1}{3}$ seconds, as this is the time taken for one revolution of the magnetic drum and a longer message could not be recorded on one peripheral track. The tracks are individually scanned three times during the 10-second cycle but provision is made to connect each head in turn to the amplifier for only that period allocated to its portion of the message. These connections to the amplifier are made via four springsets operated by cams on a shaft rotating every 10 seconds, the cam dwell-times being so arranged that discontinuities in the announcement are avoided.

ANNOUNCER MECHANISM

The mechanical arrangement of the Announcer may be seen by further reference to Fig. 1.

The drum (A) is driven through a two-stage $83\frac{1}{3}$:1 reduction gear train (B) by a 1500 r.p.m. motor to obtain a drum speed of 18 r.p.m. or $3\frac{1}{3}$ seconds per revolution. By use of an additional reduction gear (C) with a 3:1 ratio, a camshaft at the rear of the drum is arranged to rotate at the required speed of 1 revolution every 10 seconds.

Four reproduce-heads (D, E, F and G) are individually employed for the preamble, hours, minutes, and seconds messages. The preamble-head has a fixed position and reads the same track on the rotating drum continuously, whereas the hours,

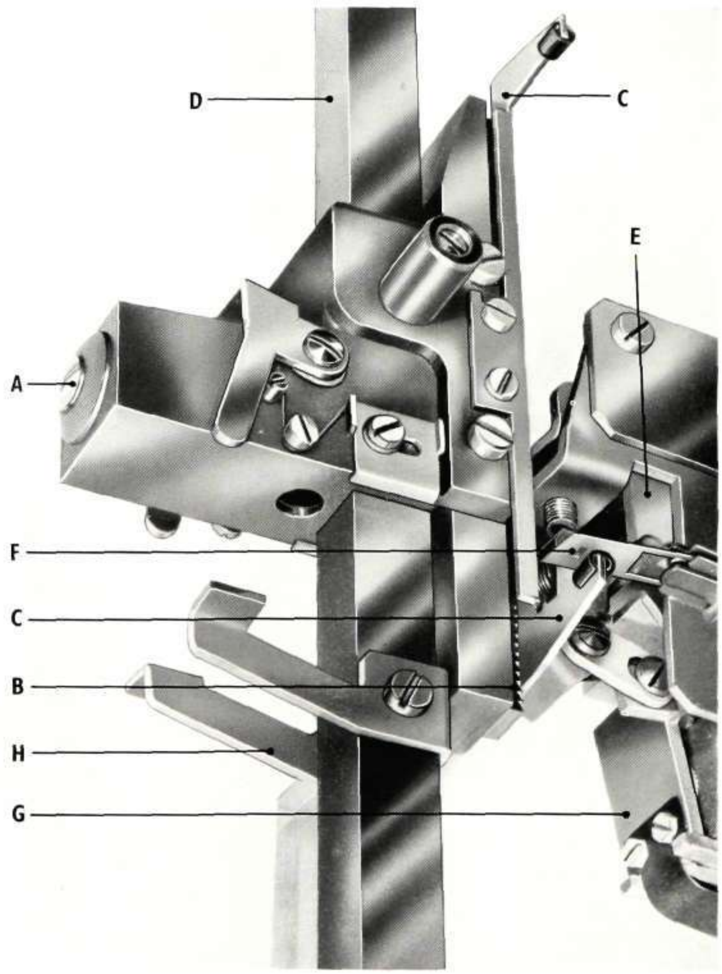


Figure 2—Close-up of minutes-head mechanism

A = Reproduce Head.
B = Vertical Ratchet.
C = Extensions of Forked Bracket.
D = Shaft.
E = Stepping Magnet Frame.
F = Toggle Switch.
G = Release Magnet Armature.
H = Bottom Stop.

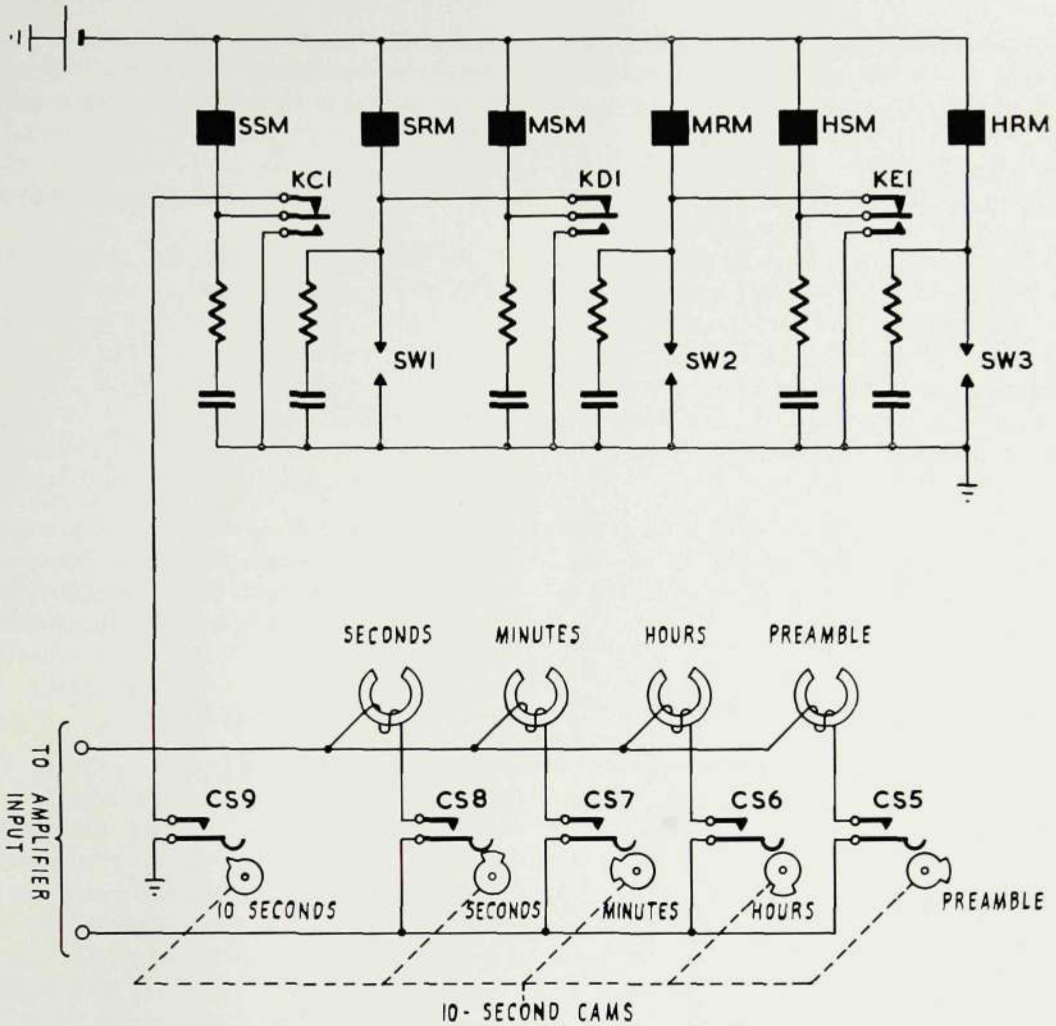


Figure 3—Simplified Schematic for interlocking of recording heads

minutes and seconds heads step over a number of positions and read off twelve, sixty and six messages respectively.

An exploded view of a typical moving-head mechanism is shown in Fig. 2. The reproduce-head assembly consists essentially of the reproduce head (A), a vertical ratchet (B) and a forked bracket with upper and lower extension arms (C). The assembly is mounted on a square vertical shaft (D) arranged parallel to the drum (not shown) and, at regular time intervals, a stepping magnet (E) is operated to cause a pawl to engage with the vertical ratchet and step the head to successive time tracks. After completion of each step the head is maintained in position by a detent pawl.

A toggle switch (F) is fitted to permit electrical interlock with other heads. This switch is mounted on the release-magnet housing and operated by the lower extension arm of the forked bracket when the moving-head assembly is stepped to its highest position. Conversely, when the moving-head assembly is subsequently released by the action of its associated release magnet (G) and returns to its initial starting position (H), the upper arm of the bracket restores the switch.

The heads are electrically interlocked by the circuit shown in Fig. 3. Springset CS9 is operated for a brief period by each revolution of the 10-second shaft and feeds an earth pulse to operate SSM (the seconds-head stepping magnet) via KC1. The seconds-head thus rises one track every ten seconds. When the sixth pulse is received, the head operates the toggle switch SW1 which completes a circuit for the operation of the seconds-head release magnet

SRM and the minutes-head stepping magnet MSM. The seconds-head is thus released and returned to its bottom position and the minutes-head is stepped up to the next track. On reaching the bottom the seconds-head restores SW1. This process continues until the end of an hour, when the minutes-head is stepped to its top position and operates toggle switch SW2. This causes the hours-head stepping magnet HSM and the minutes-head release magnet MRM to be operated, thus stepping the hours-head up to the next track and releasing the minutes-head to allow it to fall back to its lowest position and restore SW2. In a similar manner, the hours-head is released by the operation of HRM via SW3 at the end of twelve hours.

Switches KC1, KD1 and KE1 are manually-operated push buttons used to step the seconds, minutes, and hours-heads respectively when setting up the equipment.

From the foregoing, it will be seen that by increasing the hours-head ratchet steps to 24 and by use of a longer drum, it is possible to provide a 24-hour Announcer.

THE D.C. TIME ANNOUNCER

As previously mentioned, this version is identical with the a.c. machine, except that the drive is supplied by a d.c. motor and that additional equipment, in the form of a relay-set and timing shaft, is provided to control the motor speed, which varies with exchange-battery voltage, temperature, etc. A shunt field motor is used, with speed control obtained by the addition of resistance in the armature circuit.

The accuracy of the d.c. clock is maintained by comparing the time taken for three complete announcements with the 30-seconds interval between pulses from a pendulum clock. The pulses from the

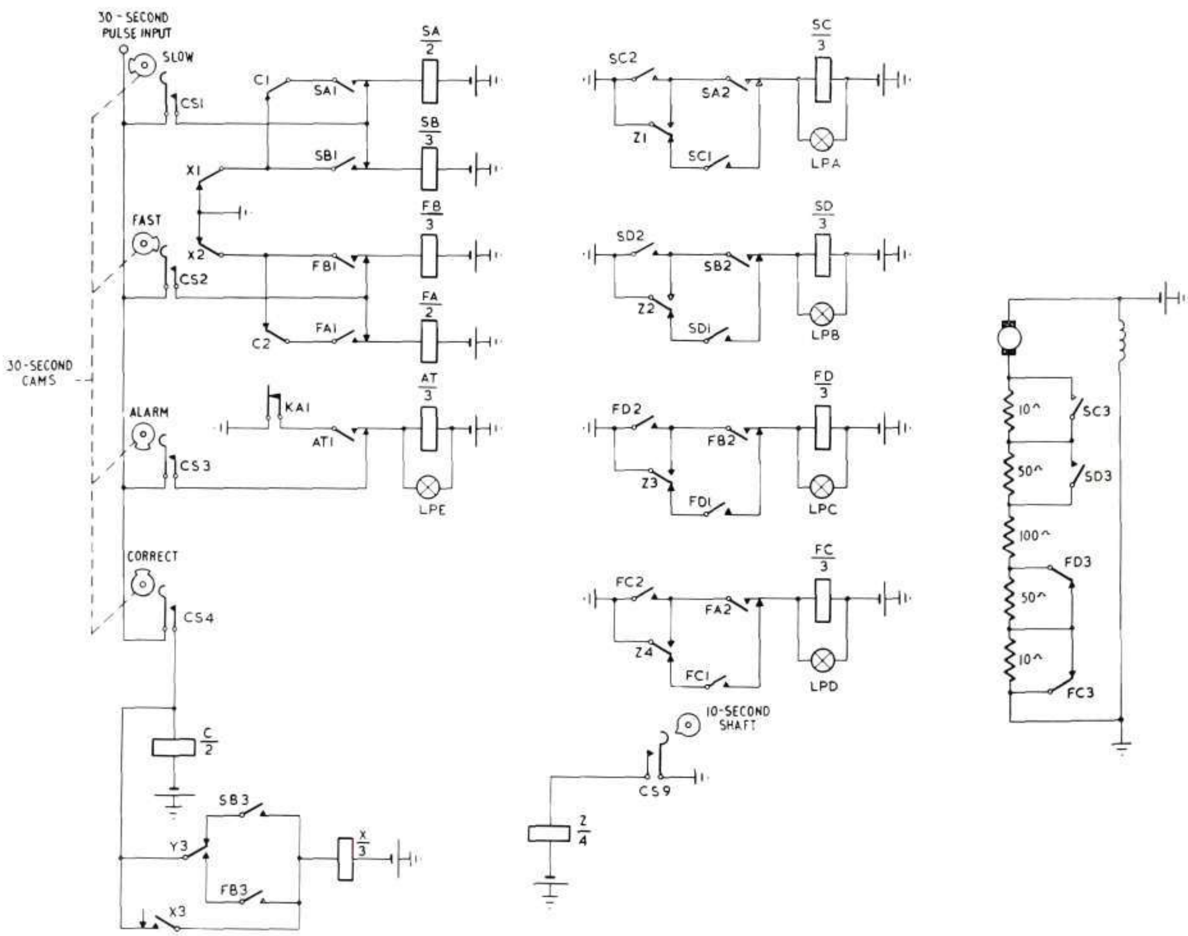


Figure 4—Simplified schematic of time-correction circuit (d.c. version)

pendulum clock are fed into different input points in a relay circuit depending upon whether the machine is running fast, slow or correctly. The relay circuit then changes the resistance in the motor armature circuit to advance or retard the clock in the sense necessary to correct the error.

The additional camshaft fitted to the machine is driven through a 3:1 reduction gear from the 10-seconds shaft to make one revolution per three messages (approximately 30 seconds). Four cams on this shaft operate springsets through which the pulse from the pendulum clock is fed to the various inputs of the relay circuit (see Fig. 4). If the clock is within ± 3 seconds of the correct time, the pulse is applied through the 'correct' springset CS4 to operate relay C. If the clock is between 3 seconds and 12 seconds slow, the pulse operates relays SA and SB via 'slow' springset CS1; if between 3 and 12 seconds fast, relays FA and FB operate. Should the clock be more than 12 seconds slow or fast, relay AT operates through the 'alarm' springset CS3, to cause the clock to stop and an audible alarm to sound.

When operated, the 'slow' relays SA and SB apply short circuits across two resistors in series with the armature circuit to increase the motor speed and cause the clock to gain. Further pulses received during subsequent closures of the 'slow' springset have no effect, but as the clock continues to gain, a pulse eventually occurs during the 'correct' period to operate relay C. This releases the SA relay and the short circuit is removed from one of the resistors in the armature circuit and the clock slowed down to approximately the correct speed.

With only SB relay operated the clock may gain or lose. If the latter condition arises, SA relay is operated in due course by a pulse during the slow period, and the same cycle is repeated. On the other hand, if the clock gains to such an extent that it is fast with respect to the pendulum clock, the next pulse operates relay X, thus releasing relay SB and returning the circuit to its original condition.

The operation of the circuit when the clock is running fast is exactly the reverse of the description above, relays FA and FB being used to insert resistance in the armature circuit.

This method of speed control works effectively on the clock since it causes the motor to be run slightly fast for part of the time and slightly slow for the remainder, thus permitting the average correct speed to be obtained. If the battery voltage is high, for example, the relays FA and FB will be operated for most of the time, whereas if the battery voltage is nominal there will only be occasional operation.

The system as described has the disadvantage that the speed of the drive motor is changed at the instant of arrival of the pulse from the pendulum clock. This could occur at any time during an announcement, whether the clock is running slow or fast; the speed change would then be heard as a slight change in the tone of the announcement. To avoid this, the speed change is delayed until the next silent period. The speed control relays SA, SB, FA and FB each have slave relays SC, SD, FC and FD respectively. Operation of the SA relay, for instance, prepares a circuit for the relay SC which only operates when the Z relay is operated at the commencement of the silent period by a cam on the 10-second shaft. Relay SC is used to change the motor speed so that the change is initiated on the arrival of the timing pulse but delayed until the next silent period. Similarly, when the SA relay is released, relay SC remains operated through a contact of the Z relay until the commencement of the next silent period.

Conclusion

The new Time Announcer is an equipment in which elaboration has been deliberately avoided to obtain an economical design, simple in concept, yet capable of providing a degree of accuracy more than adequate for all practical timekeeping requirements. The true value of the Announcer may be assessed, not only by its relatively low cost and ability to provide an accurate time source for the subscriber, but by its earning capacity and the material contribution it makes to the convenience and efficiency of operators burdened with 'time by the exchange clock' announcements.

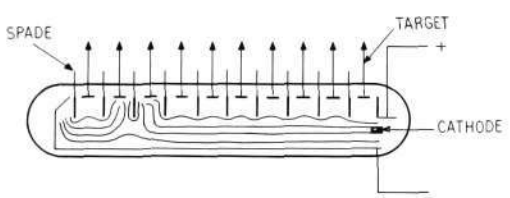
U.D.C.621.385.65 : 621.374.32

TROCHOTRON HIGH-SPEED BEAM SWITCHING TUBES

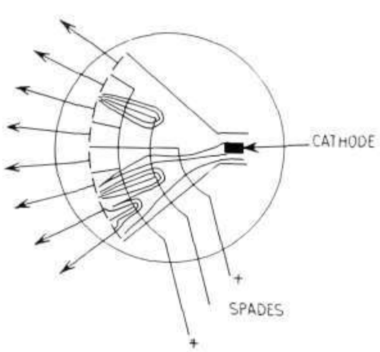
D. Reaney, A.M.Brit.I.R.E.—Valve Research and Development Laboratory

The trochotron high-speed beam switching tube is described and the characteristics discussed. Expressions for the maximum discrimination and maximum continuous counting rates are derived. Binary, single pulse and sine wave drive circuits are discussed. Methods of extending the number of output channels and of generating staircase or analogue waveforms are illustrated. Details are given of remote digitron read-out, and mention made of a method of modulation.

THE Trochotron is a hot-cathode multi-electrode tube containing a number of open box electrodes and operating in a constant magnetic field. It was first described by Professor H. Alfven in 1947-48, although the actual tube described then[1,2] was not quite the same design as the ones under discussion in this paper.

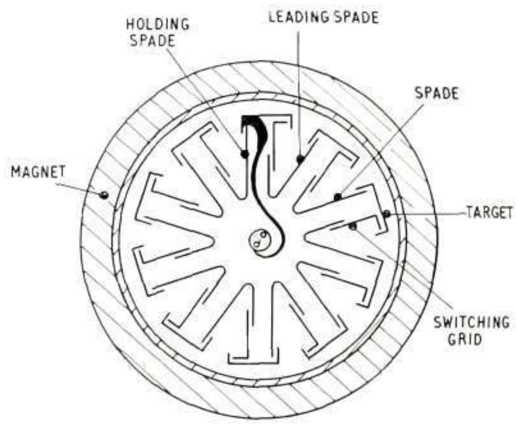


(*a*)



(*b*)

Current can be extracted from the beam in two ways: firstly the beam can impinge upon an electrode at the same potential as itself, or secondly, the beam can be guided into a narrow slit where the electric field is very much more effective than the magnetic field in the same region. This latter is the more useful, as with suitable design the beam can be completely collected. The magnitude of the current is discussed in Appendix 1. Three different basic designs of trochotron are possible and these are illustrated in Fig. 1. They are (*a*) the plane trochotron, (*b*) the binary trochotron, and (*c*) the cylindrical trochotron. Of these only the cylindrical type is at present available commercially and this paper will deal exclusively with this type.



(*c*)

Figure 1—(*a*) **Plane trochotron**
(*b*) **Binary trochotron**
(*c*) **Cylindrical trochotron**

The tube takes its name from the motion of electrons in crossed electric and magnetic fields. These are trochoidal in nature and the motion is described in many text books. The important feature is that, with a space charge present, a beam consisting of electrons each following a trochoidal path can be formed, and that the beam, as a whole, will follow an equipotential line.[3] The beam can be directed or guided by varying the position, within the tube, of the equipotential line along which it is travelling.

Further reference to Fig. 1(*c*) will illustrate the general disposition of the electrodes and the nomenclature which will be used to describe the operation.

[1] H. Alfven, *et al.*, "Theory and applications of trochotrons", *Trans. Royal Inst. Technology, Stockholm*, No. 22, 1948.
[2] J. Bjorkman and L. Lindber, "Development of trochotrons", *Ericsson Technics*, No. 1/1954, p. 6.
[3] S. P. Fan, "The magnetron beam switching tube", *J.Brit.I.R.E.*, 15, p. 335, July 1955.

Operation of the Tube

After applying suitable voltages to the electrodes it will be found that no appreciable current flows, as the tube is normally operated above cut-off, i.e. the magnetic field strength is sufficiently large to prevent electrons reaching any of the electrodes.

If the potential of one of the spades is now reduced to that of the cathode, a complex trochoidal beam is formed and follows an equipotential from the cathode across to the gap between the spade which is at zero, and the adjacent spade which is at the spade supply voltage. Once within this gap, the beam (now degenerating) is controlled completely by the electric field in the gap.

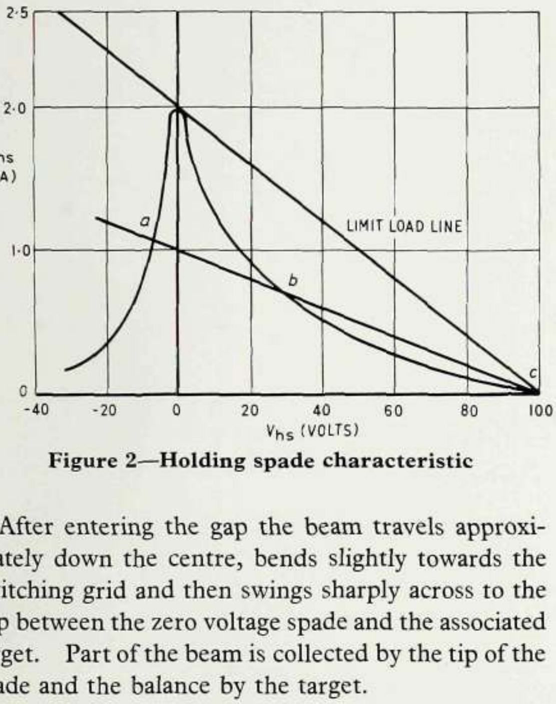


Figure 2—Holding spade characteristic

After entering the gap the beam travels approximately down the centre, bends slightly towards the switching grid and then swings sharply across to the gap between the zero voltage spade and the associated target. Part of the beam is collected by the tip of the spade and the balance by the target.

There is, as yet, no automatic locking of the beam, and this is accomplished by using the spade characteristic. This is shown as Fig. 2 and is obtained by holding all the targets, switching grids and nine of the spades at a fixed potential and plotting the characteristic of the remaining spade (holding spade).

It will be seen that it has a sharp peak in the vicinity of the cathode potential and that in conjunction with a resistive load a stable operating point exists at "a". The intersection at "b" is on a negative slope and that at "c" represents cut off.

When suitable resistors are inserted in the spade connections, the beam is formed and locked. The

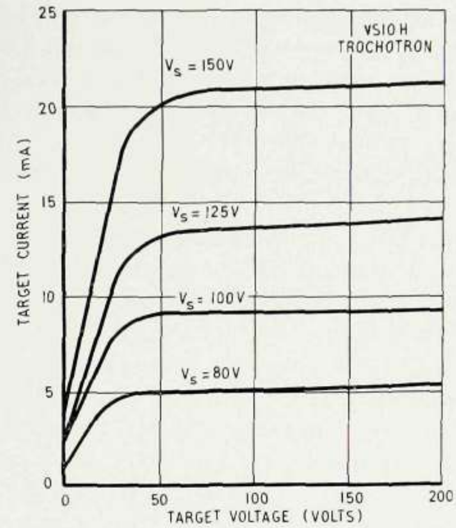


Figure 3—Target characteristic

targets are remote from the cathode and are only effective in the final collection of the beam, which results in the targets having a characteristic similar to that of a pentode. This is illustrated in Fig. 3, and above the knee of the curve the target voltage has little effect on the target current.

The magnitude of the target current is controlled by the voltage of the spades for a given tube geometry and a typical relationship is shown as Fig. 4. Design is generally aimed at achieving as high a current as possible for a given spade voltage.

The switching action of the tube is achieved by means of electrodes called switching grids, which are held normally at a positive potential equal to about

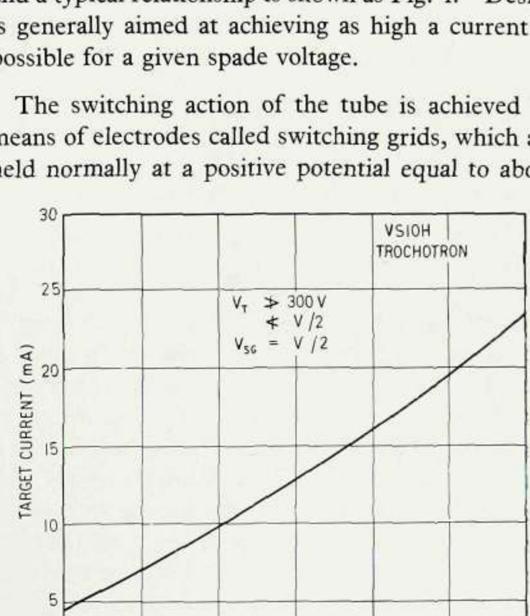


Figure 4—Relationship between target current and spade voltage

half the spade voltage. As the switching grid voltage is reduced, the equipotential that the beam is following moves nearer to the switching grid and the next spade (leading spade). This results in the leading spade starting to collect part of the beam. The potential of the leading spade begins to fall and the beam therefore moves further over. This cumulative action leads to the spade collecting the whole of the beam current. Due to the influence of the magnetic field the beam will rotate until the current is being collected by the side of the spade adjacent to the target about to draw current. As the spade potential falls, the beam current to the spade decreases and that to the associated target increases. In the normal locked condition the holding spade current is about 10% of the target current. The switching action of the tube is very fast and after switching the now lagging spade recovers to the spade supply potential.

In order to prevent the tube from switching more than once if the input drive pulse is very long, the switching grids are connected alternately in groups of five and are referred to as "odd" and "even" respectively.

Characteristics of the Tube

The most important characteristics of the tube are:

(a) Cut-off characteristic.
(b) Holding spade current/voltage relationship.
(c) Leading spade current/voltage relationship.
(d) Switching grid current/voltage relationship.
(e) Maximum discrimination.
(f) Maximum continuous speed.

These will be discussed in greater detail particularly in respect of limits.

Cut-off Characteristic

As previously stated, the tube operates above cut-off, and the effective radial electrostatic field is contributed by the spades. This results in a relatively unrestricted range of target voltages. The important parameter is the magnitude of leakage current permissible to the spades. These leakage currents arise from slight variations in the magnetic field and also from the fact that in the rotating space charge some exchange of energy takes place between electrons, resulting in some of them gaining sufficient energy to reach the spades. The number of such electrons is related to the magnetic field strength and the magnitude of voltage between the spades and cathode. The leakage current must not be sufficient to cause appreciable reduction of a spade potential when flowing through the associated spade resistor. It is thus necessary in manufacture to ensure two things, first, that the total leakage current is less than a specified value and second, that it is substantially uniformly distributed between the ten spade electrodes.

With a typical trochotron such as the Ericsson type VS10H a limit of 7·5 μA per spade is set and in production values of 3-5 μA are realized. This cut-off current is very dependent upon the uniformity of the magnetic field and any disturbance of this field due, for example, to accidental contact of the magnet with other magnetic materials will result in a greatly increased leakage current and consequent degrading of the tube performance.

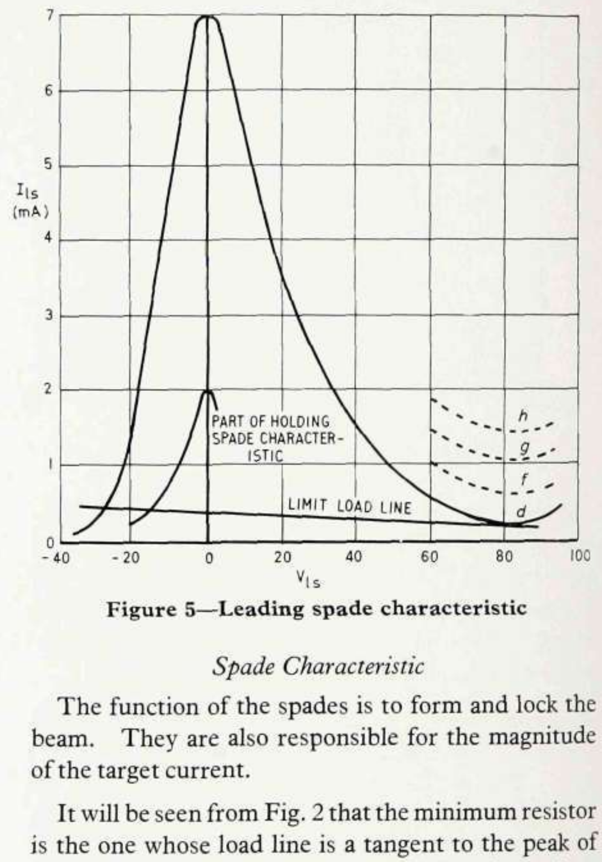


Figure 5—Leading spade characteristic

Spade Characteristic

The function of the spades is to form and lock the beam. They are also responsible for the magnitude of the target current.

It will be seen from Fig. 2 that the minimum resistor is the one whose load line is a tangent to the peak of the spade characteristic. A maximum also exists, associated with the leading spade, and this is shown as Fig. 5. This shows the current/voltage relationship of the spade next to switch while the holding spade is maintained at the appropriate holding spade voltage. The limit load line is tangential to the curve at "d" and must also intersect the holding spade characteristic at the appropriate holding spade voltage. The partial curves "f", "g" and "h" show the effect of lowering the switching grid voltage. The "tail" of the curve is quickly raised well above the load line and the tube switches, the characteristic decaying rapidly to that of the holding spade. The degree of lift of the tail of the loading spade characteristic is a measure of the reliability of the tube to switch, and is determined very largely by the geometry of the switching electrodes. As the minimum and maximum spade resistors are functions of the spade voltages, these are very conveniently combined in a single operational area diagram, a typical example of which is given in Fig. 6.

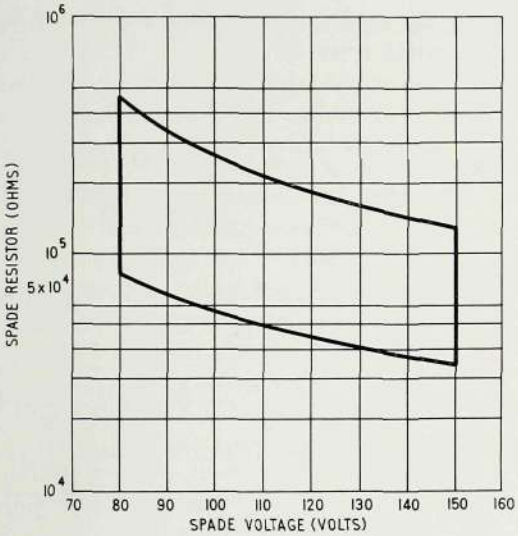


Figure 6—Operational area diagram

If the spade voltage is steadily reduced, a point is reached where the tube reverts to the cut-off condition, i.e. the beam extinguishes. This is known as the beam extinguishing voltage (V_s') and is a function of the value of the spade resistors.

A typical curve is shown as Fig. 7 and this curve is used in the design of the clearing and beam forming circuits described in Fig. 13 and also in the determination of the theoretical maximum continuous counting speed.

A further important characteristic in connection with the spades is the existence of 'N' current. This is current flowing to an electrode which is normally negative with respect to the cathode. As a result the spade which is locking the beam takes up a potential of several volts negative with respect to the cathode. The 'N' current arises from oscillations within the complex trochoidal beam which allow interchange of energy by the electrons. Those electrons which gain energy are thus able to reach spades even against small retarding fields, and in flowing through the holding spade resistor take the spade potential negative. The magnitude of the 'N' current increases with increasing spade voltage and consequently the actual holding spade voltage is a function of the spade supply voltage and the spade resistors for a given magnetic field and tube geometry. Typical values of holding spade voltage are −10 volts for the type VS10H and −2 volts for the VS10K low voltage tube. Although the lower limit spade resistor for normal operation of the tube is defined in the way described, a further limit resistor can be defined by drawing a load line which is tangential to the leading spade current peak. The area between this line and the limit of the holding spade represents a region where the tube will switch and the beam extinguish. This mode of operation is used to extend the number of output channels to greater than ten (Fig. 14) using two or more tubes.

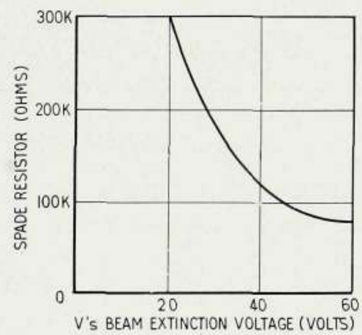


Figure 7—Relationship between spade resistor and beam extinguish voltage

Switching Grid Characteristic

The action of the switching grids is to move the equipotential, along which the beam is travelling, in such a way as to allow part of the beam to be collected by the leading spade, the resulting cumulative action causing the rapid switching of the beam to the next position.

Two characteristic types of switching electrode are possible, one using a small diameter circular rod and the other using a flat plate of much greater area. Each gives rise to a slightly different electric field distribution within the tube, and differing input impedances.

The flat plate type of electrode, such as is used in the Ericsson type VS10H draws a current of some 400 μA during part of the switching operation and has an input capacitance of about 25 pF. The circular rod type on the other hand is designed to be an essentially zero current switching grid and has a smaller input capacitance. The main advantage of the flat plate lies in the much greater lift in the tail of the leading spade characteristic resulting in a much improved switching action. The switching grids normally have a positive potential, the magnitude of which is dependent upon the voltage at which the tube switching action is initiated. It must lie outside the region of self switching and yet not be so high as to make excessive demands on the drive circuits. The voltage is also related to the spade supply voltage and should form a fixed percentage of this. Typical values are 50% for the plate type and 25% for the rod type.

Maximum Discrimination

This is defined as the ability of the tube to distinguish between two pulses occurring very close together in time. It is essentially the minimum switching time of the tube.

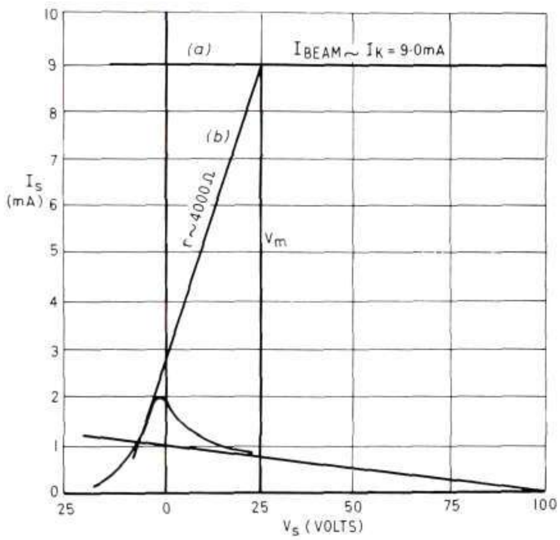


Figure 8—Diagram to illustrate method of determining minimum switching time

Reference to Fig. 8 shows a typical spade characteristic and load line for a VS10H trochotron. The time to switch is determined by the time to discharge the spade capacitance, and this may be considered as occurring in two stages. First, the whole of the beam current flows into the spade and discharges the capacitance from the spade supply voltage to a value designated V_m. This is the point at which the associated target starts to draw current and the spade capacitance then discharges to the holding voltage exponentially. This characteristic can be approximated by two straight lines, which also enable a value to be found for V_m. The two straight lines are given by (a) a line representing the beam current, and (b) a line coincident with and having the same slope as the positive side of the spade characteristic, in the vicinity of the operating point. This has a slope of $1/r$ and both are drawn in Fig. 8. The intersection of these two lines occurs at V_m. As the initial spade voltage (V_s) and spade capacitance (C_s) are known the time to reach V_m is

$$t_1 = \frac{C_s(V_s - V_m)}{I_b} \qquad \text{.......(1)}$$

For all practical purposes $I_b = I_k$ and can be used without introducing any appreciable error. From this point the spade voltage falls exponentially with a time constant given by

$$C_s\left(\frac{R_s r}{R_s + r}\right)$$

As R_s is very much greater than r the time constant can be simplified to $C_s r$ and the voltage is in the locking region in twice the time constant.

Therefore

$$t_2 = 2C_s r \qquad \text{.......(2)}$$

and the total time is given by

$$T = t_1 + t_2 = \frac{(V_s - V_m)C_s}{I_k} + 2C_s r \qquad \text{.......(3)}$$

Inserting typical values from Fig. 8 gives

$$t_1 = 0{\cdot}1\ \mu s$$
$$t_2 = 0{\cdot}06\ \mu s$$
$$T = 0{\cdot}16\ \mu s$$

Practical measurements of the switching time have shown that values between 0·15 and 0·17 microseconds are typical, and that the straight-line approximations made are reasonably justified. The significance of these results is further discussed in the section devoted to discrete pulse operation.

Maximum Continuous Speed

The maximum continuous speed is determined principally by the recovery time of the spades. Unlike the conditions when switching, there is no beam current to assist the spade to recover and the recovery time is governed by the time constant $R_s C_s$.

A complication exists in that when switching at high speed with the beam formed on a given spade and target, the other spades are all at different voltages. These range in value from near the holding spade voltage, which is negative, to substantially the spade supply voltage on the leading spade. It has been observed experimentally that it is necessary for about

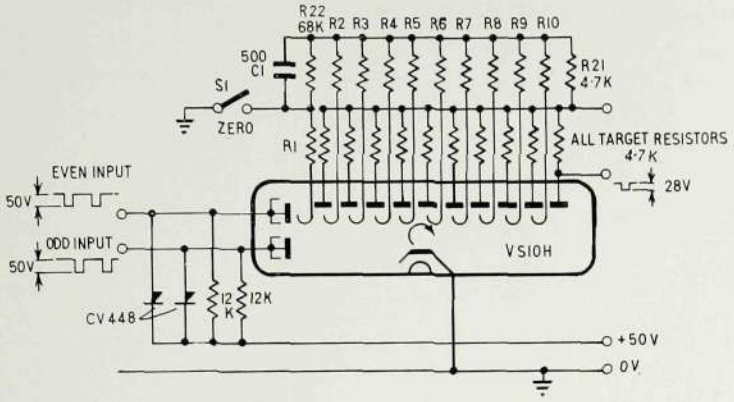


Figure 9—Basic trochotron circuit

a half of the spades to have risen to at least the minimum spade voltage (V_s') for satisfactory operation of the tube. The spade voltage after switching, is given by

$$V=(V_s-V_{hs})[1-\exp(-t/C_sR_s)] \qquad (4)$$

Referring again to Fig. 7, for a given spade resistor a minimum voltage to maintain the beam exists (V_s'), and in the limit this must be equal to V.

Therefore

$$T=C_sR_s\log(V_s-V_{hs})/(V_s-V_{hs}-V_s') \text{ seconds} \qquad (5)$$

Inserting typical values of $R_s=100\text{k}\Omega$, $C_s=10\text{pF}$, and $V_s'=45$ V from Fig. 7,

$$T=0\cdot 54 \times 10^{-6} \text{ seconds}$$

and this represents the time in which the spade has recovered to V_s'. However, as previously stated, about half of the spades should have reached at least V_s'. This leads to the maximum speed of

$$F_{max}=2/T=3\cdot 7 \times 10^6 \text{ pulses/second} \qquad (6)$$

In practice, of course, the actual maximum would have to be less than this to avoid the risk of beam extinction. If the switching grids are connected to the cathode the tube will free run and measurements show this speed to be $3\cdot 3 \times 10^6$ pulses/second typically, which gives reasonable agreement with eqn. (6).

Basic Circuits

A basic circuit is shown in Fig. 9 which is capable of operation up to 10^6 pulses/second and will produce an output pulse of some 28-30 volts. The spade voltage is the most critical as the target current is a function of this. The target voltages are relatively unrestricted.

Clearing the tube and forming the beam is accomplished using the network R21, R22 and C1. The tube is driven by negative pulses of some 55 volts amplitude and duration greater than $0\cdot 5$ μs.

Drive Circuits

Three different methods of driving the tube are available:

(*a*) Pulses applied alternately to each set of switching grids.

(b) Pulses applied to the switching grids in parallel.

(c) Use of a sine wave.

The most usual method is (a), the outputs being obtained from the anodes of a binary stage. The design of such binary counters is discussed in many text books[4] and a typical example is given in Fig. 10(*a*). The minimum input impedance of the trochotron consists of say, 30 pF in parallel with 12 k Ω and it is desirable that the coupling capacitors from the binary stage should be at least 250 pF and 330 pF is generally recommended. Diodes are used to clamp the switching grids at the bias level.

Operation is also possible if the switching grids are connected in parallel, and the drive pulse is sufficiently short to prevent the beam from switching more than once. This is described as discrete or single pulse operation and a typical circuit is shown in Fig. 10(*b*). The pulse is derived from a blocking oscillator and it may be necessary to increase the switching time of the tube by the addition of small capacitors across the spade resistors.

The third method of driving the tube is by means of a sine wave. A centre-tapped transformer is used, the switching grid bias being supplied via the centre tap. The circuit of Fig. 10(*c*) is extremely simple, but counts both half cycles so that the switching rate is equal to $2f$.

Target Output

The maximum target output is limited by:

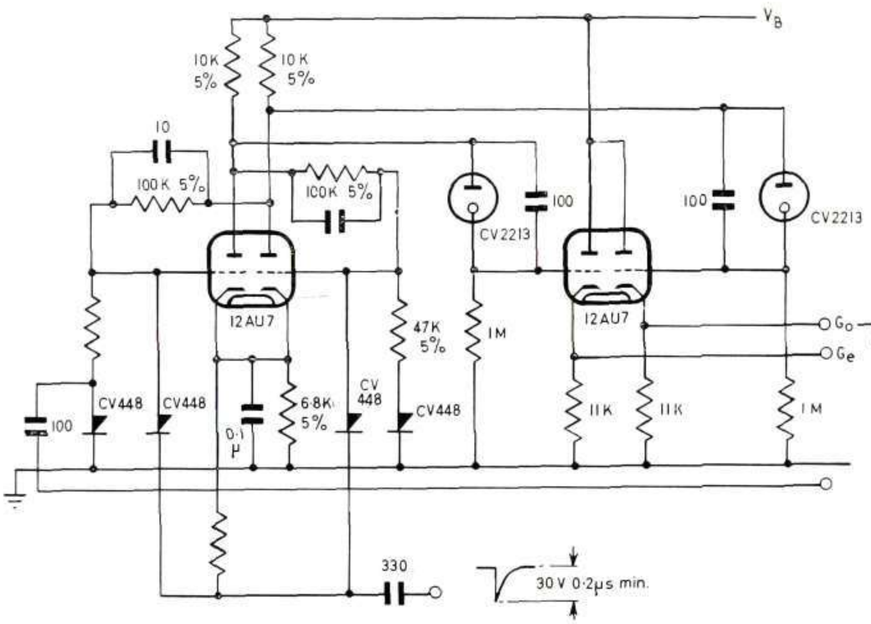
(a) The maximum permissible voltage across the tube ($V_{T\max}$).

(b) The restriction that the target voltage must not fall below the knee of the target characteristic.

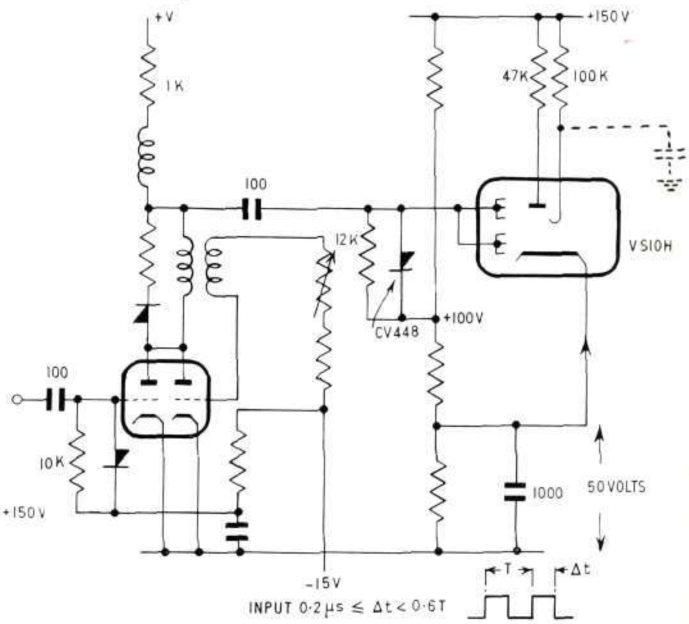
This occurs at approximately half the spade voltage and we may write

$$V_{o\max}=(V_{T\max}-V_s/2) \qquad (7)$$

[4] J. Millman and H. Taub, 'Pulse and Digital Circuits', p. 140. (McGraw-Hill, New York, 1956.)

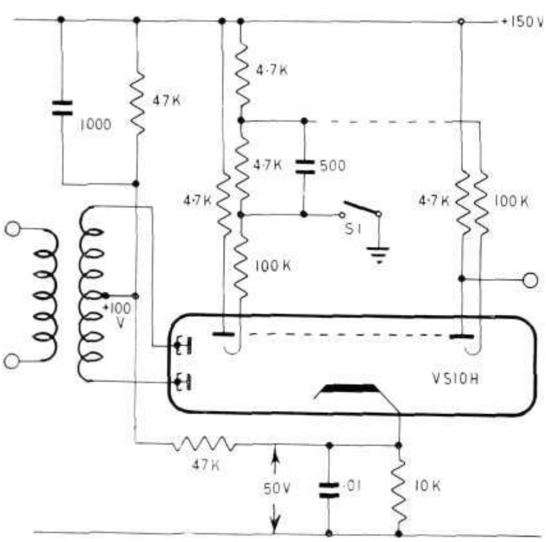


(a)



(b)

Figure 10—Typical drive circuits
(*a*) **Binary drive**
(*b*) **Discrete pulse drive**
(*c*) **Sine wave drive**



(c)

Care must also be taken that the maximum dissipation of the tube is not exceeded.

If the target output voltage exceeds about 75 volts, it is necessary to consider the effect of internal feedback via the tube inter-electrode capacitances. Undue feedback results in erratic operation and may even cause beam extinction. The effects of this feedback may be reduced by the connection of small capacitors (10 pF) across the spade resistors, although this will reduce the maximum speed of the tube.

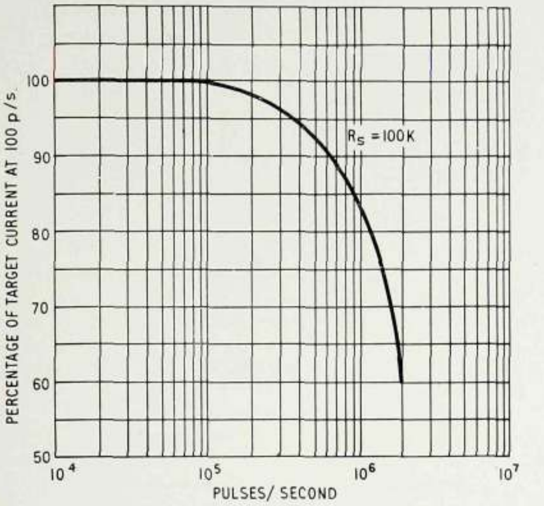


Figure 11—Variation of target current with counting rate

It should also be noted that the output voltage is a function of the switching rate above about 250×10^3 pulses/second. This arises from the inability of the spades to recover to the full spade supply voltage in the time available. A reduction in target current of about 50% occurs when switching at 2×10^6 pulses/second and Fig. 11 shows a typical variation of current with switching rate.

READ-OUT

Some convenient means of sensing the position of the beam is desirable. This may take the form of a visual read-out, and various methods are available. It is possible to use relays to operate lamps at low speeds, transistors performing a similar function, or one of the gas-filled register tubes,[5, 6] (e.g. the "Digitron") giving a direct numerical read-out. The trochotron is well suited to this latter method as there is no speed limitation, and the constant current output is the ideal condition for the Digitron. A circuit is shown as Fig. 12; it will be noted that a permanent voltage of about 120 V is maintained across the Digitron tube. The target current in flowing through the target resistor produces the additional voltage necessary to strike the appropriate digit.

RESETTING THE TUBE

This can be done either manually or electronically. The manual resetting circuit is shown in Fig. 9, and operates by first clearing the tube and then forming the beam on the selected spade and target.

The tube is cleared by momentarily reducing all the spade potentials to zero, via the switch and capacitor C1. The potential of spades other than the zero spade must then rise to a value greater than V_s' the beam extinction voltage.

Some variation of current (typically 5%-6%) exists between targets due to small physical differences and from slight non-uniformity in the magnetic field. The effects of these variations can be reduced by the introduction of negative feedback from a cathode resistor. The resistor should be by-passed with about 1000 pF and this facilitates d.c. coupling from the drive circuit to the switching grids. A typical cathode resistor should raise the cathode potential to between 50 V and 75 V to earth, and will reduce the typical target current variation mentioned by 30% to 50%.

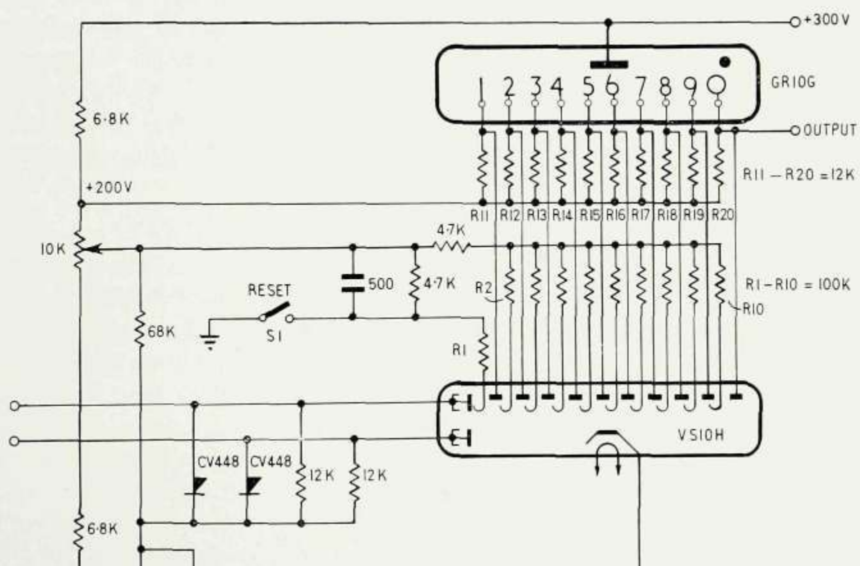


Figure 12—Digitron read-out from a trochotron

[5] N. McLoughlin, D. Reaney and A. W. Turner, 'The digitron: a cold-cathode character display tube', *Electronic Engineering*, 32, p. 140, March 1960.

[6] G. Higgins, 'A gas-filled glow discharge character display tube', *J.Brit.I.R.E.*, 22, p. 133, August 1961.

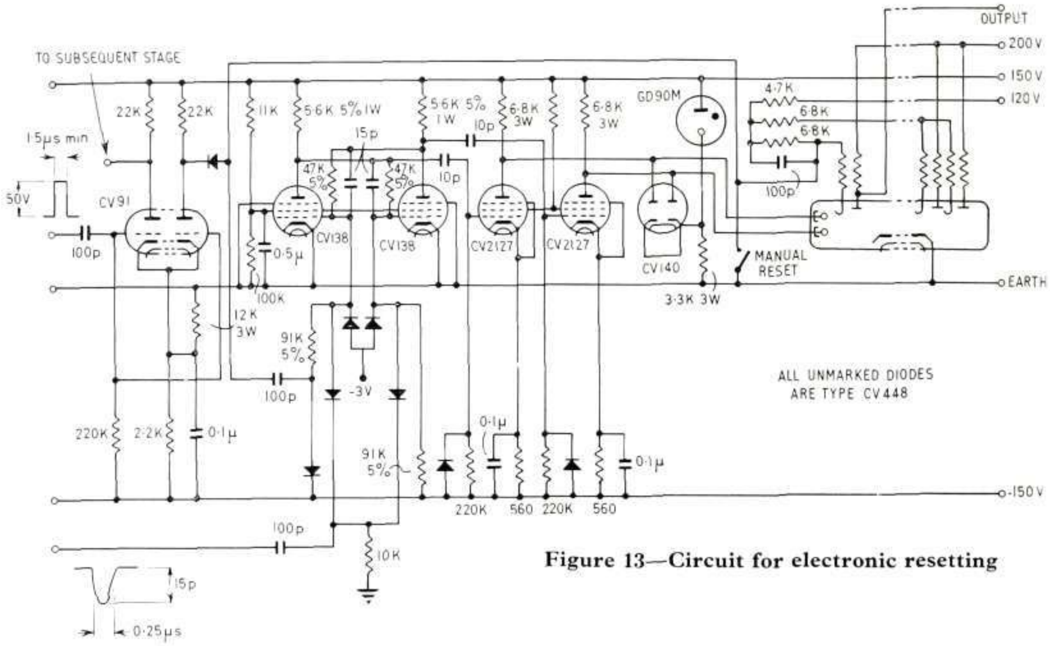


Figure 13—Circuit for electronic resetting

The rise of the zero spade potential is delayed by the charging of C1 and therefore the beam forms on the zero spade.

The design equations are as follows:

$$R_1 + R_{22} \simeq 1 \cdot 1\, R_s$$
$$R_1 / R_{22} > 10$$
$$R_{22} / R_{21} \simeq 1 \cdot 5$$
$$R_{22} C_1 > R_s C_s \quad (C_s = \text{spade capacitance})$$

Electronic resetting is possible by means of a pulse applied either to the zero spade or to the cathode.

Figure 13 illustrates one method, a negative pulse being applied to the spades having a minimum duration of $1 \cdot 5$ μs.

In the circuit shown in Fig. 13 the reset pulse is also used to reset the switching grid bistable drive circuit.

Miscellaneous Circuits

Many circuits are possible using the trochotron, but space allows only two circuits to be discussed.

The first is the extension of the outputs to numbers greater than ten. This can be achieved using two or more tubes and making use of the "switch and beam extinguish" facility. This latter has been mentioned previously and is obtained by operating one of the spades with a resistor having a value between the limits set by the peak currents of the holding spade and the leading spade. When the beam is switched to this spade it automatically extinguishes the beam, providing a short pulse at the target. This pulse is used to reduce the potential of one of the spades on the next tube and forms the beam. This action is very fast and no loss of counting ensues. A maximum of nine outputs is available from each tube. A suitable circuit is given in Fig. 14. The second circuit produces a staircase waveform or analogue voltage. This is easily achieved by the use of the circuit in Fig. 15, variation in the values of resistors enables an analogue voltage to be produced. The number of channels can be extended by the use of the circuit of Fig. 14.

Modulation

The target current can be modulated by means of a voltage superimposed on the spade supply voltage. Care must be taken to ensure that the spade voltage remains within the operating limits specified, and it is desirable that the ratio of switching frequency to modulating frequency is as high as possible. Satisfactory results have been obtained using a switching frequency of 500 000 pulses/second and modulating frequencies up to 10 000 c/s.

Tube Life

Life tests have shown that the life of these tubes is likely to be of the order of 10 000 hours or better.

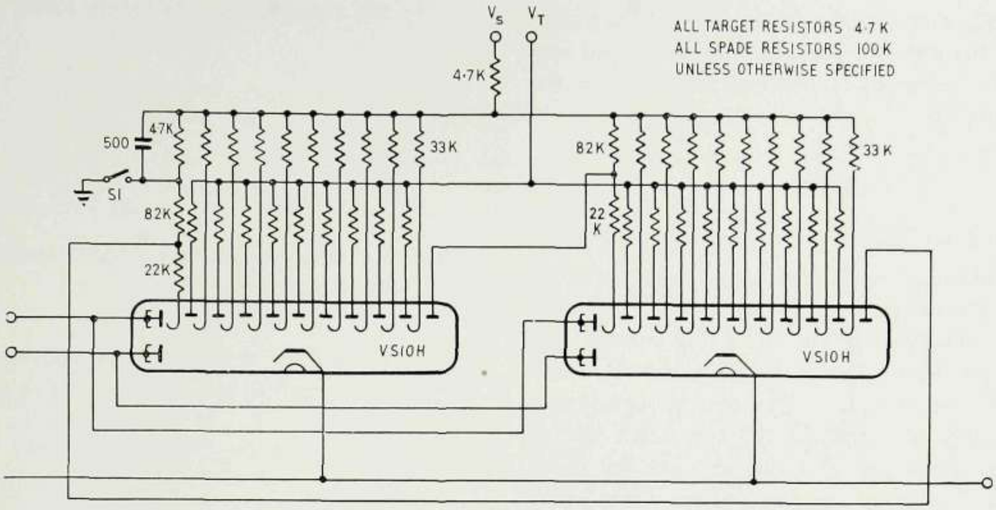


Figure 14—Circuit to extend the number of output channels

Tests over 5000 hours have shown about 5% variation in target current due, almost certainly, to ageing of the magnet.

Specialized Trochotrons

The tubes described so far have been general purpose tubes operating up to 2 x 10^6 pulses/second and with target currents between 5 mA and 20 mA.

Disturbances of the magnetic field are of the greatest importance and may cause malfunctioning of the tube. A range of tubes has therefore been developed which are shielded magnetically, and are particularly suited to operation in large stray fields, near a synchrotron magnet for example. This shielding is achieved using a mu-metal shield and a tapered magnet.

It is possible to produce trochotrons which will operate up to 10 x 10^6 pulses/second by including the spade resistors inside the bulb and reducing the stray capacitances to a minimum. The resulting target currents are of the order of a few milliamperes.

Finally mention must be made of the Burroughs' Beam X tube. This tube has the magnetic field supplied by ten rod magnets which also perform the function of target electrodes. This results in a physically smaller tube, which is less affected by external fields.

Conclusions

The trochotron is a tube capable of fast operation and good discrimination. It is fundamentally a very reliable tube requiring only that the switching grid voltage be reduced to the switching level for longer than the minimum switching time.

These tubes can perform a wide range of operations in the field of computing, particle counting, frequency and time measurement, pulse distribution, time interval generation etc., with a high degree of reliability.[7]

Acknowledgments

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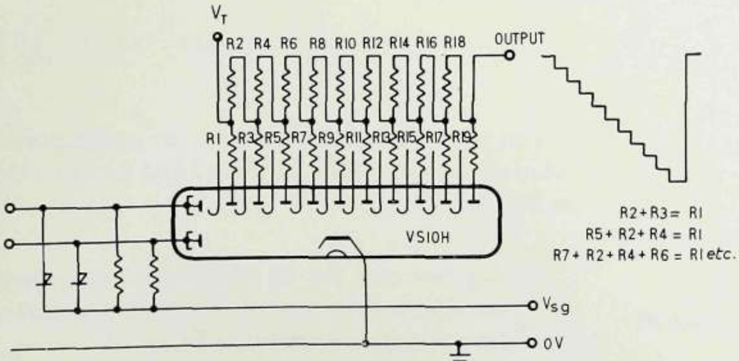

Figure 15—Generation of a staircase or analogue waveform

7 'Cold Cathode and Beam Switching Tube', Technical Handbook, Ericsson Telephones Limited, Beeston, Nottingham.

Permission given by the Institution for the publication of this paper is gratefully acknowledged and appreciation expressed for the loan of line blocks for the illustrations.

Appendix

An Approximate Determination of the Beam Current

The cylindrical trochotron may conveniently be regarded as consisting of two regions, one from the cathode to the limit of the circulating current (the beam cut-off radius) and the second from the beam cut-off radius to the target. The interest in the region lying between the cathode and the beam cut-off radius lies in the fact that this supplies the beam current to the second region. Within these limits the circulating current is not affected by the fact that one of the spades may be at cathode potential and the tangential current at the beam cut-off radius is the beam current.

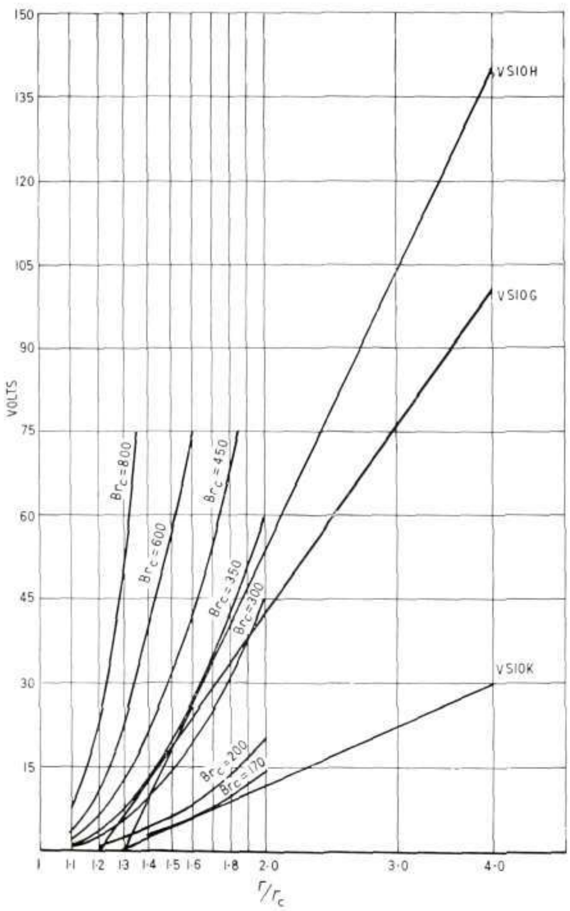

Figure 16—Graph to determine the beam cut-off radius

The differential equations for the static magnetron are

$$\ddot{r} - r\dot{\theta}^2 = -\frac{e}{m} r\dot{\theta}Bz - \frac{e}{m}E_r \qquad (8)$$

$$\frac{1}{r} \cdot \frac{\mathrm{d}}{\mathrm{d}t}(r^2\dot{\theta}) = \frac{e}{m}\dot{r}Bz \qquad (9)$$

where r_c = cathode radius, r_s = spade radius and the space charge exists up to r_h.

Assuming $\dot{\theta} = 0$ at the cathode and neglecting z components eqn. (8) can be integrated to give

$$\dot{\theta} = \tfrac{1}{2}\frac{e}{m}B\left(1 - \frac{r_c^2}{r^2}\right) \qquad (10)$$

Inserting (10) into (8) and assuming $\ddot{r} = 0$ gives the field strength

$$E_r = \tfrac{1}{4}\frac{e}{m}B^2 r\left(\frac{r_c^4}{r^4} - 1\right) \qquad (11)$$

From this can be obtained

$$\text{space charge density} = q = -\tfrac{1}{2}\varepsilon_0 \frac{e}{m}B^2\left(1 + \frac{r_c^4}{r^4}\right) \qquad (12)$$

$$\text{potential} = V = \tfrac{1}{8}\frac{e}{m}\cdot B^2 r_c^2\left(\frac{r}{r_c} - \frac{r_c}{r}\right)^2 \qquad 13$$

The beam current is the tangential current between cathode and space charge boundary (r_h) and is given by

$$I_{\text{beam}} = \int_{r_h}^{r_c} q.l.\dot{\theta} r\,\mathrm{d}r \qquad 14$$

from which is obtained a solution

$$I_B\frac{r_c}{l} = \tfrac{1}{8}\varepsilon_0\left(\frac{e}{m}\right)^2 B^3 r_c^3 \times \left[\frac{r_h^2}{r_c^2} - \frac{r_c^2}{r_h^2} - 2\ln\frac{r_h}{r_c} - \tfrac{1}{2}\left(1 - \frac{r_c^4}{r^4}\right)\right]$$

This equation is rather cumbersome and graphical solutions are given for it in Fig. 17 and for eqn. (13) in Fig. 16.

Dealing first with Fig. 16 the point corresponding to V_s and r_s/r_c is determined and a tangent is drawn from this point to the appropriate Br_c curve.

TABLE 1

Type	r_s (mm)	r_c (mm)	r_s/r_c	B (gauss)	B_{rc}	V_s	$k(r_h/r_c)$	$\frac{I_B r_c}{l}$	I_B calc. (mA)	I_B obs. (mA)
VS10G	3·44	0·85	4·0	420	350	100	1·32	0·4	12·0	10·0
VS10H	3·44	0·85	4·0	420	350	140	1·43	0·7	22·0	20·0
VS10K	3·44	0·85	4·0	200	170	30	1·43	0·075	2·3	2·0

(l = 26 mm)

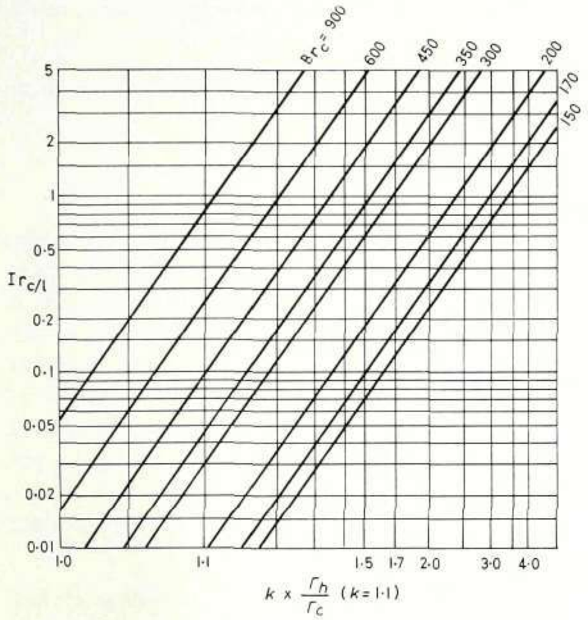

Figure 17—Graph to determine the approximate beam current

The tangential point gives the values of V for the edge of the space charge and the value of r_h/r_c—which yields the beam height.

The value of r_h/r_c multiplied by an empirically determined constant ($k = 1\cdot 1$) is now entered in Fig. 17 together with the value of Br_c and $I_B(r_c/l)$ is read off. The value of I_B can then be determined.

The process is illustrated for three tubes of similar geometry, but differing fields and spade voltages in Table 1. From the results it will be seen that tolerably good agreement exists, bearing in mind that the effects of beam degeneration etc., have been disregarded.

TRANSISTOR MULTI-CHANNEL TRANSLATING CARRIER EQUIPMENT, TYPE ETG 121

J. Attewell—Carrier and H.F. Development Department

This article describes the latest type of carrier equipment developed as a basic channelling unit for use in translating equipment for multi-channel transmission systems employing radio links or symmetrical pair cables as the transmission medium. The design complies with CCITT recommendations, and the equipment is constructed of miniature components in such a way that three 12-channel groups, including 2-wire and 4-wire terminations, can be accommodated on one single-sided 9 ft. rack. Operation is from a 24 or 50-volt d.c. supply.

Subsequent articles will appear in the Bulletin detailing the frequency-generating equipment used with the system and the particulars of a typical installation.

ETG 121 is a channel translating equipment used for assembling twelve 4-wire audio circuits of 300-3400 c/s bandwidth in the 60-108 kc/s band; it is designed to meet the recommendations of the CCITT over a change in ambient temperature from −10 to +50°C and a variation of ±10% from the nominal supply voltage.

Design Considerations

Since the position of the sidebands in the frequency spectrum, the frequency of the signalling tone, and the permissible level of noise are fixed by the recommendations of the CCITT, the scope of the engineer in designing an economical equipment is limited to decisions on the following points.

(*a*) To translate the speech frequencies into the correct places in the spectrum by a single or a double modulation.

(*b*) To inject and take off the signalling tones at the actual or virtual frequency of 3825 c/s.

(*c*) To decide whether it is reasonable to provide facilities for various conditions of signalling (tone-on-busy, tone-on-idle, etc.) and for both high and low levels of signalling tone.

(*d*) To allocate the permissible noise level between the various types of noise, basic noise, cross-talk and sideband interference.

The modulation plan for the system is shown in Fig. 1. Translation by double modulation is preferred to single modulation to enable channel selection to be made at comparatively low frequencies and so allow the use of robust coil and capacitor filters instead of the crystal filters necessary for single-modulation translation. Moreover, by use of double modulation, the number of carrier frequencies can be decreased from twelve to seven and high-frequency sub-groups arranged in multiples of 12 kc/s instead of 4 kc/s, thereby making the requirements for carrier supply filtration less stringent. The price paid for these advantages is additional equipment in the form of sub-group modulators, demodulators and filters, although the extra cost incurred for these items is largely offset by the reduction obtained in the number of types of filters used.

Four three-channel sub-groups are first assembled in the 12-24 kc/s band before being translated up to 60-108 kc/s by a second modulation.

General Circuit Arrangements

A circuit block schematic of the equipment is shown in Fig. 2. Considering channel 1, signals incoming to '4-wire transmit' are attenuated to −14 dbr at the input to the channel modulator, which incorporates a back-biased germanium diode limiter set to clip the peaks of any sinusoidal voltage greater than +4 dbmO. The ring modulator of the modulator-limiter is fed by a 12 kc/s carrier and uses germanium diodes, the resistances of which are compensated for by the addition of L-pads at the input and output. These pads, together with the rectifier resistances, form T-attenuators which improve the return loss of the modulator.

The output is fed through a transmit-channel filter which selects the upper sideband of the modulation and adequately rejects all the other products of the modulation. Speech frequencies and intermodulation products falling into the signalling channel are also well attenuated. The outputs of the filters for the

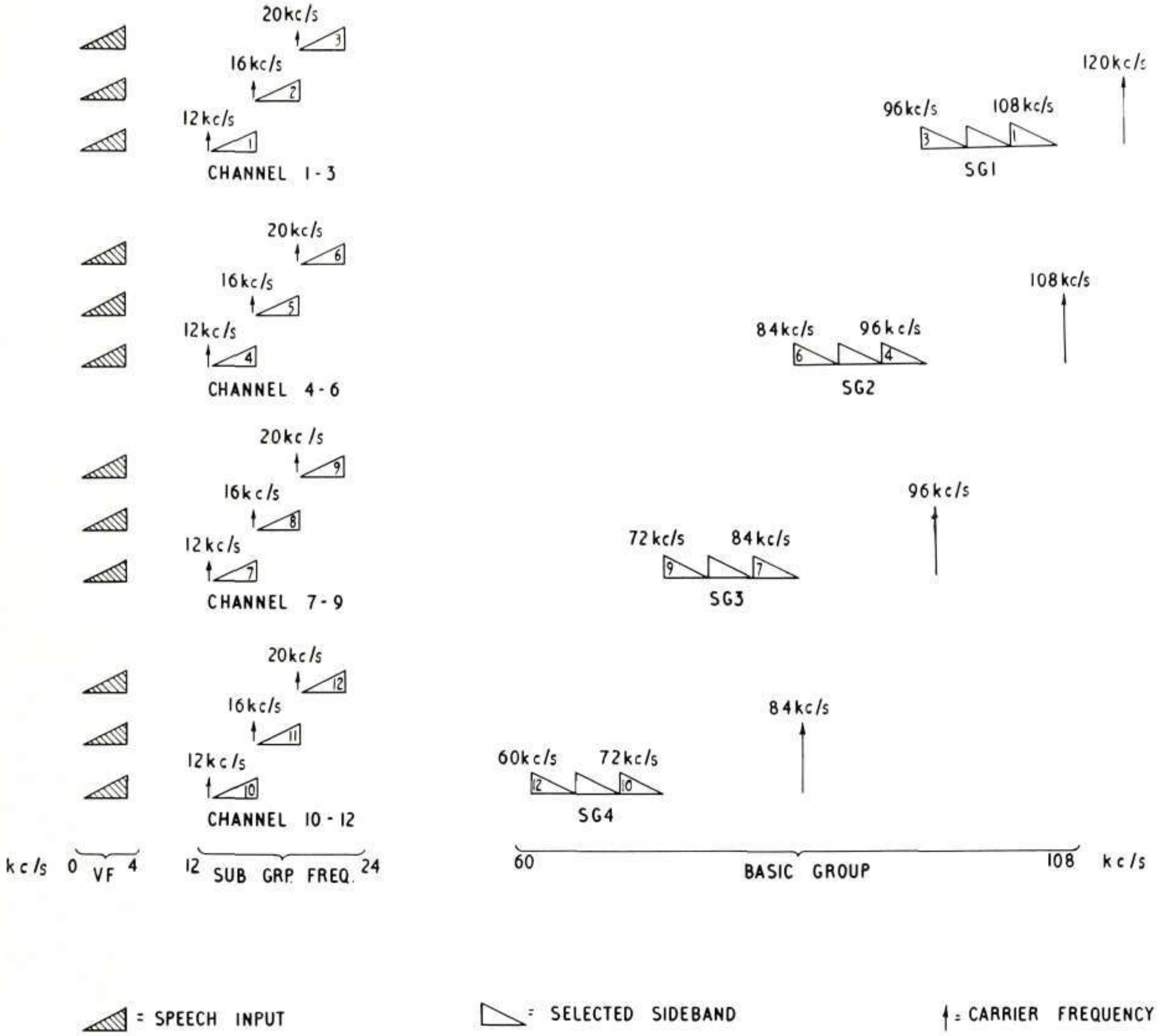

Figure 1—Modulation plan for formation of basic group

three channels in the subgroup are paralleled together with a susceptance annulling network.

Thus, three sidebands, forming a basic subgroup in the range 12-24 kc/s, are assembled at the output of the filters, at which point the signalling tones are injected. Speech and signalling tones are fed via a variable attenuator to a second modulator, where a 108 kc/s carrier is modulated. The sub-group filter selects the lower side-band, 84-96 kc/s, and suppresses the other products of modulation. Similarly, the other sub-groups modulate carriers of 120, 96 and 84 kc/s, producing sidebands to complete the primary group 60-108 kc/s. The outputs of the filters associated with sub-groups 1 and 3 are connected in parallel and combined with the paralleled sub-group 2 and 4 filters through a hybrid transformer. The hybrid output is fed via a variable attenuator and a 23 db-gain group amplifier to 'transmit out' at a level of −37 dbr.

A similar process, in reverse, applies to the receive path. Signals are fed into 'receive in' at −8 dbr, and the sub-groups, after being reduced in level by a variable attenuator, are separated by a hybrid and by sub-group receive filters identical with the transmit filters, and are demodulated by sub-group carriers to produce sidebands in the 12-24 kc/s basic sub-group range. A simple low-pass filter removes most of the unwanted products of the demodulation, and a sub-group amplifier variable in gain between 40 and 47 db, raises the level to the receive-channel filters which separate the three channels of the sub-group and complete the suppression of the unwanted

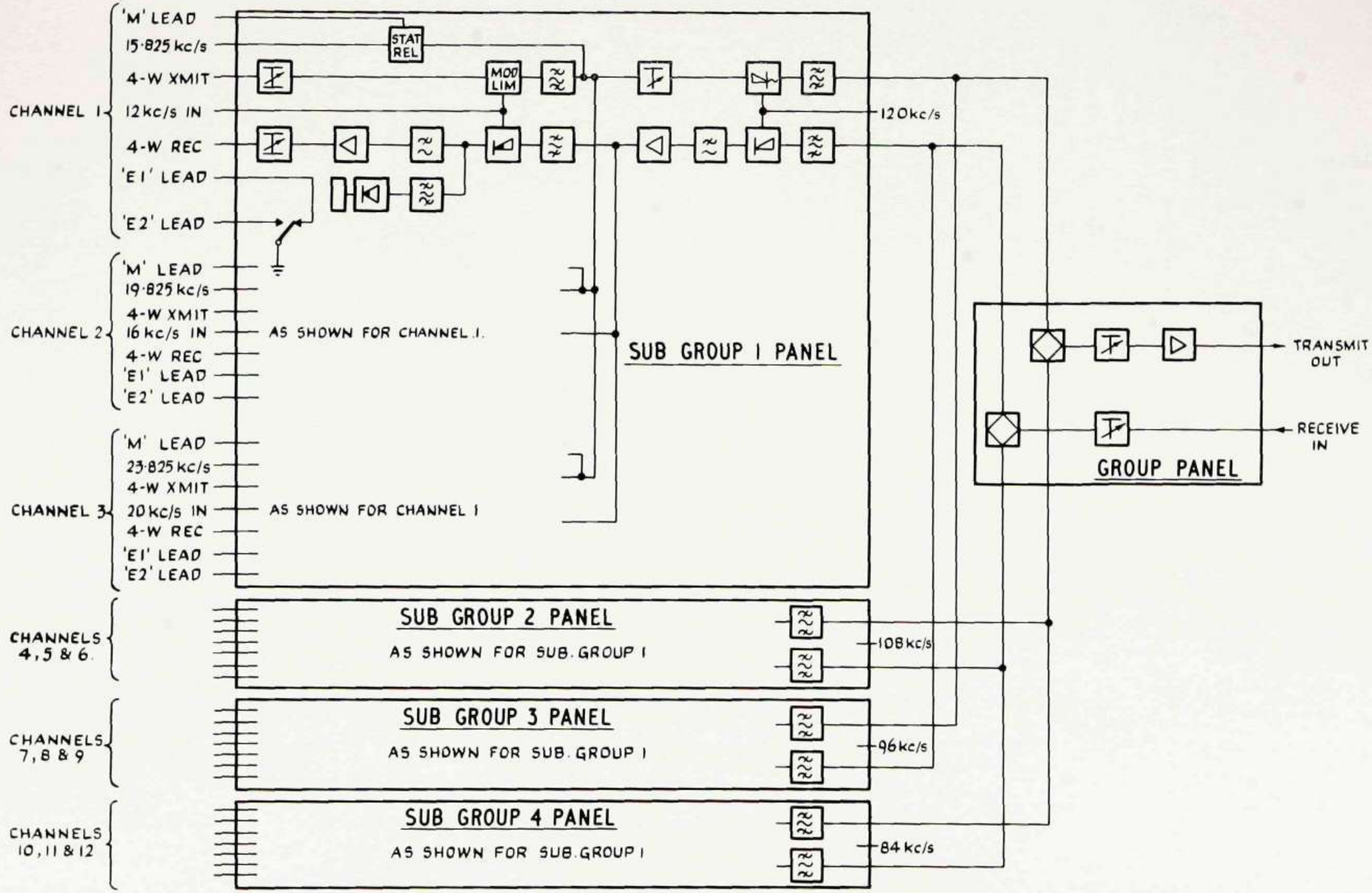

Figure 2—Block Schematic—ETG 121

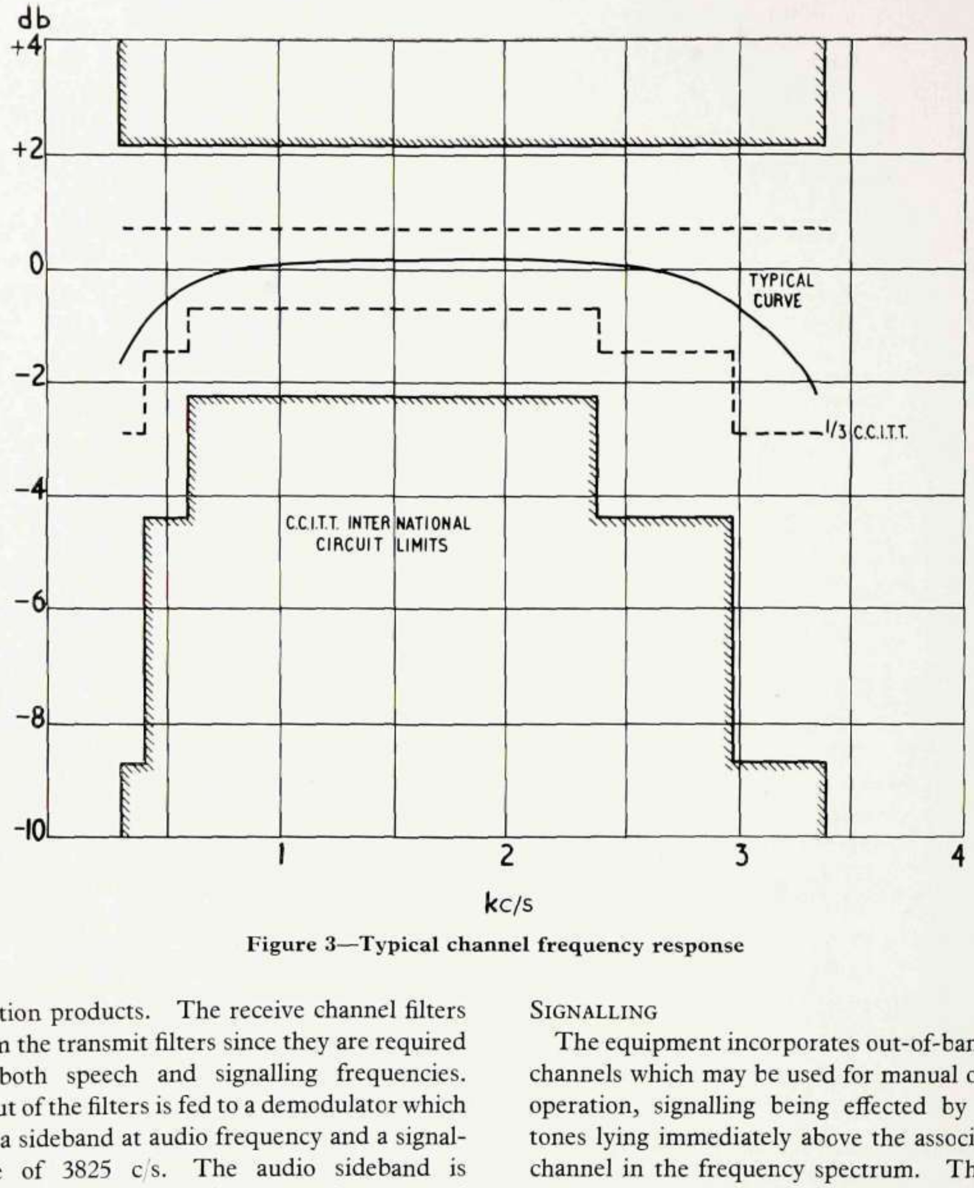

Figure 3—Typical channel frequency response

demodulation products. The receive channel filters differ from the transmit filters since they are required to pass both speech and signalling frequencies. The output of the filters is fed to a demodulator which produces a sideband at audio frequency and a signalling tone of 3825 c/s. The audio sideband is selected by a low pass filter which rejects the unwanted products of the demodulation and particularly suppresses the signalling frequency. The level is raised to +10 dbr by the 35 db-gain channel amplifier, from the output of which the signal is fed via a variable attenuator to '4-wire receive'. A simple resistance-capacitance shunt equalizer fitted across the amplifier input terminals, modifies the frequency response to enable the CCITT requirements to be met. A typical response curve is illustrated in Fig. 3.

Each channel may be used to carry up to 24 channels of v.f. telegraph or data, a typical curve of the variation in group delay being shown in Fig. 4.

SIGNALLING

The equipment incorporates out-of-band signalling channels which may be used for manual or automatic operation, signalling being effected by the use of tones lying immediately above the associated speech channel in the frequency spectrum. The signalling tones are injected into the circuits, at sub-group frequency, between the output of the transmit-channel filters and the sub-group modulator. Three different frequencies, 15.825, 19.825 and 23.825 kc/s are required, necessitating three signalling oscillators instead of the one which would be required if 3825 c/s were injected before the channel modulator. However, considerable advantage accrues from high frequency injection, since the separate transmit v.f. filter and modulator which would be necessary if the signalling tone were injected at the actual frequency of 3825 c/s are not required. Any intermodulation products developed in the modulator and limiter, which could affect the signalling channel, are blocked by the filter.

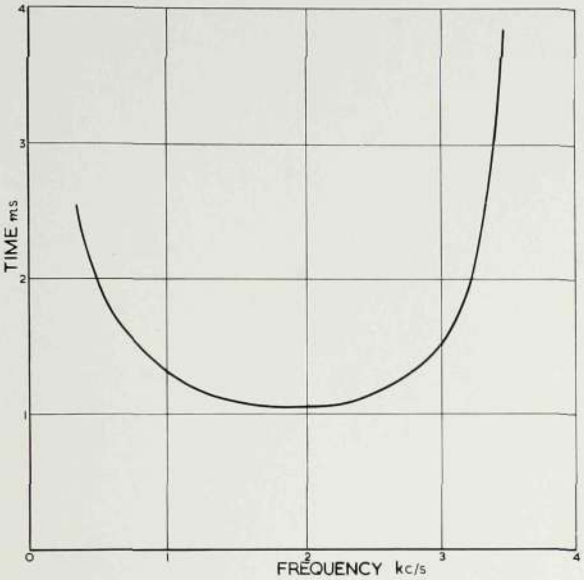

Figure 4—Group delay of a typical channel

At the receiving end of the circuit it has been found to be more advantageous to extract the signalling tone at the frequency of 3825 c/s after the normal channel demodulation, instead of using narrow band filters at the subgroup frequency. The signalling tone is picked off by a signalling filter, connected in parallel with the v.f. filter and fed to the signalling receiver, which converts the pulses of tone to d.c. pulses to operate the high speed polarized relay. The relay springset has changeover contacts giving a variety of possible 'E'-lead conditions (loop, earth, battery or disconnection) when tone is applied to the receiver input. The amplifier gain may be changed by strapping resistors in and out of the feedback path to cater for the three possible signalling levels.

There is no difficulty in providing facilities to operate the signalling system 'tone-on' or 'tone-off' by earth, loop or battery, but in offering the choice of both high and low signalling levels it is to be expected that the design requirements of the filters become more stringent. The transmit-channel filters must provide a high degree of band-edge suppression to give speech immunity with the low level signal and, to prevent tone break-through with the high level, the receive v.f. filter requires extra attenuation at 3825 c/s and the receive channel filters must have extra suppression at the signalling frequency of the adjacent channel to prevent this appearing as a 175 c/s tone after demodulation.

The filters are designed to give speech immunity and to give tone break-through levels of −75 dbmO at the low level. As the signalling level is increased, the possibility of spurious receiver operation becomes more remote but the tone break-through level increases. However, high level signalling is not normally used 'tone-on-busy' and therefore the tone is not heard by the subscriber.

The tones are injected under the control of a static relay which operates from the opening or closing of an M-wire earth loop from the exchange. The static relay output is fed through a simple filter to prevent dialling noise falling into adjacent speech bands, and a variable series resistance gives an adjustment of the level into the circuits. Normally, the signalling tones are transmitted at a level of −20 dbmO during the engaged period ('tone-on-busy'), but provision is made to increase the level to −12 dbmO or −6 dbmO to improve the 'signal-to-noise' ratio when the equipment is used in conjunction with a noisy bearer circuit. When the increased levels are used, different signalling conditions should be employed to prevent over-loading ('tone on' during the idle condition for the −12 dbmO level, and a pulsed tone for the −6 dbmO level) and, to cater for this, simple strapping arrangements on the static relay give choice of either 'tone on' or 'tone off' with the 'M' wire earthed. The relay normally operates by the application of an earth or a loop from the exchange to the 'M' wire, but may be modified by strapping to operate from an extended battery.

Construction

The mechanical design of the equipment mainly conforms to the standard adopted by the British Post Office under the designation '51 type'. The circuit elements are built up in units as shown in Fig. 5, each unit being a complete functional component such as an amplifier or a filter. Units such as filters, to which access is seldom required, are enclosed in hermetically sealed cans; other units, the components of which are mounted on wired boards, are protected by removable dust covers.

The units are assembled on panel frames in such a way that each panel is a self-contained section of the equipment. For example, the 7″ sub-group panel, illustrated in Fig. 6, includes all the apparatus for modulating the three channels of a sub-group into their correct positions in the 60-108 kc/s frequency spectrum in the transmit direction and for demodulating them back to audio frequency in the receive

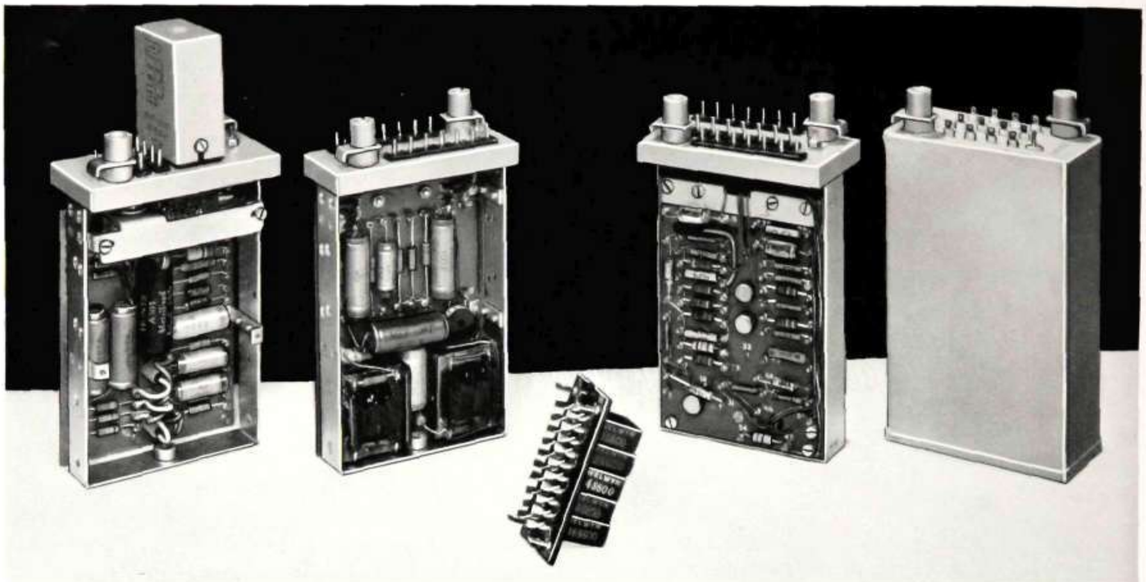

Figure 5—Typical equipment units

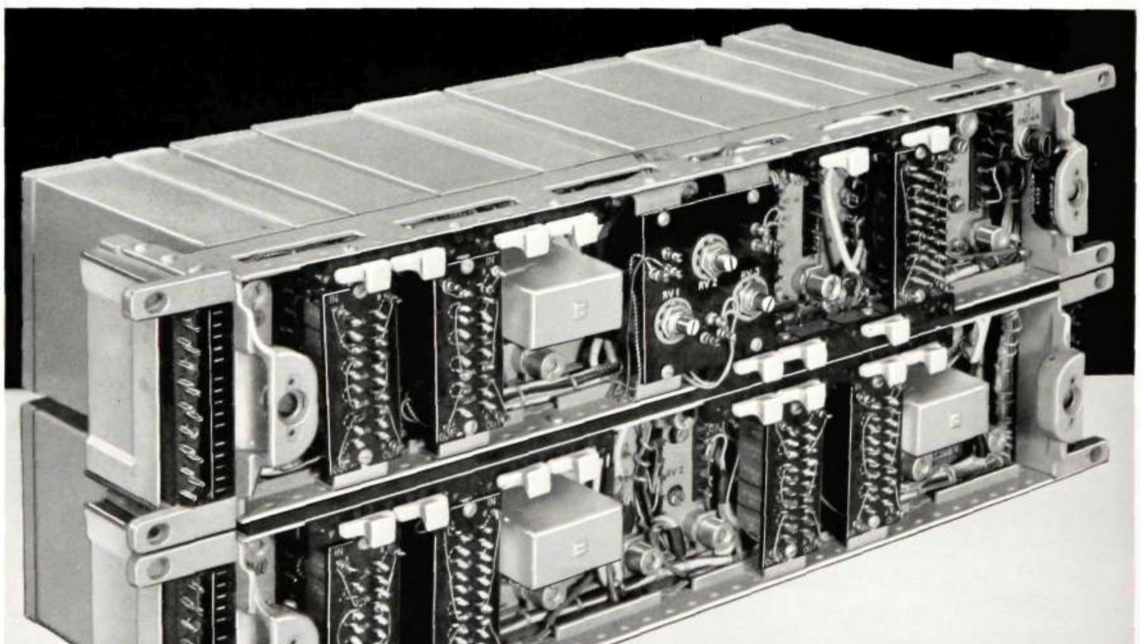

Figure 6—Sub-group panel

direction. The panel also includes the built-in signalling equipment for the three channels.

The complete equipment comprises four sub-group panels and a $3\frac{1}{2}''$ group panel, and three such equipments may be mounted on a 9 ft. rack consisting of a pressed steel frame with built-in earth bars, power distribution, connection strips, etc. The connections between the bay cable forms and the panel cables are completed by plug-in links. Each panel has a separate front cover, held in place by quick release studs, and the fronts of the covers are flush with the front of the rack. Labels which identify the test points are attached to the front of the rack, adjacent to the panel ends.

Monitoring Facilities

A monitor panel, with its associated handset, gives facilities for 2-wire and 4-wire monitoring and speaking over the carrier circuits and over the exchange line which is terminated on the panel to permit access by a subscriber on the local exchange. 'E and M' signalling may be effected in both directions, to the local exchange and over the transmission link to the distant exchange. If 'ring-down' signalling is used, ringing can be initiated and received at the panel from the 2-wire points in the circuits. When three ETG 121 equipments are mounted on one rack, the monitor equipment may be fitted in the spare space available on one of the group panels.

Power Supply

The equipment is designed to operate from a normal 24-volt exchange battery, the current drain being approximately 700 mA per 12-channel group, and a resistance-capacitance unit is fitted in the power distribution area to drop the voltage to the 21 volts required by the equipment. If it is required to operate from a.c. mains or a 50-volt battery, a power panel may be fitted immediately above the power distribution area. With this arrangement, it is only possible to fit two group equipments on the 9 ft. rack, but 2-wire/4-wire terminating panels and a monitor panel may be fitted. A typical rackside assembly is shown in Fig. 7.

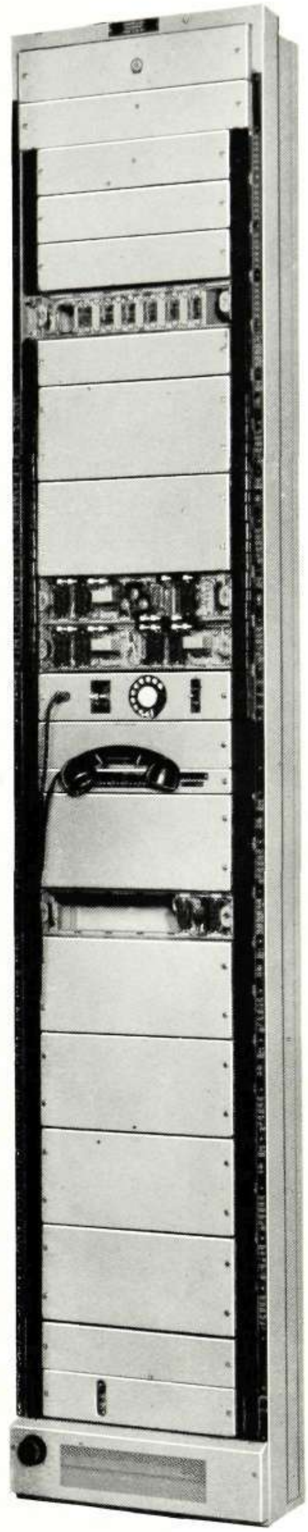

Figure 7—A typical ETG 121 rackside layout; two channel translating equipments with power, monitor and 2-wire/4-wire terminating panels