

The Journal of the BRITISH INSTITUTION OF RADIO ENGINEERS

FOUNDED 1925

INCORPORATED 1932

*“To promote the advancement of radio, electronics and kindred subjects
by the exchange of information in these branches of engineering.”*

VOLUME 21

MARCH 1961

NUMBER 3

LANGUAGE

LANGUAGE is the vehicle of communication and the vestment of thought. The ability to use it attractively is a desirable accomplishment.

The ability to use it merely adequately is a prerequisite for the dissemination of knowledge and for the resolution of misunderstanding. It is undoubtedly true that many who could make a useful contribution to knowledge are prevented from doing so by inability to express their thoughts. Even day to day reports, specifications and instructions regularly fall short of the necessary standard of clarity. There is an increasing tendency to employ professionally trained writers to prepare instruction and maintenance manuals relating to complex engineering equipment. It is recognized that those who know most about the equipment, the engineers and designers, are not always adequately trained in the use of language.

Admission to the Graduateship examination of the Institution—and of most other engineering Institutions—is granted only to candidates who have passed the English Language paper, either of the General Certificate of Education, or of an equivalent examination. The Council of the Institution is not altogether satisfied, however, that this is a sufficient requirement. It is possible that the Institution's proposal to include a compulsory paper on Principles of Management may attract support on the ground that this would provide an opportunity for a further test in the use of language and in essay, report or précis writing.

As pointed out in an earlier editorial,† the English language has the greatest currency of all the world's languages. This in no way lessens the Englishman's need to learn a second language. The average British engineer does not receive the encouragement given to engineers in other lands to become proficient in a language other than his mother tongue. The acquisition of a second language not only contributes to the breaking down of a barrier to international amity, but also enriches the individual and reveals to him that problems which he thought peculiarly his own are being faced—and are being solved—in other lands.

Although opinion at present is divided on the matter, there is much to commend the understanding of a second language as part of the qualification required of the future professional engineer.

E. W.

† “Time to Read”, *J. Brit. I.R.E.*, Vol. 17, Dec. 1957.

INSTITUTION NOTICES

New Members of A.B.C.

Membership of the Audit Bureau of Circulations is being sought by an increasing number of professional Institutions. This is shown in the latest official Handbook of the A.B.C. which includes, for the first time, circulation details of a number of Institution journals. The Handbook also shows that for the first time, all British journals concerned with radio and electronics are now being submitted to the Audit Bureau of Circulations.

The Institution has now been in membership of the A.B.C. for eight years. The first A.B.C. Certificate in respect of the *J.Brit.I.R.E.* was granted in July 1953 when the average circulation was 4,983 copies per month. The latest Certificate was for the six month's period, July to December, 1960, and showed that the average monthly circulation during that period was 7,834 copies per issue. This figure does not of course include Journals distributed *after* publication of the Certificate.

It is noted that a number of new members of the Audit Bureau of Circulations prefer to obtain a Certificate based on an average circulation over twelve months. The *J.Brit.I.R.E.* will continue, however, as it has in the past eight years, to apply for an A.B.C. Certificate every six months. The growth in membership of the Institution, as well as the increasing number of subscribers, give every indication that the circulation figure of the *J.Brit.I.R.E.* for the first half of 1961 will well exceed 8,000 copies per month.

The New Journal and Advertisers

One of the factors which influenced the decision to increase the page size of the *J.Brit.I.R.E.* was the desirability of making the format similar to that adopted by many contemporary technical periodicals in Great Britain.

Engineers concerned with the problems of standardization will appreciate that this conformity of size has many advantages. It particularly helps advertisers to make certain economies in the production and use of advertisement plates.

The change has been very well received and favourably commented upon by many members who have been kind enough to write to the Institution especially on this topic.

The Council hopes that members will draw the attention of their commercial colleagues concerned with the buying of advertising space to the acknowledged value of *J.Brit.I.R.E.* The Institution's Advertising Manager will gladly send on request a copy of the new Rate Card as well as any further information required.

A Record Volume

Although there has not been previous editorial comment, many members have observed that Volume 20 (January–December 1960) of *J.Brit.I.R.E.* was the largest ever published by the Institution.

Comparison with other journals devoted wholly to radio and electronic engineering has to take into account different formats, general typographical use and arrangement, and the technical content, as opposed to items of general or commercial interest. Due allowance being made for these factors, Volume 20 of the Institution's *Journal* provided as much technical content as any other comparable journal published in the British Commonwealth.

This achievement is evidence of the value now placed upon the *J.Brit.I.R.E.* by radio and electronic engineers. It is also a tribute to the invaluable work of the Institution's Papers and Group Committees.

It is known that the Proceedings for the current year will make a further record for the Institution. It is for the reason of easy reference that the Council announced in the January *Journal* that the monthly issues will in future comprise two Volumes each year, e.g. Volume 21 will cover the period January to June, 1961, and Volume 22 from July to December, 1961.

Symposium on Electronic Instrumentation for Nuclear Power Stations

A half day meeting on "Electronic Instrumentation for Nuclear Power Stations" will be held on Wednesday, 29th March, at the London School of Hygiene and Tropical Medicine, starting at 2.30 p.m.

The following papers will be presented:

- "Background Factors to the Design of Control Equipment for the Civil Nuclear Power Stations." R. D. Trotter.
- "Instrumentation at Berkeley Power Station." R. E. B. Dawson and M. W. Jervis.
- "Reactor Instrumentation for Bradwell and Latina Nuclear Power Stations." R. V. Ingham.
- "Hinkley Point Neutron Flux Measurement System." P. J. Keeley.
- "Hinkley Point Temperature Scanning Equipment." R. I. Ostler and J. M. Tyrrell.
- "The Shut-down Amplifier." J. Hazell.
- "The Use of Transistors for Reactor Instrumentation." E. P. Fowler.
- "The Design of a Pulse Counting Instrument for Measuring Neutron Flux." R. B. Stephens, J. N. Evisdon and E. P. Fowler.
- "A Transistor Thermocouple Trip Amplifier." G. G. Ballard.
- "A Gamma Radiation Monitor." A. A. Luskow.

Members wishing to attend the Symposium are asked to obtain tickets from the Institution.

A Dielectric Drum Storage System

By

S. MORLEIGH

(Associate Member) †

Presented at a meeting of the Computer Group, held in London on 5th October, 1960

Summary: An examination is made of a new storage system proposed for use with digital computers and data processing equipment. This system, which utilizes a metal drum coated with a thin layer of a dielectric material, would employ two distinct methods of storage and could be used to fulfil a wide range of functions connected with computing and associated devices. The first of the proposed methods of storage would be in the form of charge patterns on a dielectric surface, and could probably be used to store data for periods ranging from milliseconds up to a few hours, while the second method, which is intended for long term storage, would be by means of internal polarization of the dielectric.

1. Introduction

With the advent of the modern digital computer, and the employment of digital techniques in a wide range of data processing installations, the requirement for the speedy recording and recovery of data at will has led to the necessity for the thorough investigation of various physical phenomena with a view to their exploitation for this purpose. Hence, a critical assessment of the properties of all media possessing two stable states is essential, as with the development of new techniques it may become possible to design cheaper and more efficient storage systems.

In the design of a digital storage system, careful consideration must be given to such factors as bulk, cost per unit storage cell, operational speed, power consumed in the switching process, possible difficulties in manufacture and in operation, and also the overall reliability. The present paper is based upon a series of investigations into the storage properties of a rotating dielectric-coated drum employing barium titanate ceramic as a storage medium.

This device can in rather general terms be considered a dielectric counterpart of the magnetic drum memory systems which are at present extensively employed in digital computing devices. In storage systems of the latter type a drum, the surface of which has been coated with some magnetically sensitive material, is rotated at a fixed speed under a row of recording and reading heads. Data is stored in the form of magnetized regions on the drum surface.

In the dielectric system a cylindrical conducting surface is coated with a high- K dielectric material in ceramic form. The operations of recording and reading can be carried out by a number of methods,

certain of which utilize metallic brushes for making electrical contact with the surface of the cylinder. Thus, in the ferroelectric version information would be stored in the form of polarized regions on the drum surface, whilst in the electrostatic case storage would consist of charge patterns on the surface of the dielectric. The essential features of the proposed system are illustrated in Fig. 1.

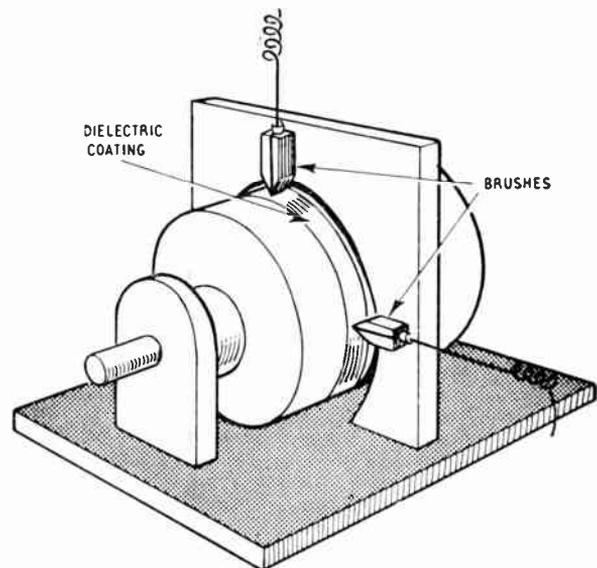


Fig. 1. Dielectric drum—essential features.

The length of the drum surface would be subdivided into a number of separate tracks, each with its associated recording and reading heads. Tracks would be of a finite width which need not exceed a few thousandths of an inch, and spacing between adjacent tracks would be of a similar order. Information would be written along these tracks in binary form, and the track position of a selected bit at any instant

† Formerly of International Computers and Tabulators Ltd., Whyteleafe, Surrey, now with Elliott Bros. (London) Ltd., Borehamwood, Herts.

would be indicated by means of a synchronous clock track. Selection of any desired element would take place during the period of a single drum rotation of the location of the associated drum track. With this method of selection it is possible in the case of the electrostatic store to identify relatively small surface charges, thus overcoming one of the major difficulties connected with the corresponding form of static store.

In a similar manner with the ferroelectric method of storage it would be possible to detect the state of internal polarization of binary cells on the dielectric surface, thus eliminating the need for an elaborate matrix array with the associated problems caused by the application of fractional switching pulses to unselected elements of the store.¹

However, although many of the limitations attendant upon the corresponding types of static store can be surmounted by means of the proposed system, certain new problems are automatically introduced and these will be examined in subsequent sections of this paper.

2. Basic Theory of the Dynamic Electrostatic Storage System

2.1. Recording

Consider a recording brush of circumferential length, a , and axial length, b , which makes intimate contact with the drum (Fig. 2).

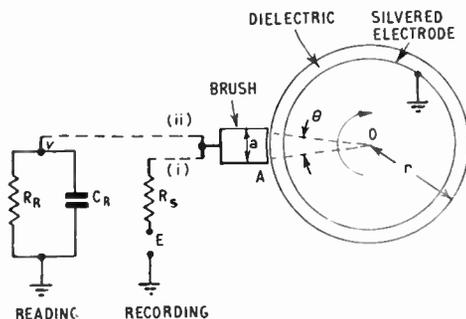


Fig. 2. Dielectric drum—equivalent input and output circuits.

Let a steady voltage pulse of amplitude E be applied from a source of internal resistance R_s , at time $t = 0$ when the line AO is coincident with the leading edge of the brush.

In Section 2.2 it will be shown that the time-constant due to the capacitance C_{ab} under the brush in series with the source resistance R_s is of the order of millimicroseconds, while the time needed for an element of the drum surface to traverse the width of the brush is about $50 \mu s$. It will therefore be assumed that the time-constant of charging for each fresh element of

capacitance as it is presented to the brush is so short that the element instantaneously achieves the potential held by the brush at that moment.

At time t allow the drum to have moved through an angle θ , and the voltage on the brush to have risen to v . After a further time δt let θ and v increase to $\theta + \delta\theta$ and $v + \delta v$ respectively.

Let C be the capacitance per unit area of the drum and r its radius, hence

The uncharged area presented to the brush is $br \delta\theta$.

The charge taken by this area is $Cbr \delta\theta (v + \delta v)$.

The increase of charge on the rest of the area under the brush is $C(a - r \delta\theta)b \delta v$.

Therefore the net increase of charge on the drum is $Cbr \delta\theta (v + \delta v) + C(a - r \delta\theta)b \delta v = Cbr \delta\theta \cdot v + Cab \delta v$

However, the current from the source must equal the rate of flow of charge out of the brush, i.e.

$$\frac{E - v}{R_s} = Cbr \frac{d\theta}{dt} \cdot v + Cab \frac{dv}{dt} \quad \dots\dots(1)$$

Let the velocity of the drum be n revolutions per second.

Thus the angular speed

$$\frac{d\theta}{dt} = 2\pi n \text{ rad/s}$$

Therefore

$$E - v(1 + 2\pi n Cbr R_s) = Cab R_s \frac{dv}{dt} \quad \dots\dots(2)$$

or
$$dt = \frac{Cab R_s}{E - v(1 + 2\pi n Cbr R_s)} dv$$

Integrating

$$t = \frac{-Cab R_s}{1 + 2\pi n Cbr R_s} \log \left[\frac{E - v(1 + 2\pi n Cbr R_s)}{E} \right]$$

since $v = 0$ at $t = 0$,

$$\text{or } v = \frac{E}{1 + 2\pi n Cbr R_s} \left\{ 1 - \exp \left[\frac{-(1 + 2\pi n Cbr R_s)}{Cab R_s} t \right] \right\} \quad \dots\dots(3)$$

2.2. Practical Considerations

Taking values used in the experiments we have:

$$C = 1500 \text{ pF per cm}^2$$

$$b = 0.3 \text{ cm}$$

$$a = 0.006 \text{ cm}$$

$$r = 1.27 \text{ cm}$$

$$n = 1000 \text{ rev/min}$$

$$R_s = 500 \Omega$$

hence
$$2\pi n Cbr R_s = 5 \times 10^{-6}$$

$$Cba R_s = 1.4 \times 10^{-9} \text{ s}^{-1}$$

and hence

$$v = \frac{E}{1 + 5 \times 10^{-6}} \left[1 - \exp\left(\frac{-t}{1.4 \times 10^{-9}}\right) \right] \dots\dots(4)$$

From these values it can be seen that for all practical purposes the charge pattern on the drum will correspond exactly to the voltage pulse applied to the brush, and that the pattern is dictated only by the trailing edge of the brush. The inherent rise time for a pulse applied to the drum, calculated as 1.4 μs, is in all probability sharper than that of the applied pulse, and the amplitude reached, calculated as *E* to within 5 parts in 10⁶, will not in fact be achieved due to imperfect contact of brush and drum. In considering the charge pattern corresponding to the end of the pulse account must be taken of the source impedance at zero voltage output. Provided this does not rise unduly (say not above 1 MΩ) then any charge under the brush at the end of the pulse is instantaneously dissipated by the source.

Consider the charge *Q* deposited on a sector *r δθ* of the drum from a voltage source *E*, we have

$$Q = Cbr \delta\theta E$$

The rate of deposition of charge is

$$\frac{dQ}{dt} = Cbr \frac{d\theta}{dt} \cdot E$$

but $\frac{dQ}{dt} = i_s$, the current flowing from the source.

$$\text{Therefore } \frac{i_s}{E} = 2\pi n Cbr$$

However, $\frac{E}{i_s}$ has the dimensions of resistance and it can be seen that a drum of capacitance *C* per unit area and radius *r*, rotating at a speed of *n* rev/s appears to a record-brush of length *b* as a conductance of value $2\pi n Cbr$.

We can therefore write

$$R_D = \frac{1}{2\pi n Cbr} \dots\dots(5)$$

where *R_D* is a constant of the drum, its speed and the brush. Also we can write (*Cab*) as *C_D* where this is the capacitance under the brush.

Rewriting eqn. (3)

$$v = \frac{E}{1 + R_s/R_D} \left\{ 1 - \exp\left[-\frac{1 + (R_s/R_D)}{C_D R_s} \cdot t\right] \right\} \dots\dots(6)$$

2.3. Conditions at the Read Brush

Consider a read-out circuit consisting of *R_R* and *C_R*, as shown in Fig. 2, and the effect on it of a square voltage pattern which is caused to pass under it by the rotation of the drum.

As soon as the leading edge of the charge pattern comes under the brush the charge contained by it will be spread over the whole of that area of the drum which is instantaneously covered by the brush, and portions of the drum will begin to emerge from under the brush charged to a potential equivalent to that instantaneously on the brush.

Let *t*=0 as the leading edge of the charge pattern strikes the leading edge of the brush, and at time *t* let the drum have rotated through an angle *θ* and the brush have reached a voltage *v*. Consider increment *δt* and *δv* as before.

The charge given to the brush from the charge pattern is *Cbr δθ.E*.

The charge shared over the drum by the brush is

$$C(a - \frac{1}{2}r \delta\theta)b \cdot \delta v$$

The charge lost to the portion of the drum emerging from the brush is

$$Cbr \delta\theta \cdot (v + \frac{1}{2}\delta v)$$

Hence net charge collected by the brush is

$$\begin{aligned} Cbr \delta\theta \cdot E - C(a - \frac{1}{2}r \delta\theta)b \delta v - Cbr \delta\theta(v + \frac{1}{2}\delta v) \\ = Cbr \delta\theta \cdot E - Cab \delta v - Cbr \delta\theta \cdot v \end{aligned}$$

The net rate of collection of charge is therefore

$$Cbr \frac{d\theta}{dt} (E - v) - Cab \frac{dv}{dt}$$

This collection of charge is balanced by the current flowing out of the brush into *R_R* and *C_R*.

This current is

$$\frac{v}{R_R} + C_R \frac{dv}{dt}$$

Hence

$$Cbr \frac{d\theta}{dt} (E - v) - Cab \frac{dv}{dt} = \frac{v}{R_R} + C_R \frac{dv}{dt} \dots\dots(7)$$

or writing $R_D = \frac{1}{2\pi n Cbr}$ and $C_D = Cab$

$$\text{we get } \frac{E - v}{R_D} - \frac{v}{R_R} = (C_D + C_R) \frac{dv}{dt}$$

$$\text{or } E - v \frac{(R_R + R_D)}{R_R} = R_D(C_D + C_R) \frac{dv}{dt}$$

Integrating we get

$$v = \frac{R_R E}{R_R + R_D} \left\{ 1 - \exp\left[-\frac{R_R + R_D}{R_D R_R (C_D + C_R)} t\right] \right\} \dots\dots(8)$$

Similarly for the decay of the pulse it can be shown that

$$v = \left(\frac{R_R E}{R_R + R_D} \right) \cdot \exp\left[-\frac{R_R + R_D}{R_D R_R (C_D + C_R)} t\right] \dots\dots(9)$$

3. The Experimental Storage Units

For reasons which will be apparent later the bulk of this investigation was devoted to the electrostatic method of storage and a description of the experimental units used for this purpose will now be given. Details of the ferroelectric device will be given in the section devoted to experiments with that type of store.

Each drum consisted of a ceramic tube fixed to a metal shaft by a conducting cement. The inner surface of the tube was silvered, and electrical contact was made via the metal shaft. For experimental purposes, the processes of recording, reading and erasure were carried out with brushes of similar types, these being spaced at intervals over a single track. Each brush was formed of a strip of stainless steel, 0.0025 in. thick and 0.15 in. wide, secured between two pieces of p.t.f.e., the latter serving as a lubricant in addition to providing means of support.

Pick-up was reduced to a minimum by screening the read-out brush and the output leads. The erasing brush, which was earthed, was found necessary in order to eradicate stored information. It was also possible to alter the position of the drum relative to the brushes to enable selection of alternative tracks. Drum speed was controlled by means of a variable speed gear coupled to the driving shaft.

Two types of ceramic tube, referred to subsequently as types A and B respectively, were used for the purpose of these experiments. Type A had an outside diameter of 1.15 in. and a wall thickness of 0.05 in., while type B was 0.875 in. in outside diameter and 0.062 in. in wall thickness. The value of dielectric constant of the material was 3000 in each case. Unfortunately, owing to cracks and other blemishes that appeared on the surface of the ceramic, it was not possible to use tube A for more than a few tests. The experiments are all described in the next section.

Input data, in the form of rectangular pulses, was supplied from a low impedance source. Measurements of output voltage were taken on an oscilloscope having an input impedance of 10 megohms. The efficiency of the overall system as described is affected by losses from various causes, particularly those due to irregularities both in the drum surface and in the shape of the brushes, which lead to the presence of an air film between brush and drum.

4. Experiments in Electrostatic Storage

A number of tests were carried out in order to investigate the storage properties of the electrostatic drum, and to note the closeness with which the theory of this subject can be verified. The only test equipment used were: a signal generator having a low source impedance (500 Ω); an oscilloscope—used on the ranges having 10 M Ω input impedance; a stroboscope;

and a 500-V d.c. megger, which was required only for the first of these tests.

All experiments, except for one of those described in each of Sections 4.2.2 and 4.3, were carried out with drum B.

4.1. Input Impedance as a Function of Drum Speed

The purpose of this series of tests was to measure the input impedance of the drum for different speeds of shaft rotation; the megger was connected to the recording brush, the erasing brush remained earthed, and the read-out brush was disconnected. The speed of drum rotation was varied from 260 to 1000 rev/min in steps.

Input impedance over this range varied from 23 M Ω at 260 rev/min, to 6 M Ω at 1000 rev/min. Values of conductance, i.e. $\frac{1}{R}$, plotted against speed of rotation (Fig. 3) clearly follow a linear law.

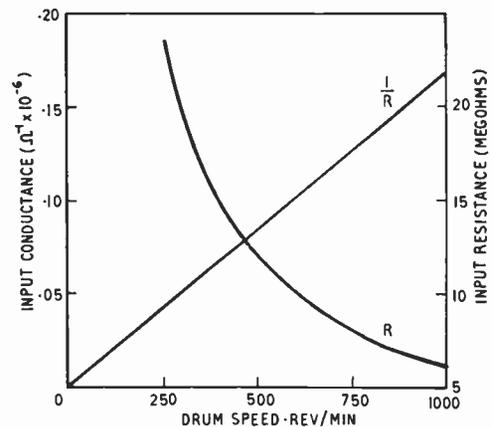


Fig. 3. Electrostatic drum: input resistance of drum as a function of shaft rotation.

4.2. Output Voltage and Signal/Noise Ratio as Functions of Width and Amplitude of Input Pulses

The drum was now rotated at 1000 rev/min whilst rectangular pulses at a repetition frequency of 50 c/s were applied to the input circuit. Readings of output voltage were taken on the oscilloscope.

4.2.1. Variation with pulse width

Pulse width was varied from 25 μ s to 250 μ s in steps, the pulse amplitude being maintained at 110 V.

Output voltage appears to increase in value asymptotically as input pulse width is expanded up to about 50 μ s. The increase is then approximately linear for pulse widths up to about 200 μ s, after which the rate of increase falls. Signal/noise ratio seems to increase asymptotically with pulse width, reaching a maximum of 12 : 1 for pulse widths of the order 200 to 250 μ s. Both sets of results have been plotted in Fig. 4.

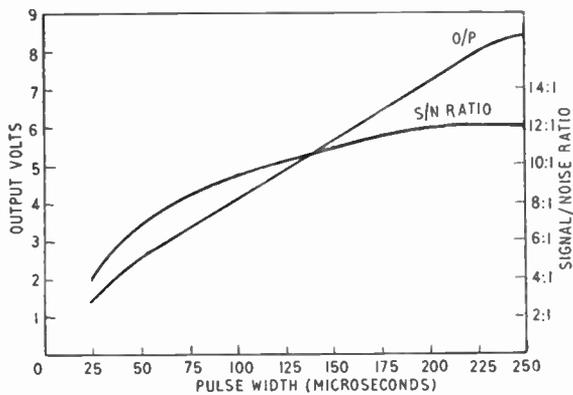


Fig. 4. Electrostatic drum: output voltage and signal/noise ratio as functions of input pulse width.

The initial shape of the output voltage curve is probably caused by the finite thickness of the read-out brush (0.0025") as this takes about 50 μs to be traversed by any element of the drum surface. The remainder of this curve should theoretically follow a law of the form $E = k [1 - \exp(-t/CR)]$. Output voltages obtained experimentally will, however, be rather lower than the theoretical values because of the losses in the overall system.

4.2.2. Variation with pulse amplitude

Amplitude of input pulses was increased from 12 V to 110 V in steps. Output voltage over this range was recorded for pulse widths of 100 and 250 μs.

Both sets of results (Fig. 5) show a linear relationship between amplitudes of input and output signals. Maximum output levels of 8.4 V and 4 V were obtained for the input pulses widths of 250 and 100 μs respec-

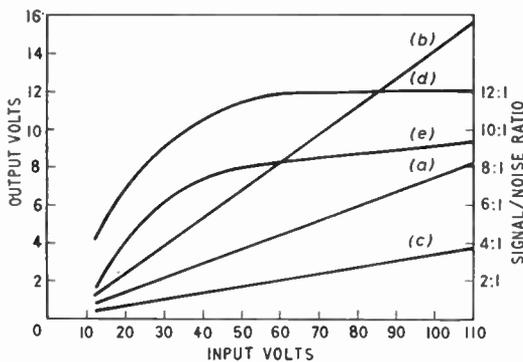


Fig. 5. Electrostatic drum: output voltage and signal/noise ratio as functions of input pulse amplitude.

Drum speed 1000 rev/min. Input p.r.f. = 50 c/s.

- (a) Output drum "A" for 200 μs width input pulses
- (b) Output drum "B" for 250 μs width input pulses
- (c) Output drum "B" for 100 μs width input pulses
- (d) Signal/noise ratio drum "B" for 250 μs width input pulses
- (e) Signal/noise ratio drum "B" for 100 μs width input pulses

tively. Signal/noise ratios again seem to follow an asymptotic law.

A further test of this type, using pulse widths of 200 μs, was carried out on Drum A. The results were of a similar character, the maximum output level being 16 V in this case.

4.3. Output Voltage as a Function of Input P.R.F.

The purpose of this experiment was to examine the maximum packing densities attainable using the available ceramic drums. The drum under test was rotated at 1000 rev/min while the repetition frequency of the applied pulses was increased from 50 c/s to 2500 c/s in steps. Pulse amplitude was maintained at 110 V, and the corresponding output voltages were noted.

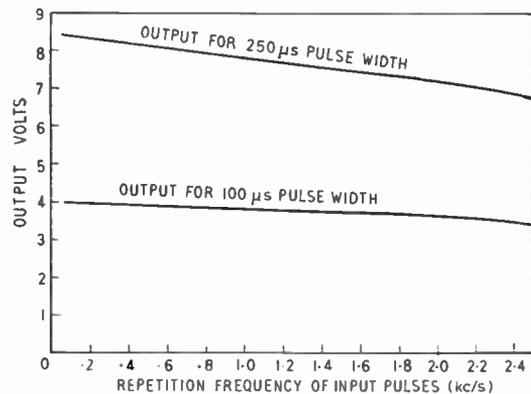


Fig. 6. Electrostatic drum: output amplitude as a function of input p.r.f.

Output readings were recorded from drum B for input pulse widths of 100 μs and 250 μs. The results (Fig. 6) indicate a slight drop in output voltage over the input frequency range 50 to 1000 c/s, after which the decrease in amplitude is gradually accelerated. However, this loss of output, over the entire frequency range covered, is only about 20%. Repetition frequencies of the order of 1.8 kc/s could be used satisfactorily for storage purposes with this drum, and this is equivalent to a packing density of about 40 bits per inch.

Drum A was tested under similar conditions, but only with pulse widths of 200 μs. These results have not been recorded, but the fall in output voltage over the same range of input frequencies was less pronounced. This type of ceramic tube may therefore be operated with p.r.f.s up to about 2.3 kc/s, which is also equivalent to a packing density of approximately 40 bits per inch.

The fall in output signal amplitude with increase of pulse repetition frequency that has been noted in this series of tests can probably be attributed to incom-

plete erasure of stored data after read-out. This would have the effect of causing the level of residual charge stored on the drum to increase with frequency, so that the amplitude of output signals would appear to fall.

4.4. Output Voltage and Signal/Noise Ratio as Functions of Drum Speed

This series of tests enabled an examination to be made of the output performance of the system for different speeds of drum rotation. Pulses of 110 V at a p.r.f. of 50 c/s, with pulse widths of 250 μ s and 100 μ s were applied, and output readings taken for drum speeds varying from 250–1000 rev/min.

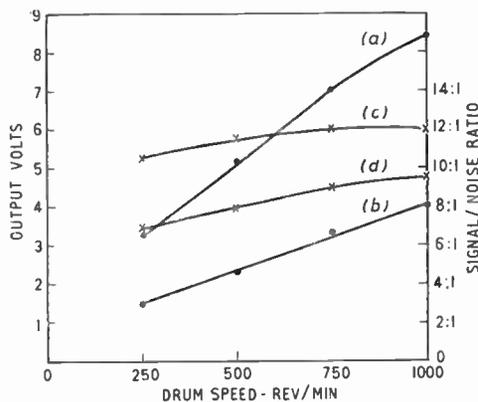


Fig. 7. Electrostatic drum: output voltage and signal/noise ratio as functions of drum speed.

Input pulse amplitude 110 V. Input p.r.f. = 50 c/s.

- (a) Output for 250 μ s width input pulses
- (b) Output for 100 μ s width input pulses
- (c) Signal/noise ratio for 250 μ s width input pulses
- (d) Signal/noise ratio for 100 μ s width input pulses

The results (Fig. 7) indicate a linear increase of output signal with drum speed. This agrees with theory as the surface area available for storage of any particular pattern must increase with the speed of drum rotation. Output signal strength increased by about 250% over the range of drum speeds covered, while signal/noise ratio also increased by a small amount.

Following these experiments it was considered of interest to reproduce a typical input pulse on an oscilloscope. For purposes of clarity a relatively high voltage pulse of long duration was used and this is shown in Fig. 8.

5. An Analysis of Experimental Results from the Electrostatic System

The results showed conclusively that the input circuit of a rotating capacitive drum, as presented to a fixed recording brush, is equivalent to a conductance, the value of which is dependent upon the speed of rotation and capacitance per unit area of the drum.

Input and output impedances of the experimental electrostatic drums were of the order of several megohms, and the design of suitable output circuits is difficult. However, this can be overcome to some extent by the use of a cathode follower reading stage employing a thermionic valve of the electrometer type.

Using a store of the latter type as a "dynamic" delay line, the overall losses are very low. For example, when storage pulses 30 V in amplitude and of 200 μ s duration were applied to a ceramic drum having a 0.05 in. wall thickness, the output pulses, measured across a 10 M Ω impedance, were 4 V in amplitude after an 11 ms delay.

Packing densities of about 40 bits per inch were obtained from the experimental units, but much higher packing densities should be attainable.

Signal/noise ratios of about 12:1 were obtained from the experimental stores and it is probable that these values can be considerably increased.

The leakage time-constant of the dielectric is approximately 6.6 hours, and pulse patterns are easily identifiable after 1.5 hours storage with the drum stationary. However, due to the spreading of the charge pattern consequent upon its passage under the brushes, the pattern is seriously affected after a few drum revolutions.

Alternative methods of recording and reading which may overcome the latter problem will be discussed in the next section, whilst the decay time of a surface charge will be examined under the appropriate heading.

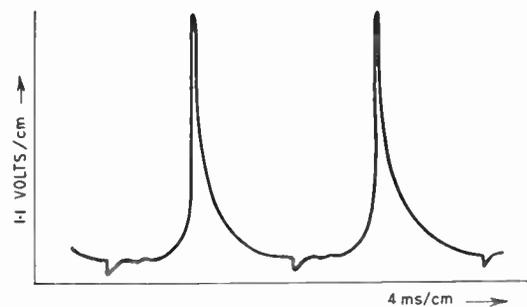


Fig. 8. Electrostatic drum: output signal for 110 V 250 μ s input pulse. Drum speed approx. 1000 rev/min. Reproduced from an oscillogram.

6. Experiments in Ferroelectric Storage

An investigation into this method of storage was carried out using a dielectric drum of similar dimensions to type B employed for electrostatic storage. The dielectric consisted of a hollow cylinder of barium titanate ceramic produced by a moulding process; the material was initially polarized by being cooled through its Curie temperature whilst under the influence of an electric field. With the application of

high intensity electric pulses it was possible to store digital pulse patterns on the drum surface and to identify these by examining the direction of the internal polarization.

Unfortunately, due to the thickness of the dielectric, the voltages required for polarization were of the order of 1 kV, thus severely limiting the number of tests which could be carried out at the time. However, by means of spraying techniques dielectric coatings only 0.005 in. or even less in thickness have since been produced.² The intensity of the applied field necessary for switching elements of a ferroelectric in a given time is approximately inversely proportional to the dielectric thickness,¹ and it appears probable that with the application of pulses of the order of say 30 to 40 V across the dielectric, switching should be completed within a matter of microseconds.

7. Methods of Recording and Reading

The experiments on electrostatic storage were all carried out using recording and reading brushes of the type described. This system was found to be unsatisfactory for the following reasons:

- (i) Due to wear it would be necessary to replace brushes after a period of constant use.
- (ii) Each brush must have a finite width, even if only say 0.0025 in, therefore with each successive rotation of the drum as soon as the charge pattern reaches the reading brush it will consequently be spread by this brush to previously uncharged areas of contact. This sharing of the charge will also effectively reduce the amplitude of the stored signal so that the charge pattern will be rendered indecipherable after a few drum revolutions.

There appear to be a number of possible methods of overcoming these problems, although none of them is without its attendant difficulties. The first would entail the use of retractable brushes, or preferably a single retractable read/write brush, which need only make contact with the drum surface at the moment of reading or writing. Systems of this nature have been successfully employed with magnetic drums, and should not be very difficult to produce. Another possible method would require the reading and rewriting of all stored data with each drum revolution. It would of course be essential to use a small restandardizing unit to reshape and amplify the pulses before rewriting, but this need only be a relatively simple device as a single stage of amplification should suffice. It would, however, still be necessary to replace the read and write brushes after a fixed period of continuous use, although this would be quite an easy matter in view of the simplicity of construction of brushes of this type.

An alternative method of writing would be to utilize an ionization recording head to enable charge to be transferred to the surface of the dielectric through a conducting path of ionized air produced by a stable r.f. corona discharge. Any element of the drum surface passing through the discharge region would become charged to the mean potential of this locality. The only changes in the charge pattern on the dielectric surface which can take place outside this conducting area would be those due to leakage. The latter effect, which is comparatively slow, is discussed in the next section. Read-out of stored data could be provided by means of a simple form of capacitive probe, as the variations in charge distribution on the surface of the rotating cylinder will cause proportional variations to take place in the e.m.f. induced in any conductor held in its proximity.

A system of this type is reported³ to have been successfully employed for recording analogue information. However, the necessity for positioning the heads, particularly the reading head, away from the drum surface must bring with it obvious difficulties due to the resultant attenuation of output and reduction of signal/noise ratio as compared with the systems using direct contact brushes.

A method by which the processes of recording and reading could be accomplished without the effects of charge spreading has been proposed by a former colleague, C. K. Burchell. This would require ancillary dielectric drums maintained in contact with the main storage drum and although the practical problems associated with such a system would be difficult to overcome it is still worthy of consideration.

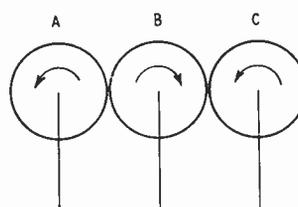


Fig. 9. Basic arrangement of proposed "line of contact" read/write system utilizing ancillary drums.

The idea consists in using three dielectric drums A, B and C, identical in size and geared to rotate at the same speed while maintaining line contact with one another. The system is illustrated in Fig. 9. Drum B would be used for storage purposes while A and C would be used for writing and reading respectively. Writing would be effected by the application of a voltage pulse, of amplitude say V , between the inner conductors of drums A and B as this would cause the dielectric material under the line of contact of each

drum to be charged. The resultant initial condition would thus be charges corresponding to 0.5 V on both A and B. The leads to the inner conductors of the drums should be effectively open-circuited when writing is not taking place, then, since only a line of contact exists, there would be no spreading or attenuation of the charge despite the rotation of the drums. Drum A may therefore be used as a writing brush of zero width, while in a similar manner drum C would be employed as a reading brush of zero width.

The system can be used as a dynamic delay line since variations in delay time can be obtained by controlling the speed of the drums or by rotating the centre of drum C about B.

Used as a permanent store it can be seen that if the drums are identical then the charge becomes divided as follows:

	DRUM A	DRUM B	DRUM C
Initially (after application of writing pulse)	0.5	0.5	0
After 180° rotation of B, charge distribution	0.5	0.25	0.25
After 360° rotation of B, charge distribution	0.375	0.375	0.25
After 540° rotation of B, charge distribution	0.375	0.312	0.312
Final charge distribution	0.333	0.333	0.333

This is, of course, assuming no losses in air-gaps, but in practice a certain amount of charge spreading may occur in regions immediately adjacent to the line of contact where the air-gap may be too small to make appreciable difference to the effective series capacitance of contacting regions of two drums. Charge spreading may also be caused by backlash in the gearing of the drums.

A slight modification of this system would be to replace drums A and C by discs which could be moved along central shafts as desired in order to contact different sections or groups of tracks on the surface of drum B. This arrangement should make the necessary intimate line contact between the drums a little easier to obtain. However, the practical difficulties in manufacturing a device of this type appear formidable so that little work has been carried out in this direction.

The ferroelectric method of storage would obviously not be affected by charge spreading, and of the read/write systems described only those utilizing contacting brushes could be employed with this type of store. The most suitable system for use with either of the dielectric memory devices would probably be that involving retractable brushes, and it is this which would be proposed for any future work which may be carried out on the dielectric drum stores.

8. Decay Time of a Surface Charge

An important property of the dielectric material forming the basis of the electrostatic drum is the decay time of a surface charge stored on it. This is determined by two unrelated factors which are (a) the characteristic decay time of the dielectric and (b) the surface resistivity.

The characteristic time constant of the material can be easily calculated and shown to be independent of the geometry and dimensions of the sample.

Let the volume resistivity of the ceramic be ρ ohms/cm³, and let K be the dielectric constant.

Consider a disc of area A cm² and thickness d cm. The capacitance is given by:

$$C = \frac{KA}{4\pi d \times 9 \times 10^{11}} \text{ farads}$$

and the resistance between opposite faces of the disc is

$$R = \frac{\rho d}{A} \text{ ohms}$$

Therefore the time constant,

$$CR = \frac{K\rho}{4\pi \times 9 \times 10^{11}} \text{ seconds}$$

The figures quoted for the material used in the experimental stores are $K=3000$ and $\rho=10^{14}$ ohms/cm³.

$$\begin{aligned} \text{Hence } CR &= \frac{3}{36\pi} \times 10^6 \text{ seconds} \\ &= 6 \text{ hr } 40 \text{ min} \end{aligned}$$

Leakage effects due to surface resistivity are dependent to some extent upon factors such as the humidity of the surrounding atmosphere and blemishes on the surface of the ceramic, but mainly upon geometrical considerations. An investigation into the decay of a sinusoidal charge on a cylindrical surface has shown that for wavelengths which are long in comparison with the dielectric thickness, the decay time is proportional to the square of the wavelength of the surface charge and directly proportional to the resistivity of the dielectric surface.⁴ The effects of surface resistivity must therefore tend to distort the charge pattern of recorded pulses.

However, despite these factors it was possible to identify charge patterns stored on the surface of a stationary drum after a period of about 90 minutes. It must in any case be borne in mind that this method of storage is primarily intended to be of a temporary nature, and that the majority of the applications of such a device require storage times ranging from two or three milliseconds to a few minutes.

9. Conclusions

The storage of digital information in the form of surface charges on a ceramic drum would have many applications for purposes of dynamic storage, particularly on the grounds of cost and simplicity of construction. It would be necessary to carry out further work on methods of recording and reading before the store could become a practical proposition, the suggested methods involving either the employment of a retractable read/write brush or the regeneration of stored data with each drum rotation. However, if the drum were stationary, or if the brushes were removed, the charge pattern should still be identifiable after a period of some hours.

Permanent storage can probably be carried out by means of internal polarization of the dielectric, although only a limited amount of work has as yet been carried out in this direction. With this type of store it appears probable that stored data would be automatically erased by the read-out process, but a method of rewriting this information can be adopted if non-destructive read-out is required.

In a large scale dielectric drum memory system the greatest efficiency may be obtained by a combination of these methods of storage.

Packing densities of about 40 bits/inch which were obtained from the experimental electrostatic drum stores are comparable with those obtained from magnetic drums in use with some commercial computers. These values are, nevertheless, considerably lower than those obtainable from certain other magnetic drum stores now available. However, with further development higher packing densities than these should be attainable from an electrostatic store.

The comparative cost of drum materials and coatings for the two systems is roughly equal, but the

magnetic head is much more complicated than its dielectric counterpart. In addition to this the overall losses of the magnetic system are much higher than those of the dielectric store so that a more expensive type of amplifier is essential. On the basis of these factors the cost per track of magnetic drum storage is by far the higher of the two.

A new digital storage system such as that proposed could have many industrial applications on the grounds of its simplicity and economy as compared with existing memory devices. Further work would, however, have to be carried out into various associated problems before the system could really be of commercial value.

10. Acknowledgments

The author's thanks are due to Mr. J. Drewe, Manager of the Research and Design Division of International Computers and Tabulators Ltd., for permission to publish this paper, and to his former colleagues, Messrs. C. K. Burchell and A. Foster for their valuable assistance and encouragement during the course of this work.

11. References

1. S. Morleigh, "Ferroelectric storage devices", *Electronic Engng*, **30**, pp. 678-84, December 1958.
2. G. V. Planer and A. Foster, "A flame-sprayed ceramic dielectric for transducers", *J. Brit. I.R.E.*, **19**, pp. 699-702, November 1959.
3. V. C. Anderson, "Dielectric recorder", *Rev. Sci. Instrum.*, **28**, pp. 504-9, July 1957.
4. V. C. Anderson, "A Recording-Reproducing System Using a Dielectric Storage Medium", University of California Marine Physics Laboratory, S.I.O. Ref 55-6, 4th January 1955.

*Manuscript received by the Institution on 28th June 1960.
(Paper No. 615).*

scribed into the film to divide it into two separate resistance tracks. In this configuration the mercury drop effectively fills the bore of the tube, and in fact the depth of the scribed lines may be used to control the degree of damping, that is, to regulate the amount of gas flow across the mercury charge during movement of the latter. Another means of controlling damping of the switch is by adjustment of the gas pressure under which the unit is sealed, or where high inertia is required by filling it with liquid instead of gas.

In either of the above methods of deriving the resistance law, the parameters of tube or track shape and surface resistance are calculated, taking into account the given values of the envelope dimensions, maximum permissible wattage rating of the track, and safe limit of ohms/square value.

An important factor in the functioning of the switch is the mobility of the mercury. Prolonged tests with and without electrical load have shown the oxide to remain unaffected in contact with the mercury; the angle of contact, as with many other surfaces, is in the absence of special treatments relatively low and this would lead to irregular movement of the mercury. It has been found that this difficulty can be overcome by a special surface treatment of the interior of the envelope; this involves superposition of a slightly porous oxide coating of, for instance, titanium dioxide, stannic oxide or tungstic oxide, deposited from a solution. In this way, the contact angle is increased appreciably, with consequent uniform traverse of the mercury charge even under vibration free conditions. The treatment moreover has no noticeable effect on the contact resistance between the mercury and the resistance track. Naturally, the magnitude of this contact resistance should be as low as possible in relation to the overall resistance and its effect is minimized by designing the switch to have the maximum permissible oxide track resistance.

Where accurate shaping of the track is required, that is, if the latter is used to determine the resistance law, the portions of the deposit to be retained are masked with a varnish and the remainder removed chemically. Alternatively, where the envelope shape determines the law, two narrow lines are simply scribed into the deposit. The units are normally gas filled, for instance with pure nitrogen or argon. Where a high degree of damping is required, as already said, a liquid may be used instead.

The procedure of sealing the glass envelope is also of some importance; the conditions have to be controlled in such a way that the oxide film with the overlying noble metal contact layer permeates the glass seal satisfactorily, since the film must not be disrupted when the seal is made. Also, as already referred to, the glass is arranged to cover the noble metal reinforce-

ment so that no part of the latter protrudes into the interior of the envelope.

In some applications the switch is required to deal with isolated signals many times greater than those provided for by the law for which it was designed. This can be allowed for by incorporating a pair of tungsten contacts sealed into the end of the glass envelope with the requisite connexions to short out part of the series resistor when the mercury drop reaches one of the ends of the tube.

The resistance values of the films at present used are normally of the order of 250 ohms per square, that is equivalent to values of 1500 ohms for each of the two tracks. The dimensions of the envelope are of the order of 5 cm length by 0.6 cm diameter.

The maximum current rating of the type of switch produced at present is 30 mA and the output, in the form of a current difference in two 100- Ω load coils, conforms to the prescribed law within about $\pm 1\%$; the output is reproducible to within ± 3 min over a tilt range of ± 3 deg.

Electrical load tests at the rated voltage (28 V) have been carried out over 2000 hours. Overload tests at three times the rated voltage have been continued over some 100 hours without noticeable deterioration; the switches were tilted continuously on a moving platform during these tests.

3. Continuous Track Potentiometer

The second device, a miniature continuous track potentiometer with high linearity, utilizes again a stannic oxide type resistance element on glass base and is designed as a potentiometric pick-off for use in various types of control systems.

The dimensions of the effective oxide track in one such device are $\frac{1}{10}$ in. swept length by $\frac{1}{32}$ in. width, the wiper consisting of a metal wire. The linearity along the swept length of this device is of the order of 0.1%, substantially better than is normally obtainable in wire-wound elements of similar dimensions. To attain this accuracy, it is necessary to define the track shape by a photographic process, and to ensure a high degree of uniformity in the application of the oxide film. In addition lapping of the surface of the oxide track has been found to result in improvements in the noise and wear characteristics. The terminals are constituted by bands of fired-on metal paint to which soldered connexions are made. As the wiper a short length of an alloy wire, for instance of copper-silver-gold or platinum-iridium, is used. This is arranged to traverse the track at right angles to the latter, the end of the wire being formed into a hemispherical shape of diameter 0.008 in.

In one particular transducer requirement the track resistance is 1200 Ω , equivalent to 300 Ω /square, with

a maximum permissible loading of 30 W per square inch of film. This element fulfils the requirement of maintaining a linearity of 0.1% over the period of a wear test of 100 000 sweeps at a rate of one sweep per second. The operating temperature range for these elements extends from -40° to $+85^{\circ}$ C. An important aspect of these devices is the sweep-noise value. In the present construction, this value can be maintained at a level of about 0.01 mV/V, with 12 V d.c. applied over the duration of the 100 000 cycle wear test. The noise may be monitored oscilloscopically during the test and Figs. 3 and 4 show the form in which this characteristic is followed. Figure 3 relates to an oxide track swept by a conventional metal stud wiper. The upper sinusoidal trace indicates the movement of the wiper and the lower one shows the noise pattern, which in practice is evaluated on a calibrated screen. Figure 4 shows a similar trace in the case of a wire wiper of the type previously referred to; this results in an appreciably lower noise level of the order of about 0.01 mV/V. On completion of

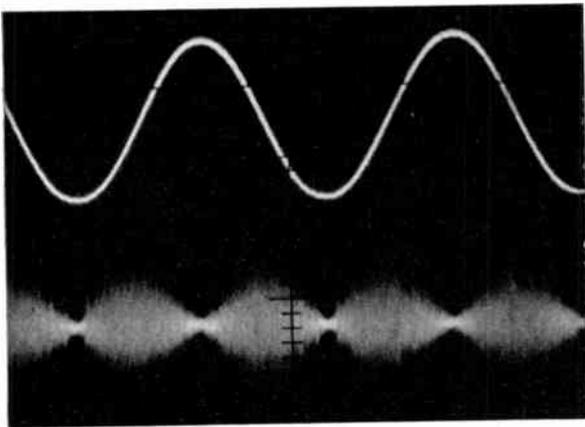


Fig. 3. Determination of noise generated by an oxide track swept by a metal stud wiper. Upper trace shows position of wiper, lower trace the noise pattern.

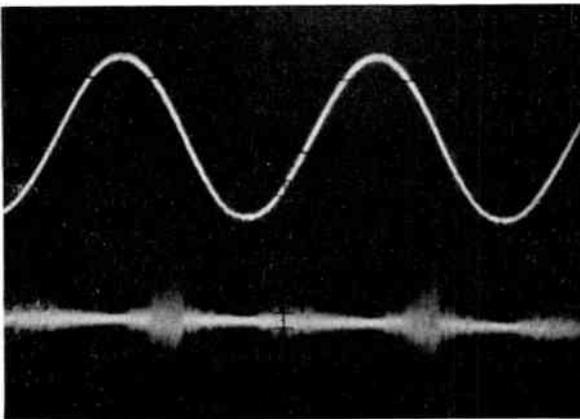


Fig. 4. As for Fig. 3 but showing improvement obtained by use of a wire wiper.

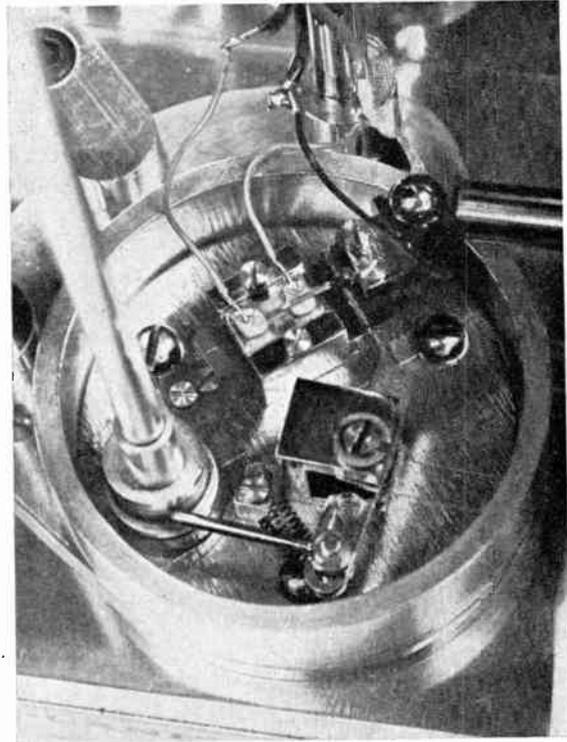


Fig. 5. Miniature potentiometer mounted in the wear and linearity test machine.

the test the track is normally quite unmarked and this could evidently be prolonged considerably; however, the wear requirements are satisfied at this extent in the application for which the element was designed.

For certain uses the potentiometer is required to operate in silicone oil, and the above performance data was in fact derived with the element submerged in silicones with viscosities of 100 or 500 centistokes.

Apart from the actual track and wiper configuration, the mechanical construction of the device is of course also of importance in attaining the required order of linearity as well as noise and wear characteristics. It is important that backlash in the mechanism is eliminated as far as possible. To obviate differential expansion effects over the required temperature range the mechanism is essentially made up with the use of only one type of metal.

Figure 5 shows one of the miniature potentiometers mounted in the wear and linearity test machine, which would normally be silicone filled. The full assembly comprising a drum micrometer for the linearity check is seen in Fig. 6.

With regard to the temperature coefficient of resistance, this value can theoretically be made quite close to zero in oxide film resistors by suitable balance between composition and coating thickness. In the present transducer requirement however some deviation from the conditions of optimum temperature

coefficient was dictated by the requirement of a high ohms per square value (300) together with good mechanical wear properties implying a reasonably thick film and unusually high wattage loading (30 W/in^2) for this type of film. To fulfil these requirements some compromise in the coating conditions is necessary and the value of the temperature coefficient for the $1200\text{-}\Omega$ element is normally of the order of -300 parts in 10^6 per deg C.

Brief mention may be made of a modification of the miniature potentiometer discussed, wherein the film track is deposited around a cylindrical glass filament of 0.015 in. diameter which is cemented to a flat base plate. In this way the need for photographic definition of the track dimensions is obviated, and the condition of a point-contact with the wiper is more nearly realized. Another aspect is that by the use of a continuous coating process for the filament with subsequent division into the required lengths, high uniformity along the element is more easily achieved. Elements of this new modification are currently undergoing assessment.

4. Production and Characteristics of Oxide Films

The method of producing the oxide films in the devices discussed consists essentially in spray-applying aqueous solutions of the requisite metal chlorides with subsequent hydrolysis to the oxide; the substrate is maintained at a temperature of 500° to 600°C in an electric furnace.

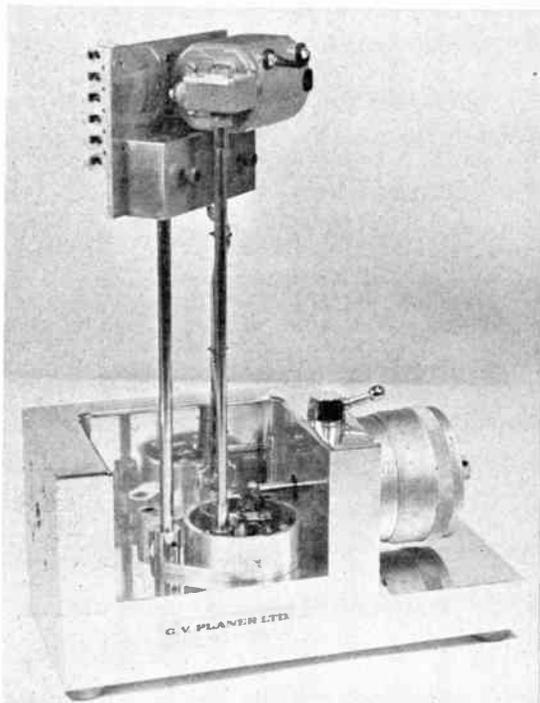


Fig. 6. The complete machine for determining wear and linearity of miniature potentiometers.

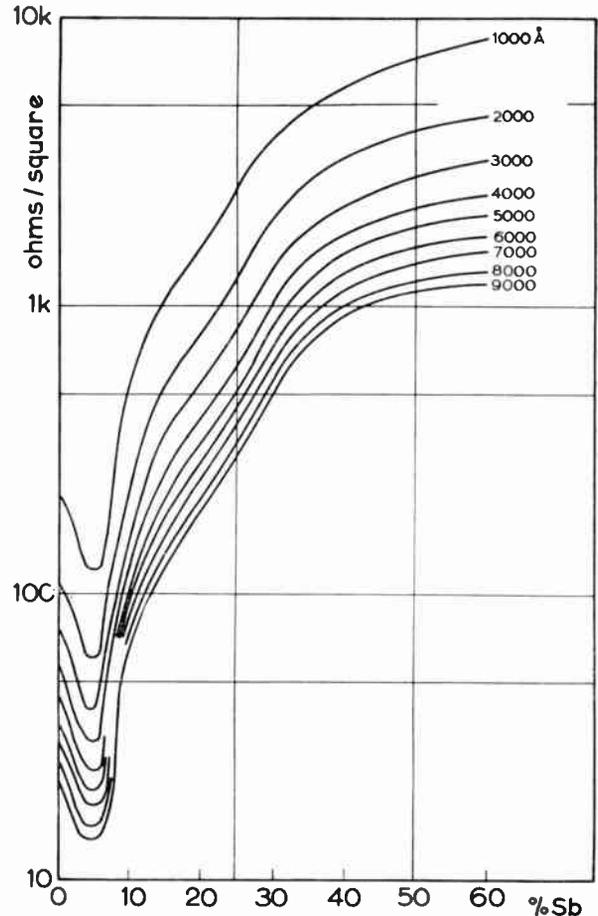


Fig. 7. The relation between resistivity and film composition and thickness for mixed tin-antimony oxides.

The resistance values are controlled by the film composition and thickness; for the case where mixed tin-antimony oxides are used for example, Fig. 7 shows the effect of varying the antimony content on the resistance for films of thicknesses between 1000 and 9000 \AA . The temperature coefficients are likewise dependent on the composition and thickness and the values can be either positive or negative. The conditions may therefore be chosen to correspond to the minimum numerical coefficient for the desired resistance value, having regard to other relevant factors such as wear and electrical load requirements.

5. Conclusion

It is evident that the devices discussed here are only examples of the use of continuous resistance films in transducers, and there would appear to be many other applications in control equipment of various types.

Manuscript received on 6th October, 1960 (Paper No. 616).

A Special-purpose Analogue Computer and its use in Reactor Engineering

By

W. A. HAVRANEK†

Presented at the South Western Section's Convention on "Aviation Electronics and its Industrial Applications" held in Bristol on the 7th-8th October 1960.

Summary: This paper deals with the description and application of a reactor analogue computer. Reactor operational and training problems suitable for analogue computer solution are dealt with and present trends in design and application indicated.

List of Symbols

n	neutron concentration
K	reactivity
δK	small increment in K
β	total fraction of delayed neutrons
l^*	mean neutron lifetime
λ_i	decay rate of i th delayed neutron emitter
C_i	concentration of delayed neutrons emitted from i th group
S	neutron source
β_i	fraction of delayed neutrons in i th delay group

1. Introduction

Flight simulation has become well established over the last 20 years, while the use of analogue computers in aerodynamic problems has also played a major part in aircraft design. Experience gained in this field by the aircraft industry can now be put to use in other spheres and this paper deals with the application of these techniques to nuclear problems.

In reactor engineering two types of analogue computing machines are in common use. The one which takes major importance is the general purpose computer for the dynamic solution of mathematical problems.¹⁻⁶ The other type is the training simulator which in design philosophy is equivalent to the flight simulator and which is primarily useful for operator training.⁷⁻¹¹

The machine described in this paper has been constructed on a new principle. It consists of a number of units whose main use is limited to nuclear reactor simulation. In addition there are basic units similar to those which can be found in various general purpose computer designs. Thus, it is possible to build up installations from these units of varying capacity in order to cope with different design or

training problems. The installations are being utilized for both training and problem solution, thereby obviating the need for separate facilities.

2. Application Philosophy of the Computer

The basic concept of the computer originated from R. F. Mathams and such a machine, having a capacity of 20 amplifiers, is now in use at A.E.I. Research Laboratory. This machine has been redesigned and extended in order to become a generally acceptable proposition to the nuclear industry and teaching institutions. The overall concept of the computers now in production is that they are normally programmed for reactor simulation taking into account the simultaneous consideration of the following effects:

1. Neutron kinetics.
2. Photo neutrons.
3. Source.
4. Linear and logarithmic power indication.
5. Reactor period.
6. Control rods.
7. Heat transfer.
8. Poisoning.
9. Applied external reactivities.
10. External loop for power station simulation.

All general purpose units assigned to these functions may be isolated by removal of shorting plugs and can then be programmed for solution of other problems (see Fig. 1). Installations of the new type are in use or in construction for Reactor Group, G.F.K.F., North Rhine-Westfalia, Germany (see Fig. 2), Rome University and the International Reactor School, Kjeller, Norway.

3. Simulation of Reactor Phenomena

3.1. Neutron Kinetics

Assuming a one-group neutron model and that no coupling exists between space- and time-dependent phenomena, seven differential equations relate the

† Miles Electronics Limited, Shoreham Airport, Sussex.

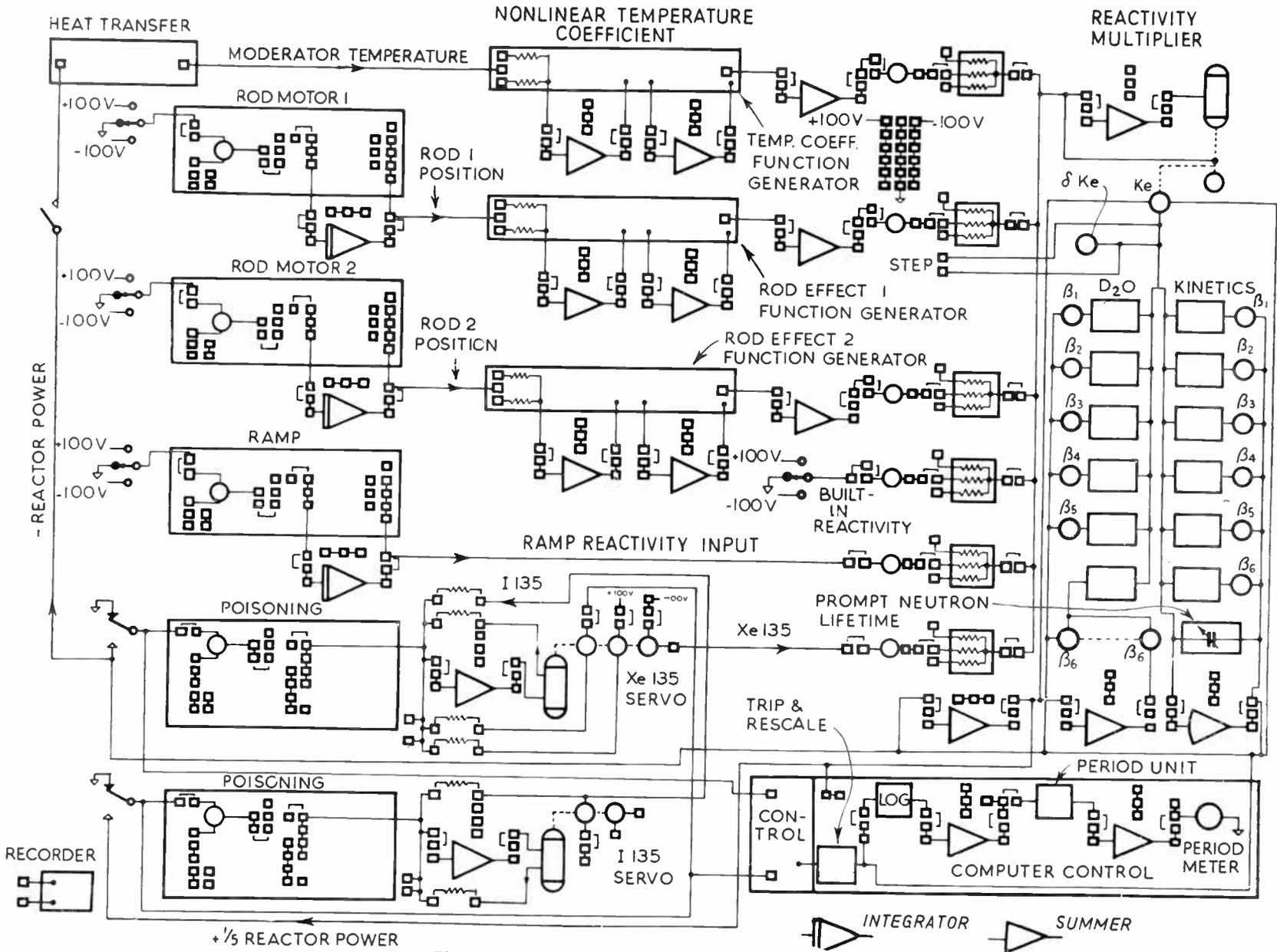


Fig. 1. Programming schematic of reactor computer.

neutron density to reactivity. These, and their constants and the derivation of the analogue equations have often been described in detail.^{3, 4, 5, 7, 12, 13, 14} Of additional interest are response solutions given in Appendix 1 for a particular set of conditions for purposes of checking the accuracy of the device.

The neutron kinetic equations can be programmed on a general purpose analogue computer, with the limitation that reactor power may only be computed over a voltage range of 100 V. The range from source level to full power level of a reactor is seven or more decades.¹⁵ A 100 V computing range can be utilized to cover three decades accurately: 1st decade = 0-1 V, 2nd decade = 1-10 V and 3rd decade = 10-100 V. Computation may be "clamped" at any time and all values read out and the scaling factors changed by a suitable amount. This method, whilst time wasting and subject to errors due to the human element and

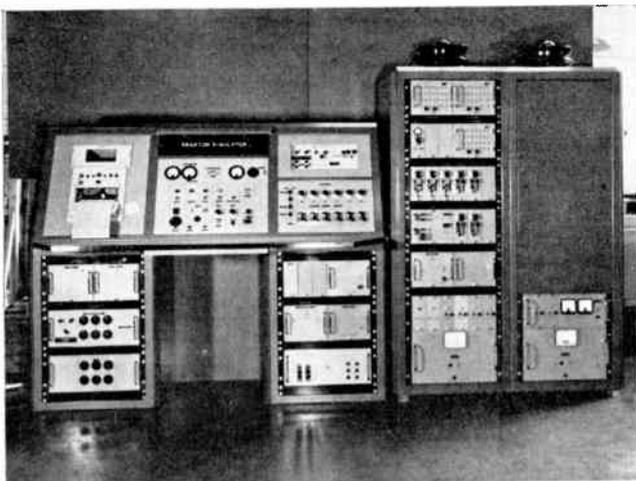


Fig. 2. Reactor analogue computer normally coupled to general-purpose computer (G.F.K.F. Dusseldorf).

zero drift if the rescaling periods are lengthy, has been found adequate by many investigators of reactor control problems. The method is however entirely unsuitable when operator training is under consideration. The representation of both the linear and logarithmic power channel must then be continuous.

This can be overcome by transforming the equations so that they yield log (power) directly. This transformation is given in Appendix 2. A computer range of 100 V can now represent 10 decades: 1st decade = 0-10 V, 2nd decade = 10-20 V, etc. The electronic derivation of the anti-logarithm now only yields accurate results for three decades. The system suffers from errors at small levels since servos or electronic multipliers will not respond to minute inputs.

In addition to the power range problems, the use of general purpose computing apparatus is uneconomic for the solution of the kinetic equations since a considerable amount of functional units have to be allocated to the computation of neutron density. This was clearly apparent when programming two-zone problems on the computer. The reactor assembly (University of Bologna) under consideration, utilized a combined uranium and plutonium core.¹⁶ The programming time for the kinetic section on the general purpose units was some two hours and on the kinetic unit two minutes.

The problem would have been much simplified had a computer with two kinetic sections been available when the programming time would have been four minutes and automatic rescaling possible on both sections. Similar advantage of using multiple kinetic sections may be gained when spatial instabilities of the neutron density which occurs in large power reactors are under consideration. These instabilities are caused by the combined effects of positive temperature coefficient and xenon poisoning. The instabilities can be demonstrated by dividing the reactor core simulation into a number of zones which are independently controlled. It is then possible to control the amplitude and orientation of the first azimuthal harmonic of flux distribution in addition to total power. A three-zone simulation as initially required for the Calder Operations School utilizing kinetic units would save eighteen operational amplifiers.

The first kinetic unit of the type now in use was developed in conjunction with R. F. Mathams, described in his paper at Brussels¹⁷ and in two previous papers by the author.^{18, 19} Most special kinetic computers in use to-day suffer from instabilities and inaccuracies and the improvements stated below to the original design resulted in very stable and reliable performance. Figure 3 shows the new circuit diagram.

(i) Extensive recalculation resulted in an overall reduction of capacitor values, without use of excessively high resistance values.

(ii) The unit was sealed and fitted with desiccators. This eliminated humidity effects on circuits containing high resistances.

(iii) Only relays associated with the level setting and rescaling were left in this unit. This reduced cross-coupling effects between wires.

(iv) The arbitrary level initial condition setting facility was changed from a cathode follower to a normal summing circuit. This resulted in the saving of a thermionic valve and has removed h.t. supplies from the unit.

(v) The wipers of all delayed neutron yield adjustment potentiometers were brought out to the front

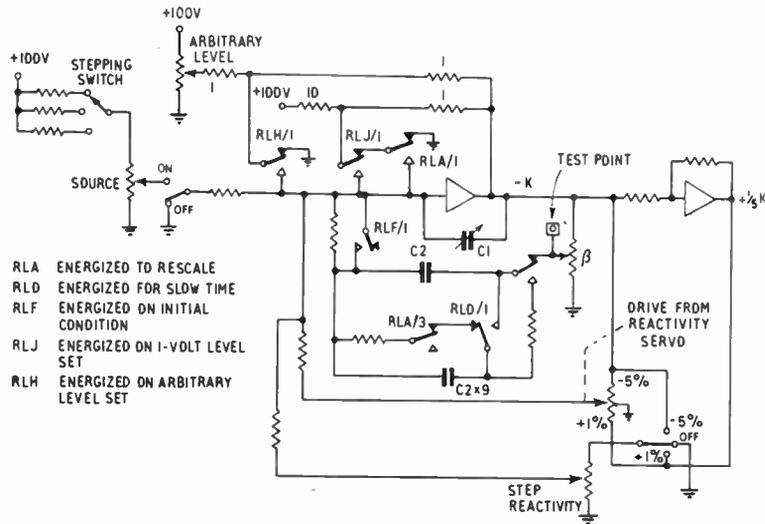


Fig. 3. Kinetic circuit, showing one delayed neutron circuit only.

of the unit in order to facilitate accurate setting with a digital voltmeter or a voltage divider box.

(vi) The setting of the prompt lifetime was carried out on a decade capacitance box. This was replaced by a switching arrangement giving 599 steps, using only eleven capacitors with the switches directly calibrated in seconds.

(vii) It was discovered that amplifiers utilizing a separate cathode follower unit as employed in the model discussed by R. F. Mathams oscillated without modification to the amplifier giving change of the cut-off characteristics. By adopting a design incorporating a power output stage this frequency response limitation was removed; 50 c/s noise was also eliminated by this change.

(viii) The arbitrary level, source and step input reactivity potentiometers were replaced by helical potentiometers in order to give finer resolution.

(ix) The rescaling circuit was changed from a dekatron system to one employing a "stepping" switch with a one plane digital display unit. This has proved simpler, more reliable and more economic. It resulted in an unambiguous display of decade.

(x) All signals disconnected from the summing junction whilst not required are referred to earth in order to eliminate computation errors due to leakage.

On training simulators the continuous representation of the linear channel in conjunction with the range changing switch on the operators console is essential. For the extension of the computer supplied to G.F.K.F. by a realistic MERLIN reactor control desk a unit was developed which provides this facility for the conversion of the rescaling system to a continuous linear representation on the recorder. This is achieved by a scaling amplifier which has the biasing voltages

and/or feedback resistors changed dependent on range switch and decade selector switch positions.

The following additional observations on design of computers for kinetic studies are made. The rescaling time is now of the order of 200 milliseconds during which all computation is clamped. A new system of rescaling is being investigated which will have a rescaling time of 11 milliseconds. This is important when testing control gear on simulated fast power excursions of the reactor. The system described will only rescale with increase in reactor power. This is adequate for most applications since two decades of "power" level are covered. Under "scram" conditions, or when long-term xenon poisoning effects are to be overridden after reduction of power below the two "power" decades rescaling in the downward sense is desirable. The new system referred to above will incorporate this facility and will form the subject for a future paper.

3.2. Photoneutron Unit

In reactors which contain deuterium or beryllium atoms, delayed photoneutrons appear which are caused by gamma radiation. These are of importance in the control of heavy water moderated reactors. It was for this reason necessary to develop a unit as extension to the original kinetic computer which simulates these photoneutron effects. Appendix 3 lists the relevant parameters. The unit employed is similar to the kinetic unit in construction, design and operation.

3.3. Source

It is important that the effect of source is taken into account for start-up problems. This is fed to the kinetic circuit and its effect reduced to $\frac{1}{10}$ th over each

of the first three decades. After this the influence on the neutron multiplication is negligible. The change in effectiveness is governed by the rescaling "stepping" switch. It is possible to switch the source off in order to simulate switching off an electrostatic neutron source.

3.4. Linear and Logarithmic Power Indication

The output from the kinetic unit is fed to the meter indicating reactor power. The sensitivity can be increased by a factor of 10 for measurement of low power levels. The linear output may also be fed to the quick response recorder where it will be displayed as shown in Fig. 4(a). The logarithm of the reactor power is derived by use of the logarithmic unit. This contains essentially a diode shaping network of nine diodes. The unit is fed by the positive and negative linear output in order to obtain the required characteristics over two decades (1V - 10V = decade 1, 10V - 100V = decade 2) (see Fig. 5). An accuracy of 1% of any value in the range of the two decades has been obtained. It was not thought desirable to use the logarithmic device originated by R. F. Mathams since the system employed was complex and dependent upon the use of exceedingly high quality components. By using the logarithmic unit in conjunction with the rescaling system a bias voltage is switched to the input of the logarithmic amplifier so that a continuous logarithmic output over as many decades as is required can be recorded (see Fig. 4(b)).

3.5. Reactor Period

A differentiating circuit follows the logarithmic

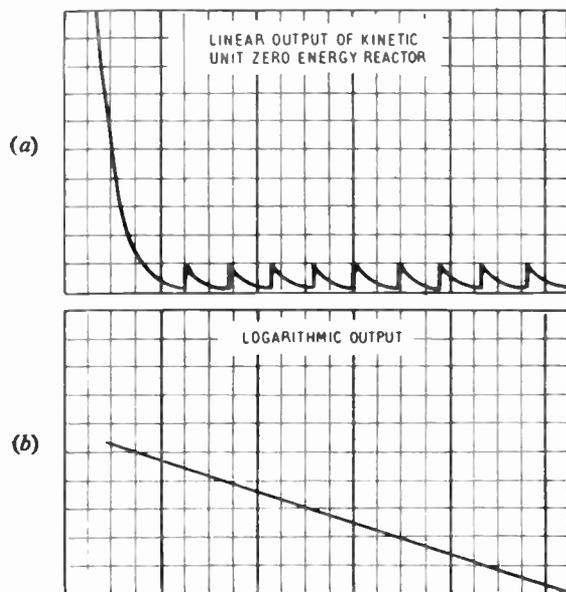


Fig. 4. Results obtained for linear and logarithmic channel on the computer (zero energy).

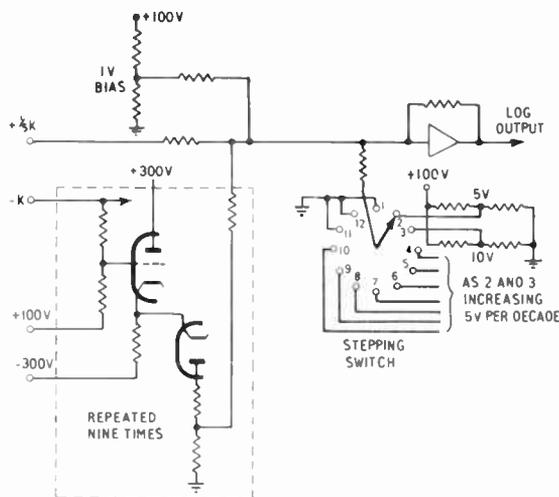


Fig. 5. Simulation of logarithmic channel.

amplifier and its output is proportional to the reciprocal value of the instantaneous period. This is indicated on a voltmeter which is calibrated like a conventional periodmeter. The response had to be limited in order to mask switching discontinuities during rescaling and the output limited to protect the meter.

3.6. Control Rods

Coarse and fine rod control are provided by means of control switches or push buttons on the control desk. For simulation, an electronic integrator and a function generator are assigned to each rod control. The electronic integrator represents the motor control and a full range of motor speeds is available.

Setting of the rod controls is effected as follows. The integrator is set to an initial condition which causes the reactivity servo to show an amount of negative reactivity corresponding to the value (with rods inserted and no other effects on reactivity considered) appropriate to the comparison reactor. The integration rate is then adjusted to give a rate of withdrawal resulting in reaching zero reactivity in the same time as would be achieved on the reactor (with rods withdrawn, and again no other effects considered). The non-linearities of the rod effect on reactivity are set up on the electronic function generator.

The control rod position can be indicated on the control desk and the effect observed on the power meter and recorder. The circuits are therefore especially useful for training purposes and the investigation of automatic servo control systems.

3.7. Heat Transfer

From source level to reaching the operating "power" level, neutron density and warming-up are sufficiently small to justify neglecting these effects. The simulation of the unmodified kinetic equations is therefore sufficiently close over many decades up to a range where considerable power is being produced.

For zero energy reactors a simulation of the warm-up and temperature effects is therefore not considered necessary and a computer consisting of a kinetic unit and associated control equipment is all that is required under all operating conditions in order to investigate the behaviour of the reactor, i.e. the control system of a zero energy reactor can be tested by replacement of the reactor through the kinetic simulator only.

After reaching the operating power level, a number of equations describe the heat transfer between fuel, moderator and coolant.^{20, 21, 22} On the computer the equations representing temperature effects are automatically switched in circuit when operating power is reached and are effective over the last two decades. Partial differential equations are needed to represent accurately the space and time dependence of reactor coolant temperature. In either a gas-cooled or boiling reactor, the equations are too complex for computer solution as they stand. Simplification and at least partial linearization of the equations must be carried out. The linearization results in a set of equations which represents the system dynamics for small perturbations and can be readily solved on an analogue computer. For fast transients or transients which consider boiling of the coolant up to eighty amplifiers may be necessary to achieve the required accuracy.²³ The coolant system of different reactors is laid out differently. Consequently the form of the equations varies with the type of reactor and the problem under consideration. It has therefore been regarded as advantageous to programme all heat transfer equations on general-purpose computer units.

The general purpose computer units used on the computer under discussion include a drift-corrected d.c. amplifier with integral power output stage. Power supply economy is achieved by an output current selection system. The amplifier is provided with a small programming panel. For summing and integration a coefficient and integrator unit are available. The patch panel of these units has been conceived in such a way that rarely more than two patch cords are needed for one unit. Programming is primarily carried out with shorting plugs. Electronic function generators are of the biased diode type, with a transistor oscillator for break point smoothing and a facility for switching each diode into any quadrant.

Servo multipliers are of conventional design and performance.

In the installation at A.E.I. for simulation of MERLIN heat transfer has been carried out around five amplifiers. The heat transfer equations are two differential equations of the first order where constant coefficients have been assumed with the mean uranium and moderator temperature as independent variables. The non-linear temperature coefficient is represented by an electronic function generator. The installation at G.F.K.F. at present uses a general-purpose computer for heat transfer simulation. The machine also uses only the amplifiers of the general-purpose computer, but on MERLIN and DIDO the installation will be expanded to an independent unit for simulation of all effects including temperature and provided with a reactor control desk for operator training. The installation in Norway for the Halden reactor again uses a general-purpose computer for heat transfer simulation in the first phase of the programme. The computer intended for Rome University will utilize a desk-size computer for heat transfer simulation. The installation maintained at our plant as a result of redesign of all units incorporates thirty amplifiers and associated linear and non-linear components for heat transfer problem solution, although it is smaller physically than the A.E.I. installation.

3.8. Poisoning

This is due to xenon (Xe 135) and samarium (Sm 149). These are nuclei amongst the fission products which have a very high capture cross-section for neutrons. For samarium this is two decades smaller than for xenon and in the power range of the reactor, the Xe 135 effects are always much larger. The equations of the poisoning effects have been quoted

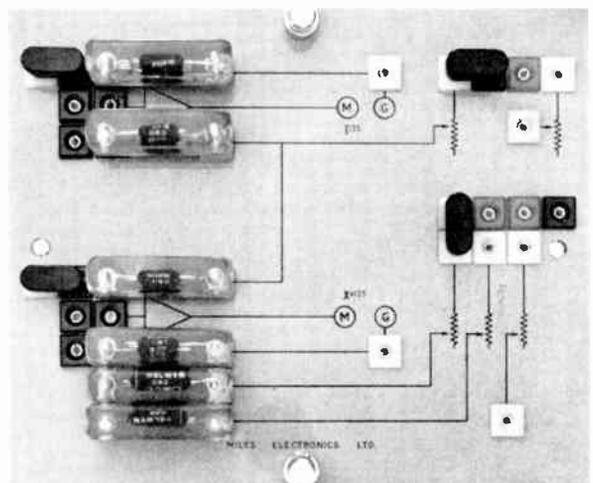


Fig. 6. Poisoning patch panel.

in the literature on reactor computation.²⁴ Neglecting Σ_m 149, there are two differential equations which contain time-constants of many hours (20–40). Two things in those equations are of importance to reactor control. The first effect is levelling-off of the poisoning which happens during operation, and the second peak poisoning which occurs after shut down. Poisoning equilibrium is reached after approximately 40 hours. Real-time simulation is of importance in training applications and when testing control components. Real time simulation is difficult with electronic integrators since errors which increase with time are caused by grid current and leakage resistance of the capacitor.²⁵ Servo integrators are therefore employed for real-time solution of the poisoning equations. Computation may be carried out simultaneously with other effects over many hours since all amplifiers are drift corrected and long term drift is of the order of 100 microvolts. Speeding-up of time scale may be effected by gear change by a factor of 3:600 or altered to any suitable time scale by change of the generator feedback on the associated patch panel (see Fig. 6). Change of the plug-in components on the patch panel enables utilization of the integrators for other long term integrating problems or use as servo multipliers.

Provided no poisoning has been left in the reactor, poisoning is so small during start-up that its effect up to reaching of the power level can be neglected. The integrators are switched in automatically when reaching this level.

3.9. Applied External Reactivities

A servo multiplier is used to sum all reactivity effects and by multiplication with power provides the input to the kinetic circuit. Reactivity step inputs are fed directly to the kinetic circuit, by-passing the servo system because of its inherently poor frequency response. Ramp function inputs, built-in reactivity and changes of reactivity due to temperature, poisoning and control rods are fed to the multiplier.

3.10. External Loop for Power Station Simulation

For investigations of the dynamic behaviour of power reactors the external feedback loop must be represented. This includes the heat exchangers, the steam system and the turbines.

The transport of the coolant through the primary loop pipes which connect the reactor to the heat exchanger gives rise to time delays which must be simulated. The voltage which represents reactor temperature is delayed and fed as input voltage, i.e. input temperature to the heat exchanger. This delay effect can be simulated by electronic methods (with time limitations) with magnetic tape or with electro-mechanical methods employing a commutator switch with capacitors.²⁶

With the coupling of the external feedback loop equations to the reactor computer the installation is transformed into a complete power plant computer. This can be utilized for the study of the self stabilizing characteristics,²⁷ the stability, the response of the plant to load variations, and all disturbances which can be attributed to operational or plant malfunctions, e.g. erroneous closing of valves, coolant or steam loss, pump failure²⁸ and accidental control rod movement. In addition, the control system may be simulated. Sometimes the computer is used as substitute for the plant for testing and optimizing control equipment.

All the equations representing the external loop can be programmed on the general-purpose computing units referred to in Section 3.7. In its simplest form, the basic power plant simulator requires fifty amplifiers and with a more sophisticated installation over 150. Forty amplifiers can be assigned to the heat exchanger alone. The operator training simulator for the Calder Operations School requires 185 amplifiers when simulating the three-zone kinetics by a two-amplifier system as described in Section 3.1.

4. Conclusions

The units described are equally suited for computing and operator training applications. They are therefore finding increasing use in reactor operational and training establishments. It is anticipated that the size and complexity of these installations will increase as simulators will be required for larger and more complex reactor systems. Simulators for nuclear powered vessels for example constitute an interesting proposition for a design study.

5. Acknowledgments

The Author would like to acknowledge the assistance given by Messrs. R. S. Chilton and T. M. Kierans in the development of the computer and the preparation of this paper. He also wishes to thank the Directors of Miles Electronics Limited for their permission to publish this paper.

6. References and Bibliography

1. I. Wilson and R. Potter, "Analogue computers and their use in nuclear reactor safety studies", *J. Brit. I.R.E.*, **18**, p. 95, February 1958.
2. "Introduction to analog computers", *Nucleonics*, **5**, p. 70, 1957.
3. G. Kourim, "Aufbau von Analogrechnern und ihre Verwendung in der Reaktortechnik", *Kerntechnik*, **1 & 2**, 1959.
4. G. Kourim, "Analogrechner in der Reaktortechnik", *Die Atomwirtschaft*, **10**, p. 327, 1957.
5. E. H. Baer, "Aufbau und Verwendung von Reaktorsimulatoren", *Die Atomwirtschaft*, **7**, p. 263, 1958.
6. S. O. Johnson and T. N. Grace, "Analog computation in nuclear engineering", *Nucleonics*, **5**, p. 72, May 1957.

7. I. Wilson and L. A. J. Lawrence, "A nuclear power plant training simulator for use at Calder Hall", *J. Brit. I.R.E.*, **18**, p. 85, February 1958.
8. R. G. Davies, "How to use the Reactor Simulator". A.E.R.E., R.S./L30 (1957).
9. "Special simulator will train Berkeley staff", *Atomic World*, **1**, p. 25, 1959.
10. W. A. Havranek, "Specification for Training Simulator for Nuclear Power Station Operators", Miles Electronics Specification MERS/N/3/1.
11. J. P. Franz and W. H. Alliston, "P.W.R. training simulator", *Nucleonics*, **5**, p. 8, 1957.
12. W. Pagels, "A portable electronic pile kinetic simulator", *Trans. Amer. Inst. Elect. Engrs*, **70**, p. 1422, 1951.
13. J. C. Moise, "Reactor System Dynamic Simulation", 8-5, p. 89, "Nuclear Engineering Handbook", (Ed.) H. Etherington (McGraw-Hill, New York, 1958).
14. M. A. Schultz, "Control of Nuclear Reactors and Power Plants", p. 289 (McGraw-Hill, New York, 1955).
15. T. P. Franz and N. F. Simci, "Nuclear reactor start-up simulation", *Trans. Inst. Radio Engrs (Nuclear Science)*, **NS-4**, p. 11, 1957.
16. P. Aiello and E. Sarti, "Simulatore Elettronico di un reattore nucleare a due regioni", Electronic Congress, VI Rassegna Internazionale Elettronica e Nucleare, Rome, 1959.
17. R. F. Mathams, "The Lance Reactor Analogue Computer", Seminar of International Society for Analogue Computation, Brussels, April, 1960.
18. W. A. Havranek, "Anwendung von Simulatoren in der Reaktortechnik", *Kerntechnik*, **10**, 1960.
19. W. A. Havranek, "Applicazione dei Calcolatori Analogici e dei Simulatori nell'Ingegneria dei Reattori Nucleari", Electronic Congress, VII Rassegna Internazionale Elettronica e Nucleare, Rome, 1960.
20. W. R. Campbell and E. G. Good, "Effect of Temperature Co-efficient on Reactor Start-up Kinetics", WAPD-T-338, 1956.
21. W. H. Hamilton, T. N. Grace, O. R. Meyer and N. E. Wilson, "Power and temperature control of pressurized water cooled reactors", *Electrical Engineering*, **75**, p. 505, June 1956.
22. E. F. Borner and B. F. Cassidi, "Analog study of boiler-reactor interaction", *Nucleonics*, **5**, p. 84, May 1957.
23. S. O. Johnson, N. J. Curlee and D. V. Reilung, "Simulation of hot channel boiling in water-cooled reactors", *Trans. Inst. Radio Engrs (Nuclear Science)*, **NS-4**, 1957.
24. M. A. Schultz, "The Control System", 8-2, p. 27, "Nuclear Engineering Handbook", (McGraw-Hill, New York, 1958).
25. G. A. Korn and T. M. Korn, "Electronic Analog Computers", pp. 170-184, 2nd Edition (McGraw Hill, New York).
26. A. D. Wright, "Commutator switch simulates transport lag", *Control*, **8**, p. 111, 1959.
27. T. N. Grace, "Synthesis of control systems for nuclear power plants", *I.R.E. Convention Record*, Part 9, p. 83, 1954.
28. H. Albers and B. Walter, "Simulation of the dynamic behaviour of the Swiss D₂O Reactor Diorit". 2nd United Nations International Conference on the Peaceful Uses of Atomic Energy, A/Conf. 15/P/231.

7. Appendix 1: Solution of Kinetic Equations

Response for positive δK steps

The standard reactor kinetic equations are:

$$\frac{dn}{dt} = \left(\frac{\delta k - \beta}{l^*} \right) n + \sum_{i=1}^6 \lambda_i C_i + S \quad \dots\dots(1)$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{l^*} n - \lambda_i C_i \quad \dots\dots(2)$$

Using Laplace Transformation and solving for $\frac{n(t)}{n(0)}$

From eqn. (1)

$$pn_{(p)} - n_0 = \frac{\delta k - \beta}{l^*} n_{(p)} + \sum_{i=1}^6 \lambda_i C_{i(p)}$$

S switched out of circuit and therefore not considered.

Note: Driving function is δK .

Therefore

$$\left(p - \frac{\delta k - \beta}{l^*} \right) n_{(p)} = \sum_{i=1}^6 \lambda_i C_{i(p)} + n_{(0)} \quad \dots\dots(3)$$

From (2)

$$pC_{i(p)} - C_{i(0)} = \frac{\beta_i}{l^*} n_{(p)} - \lambda_i C_{i(p)}$$

$$(p + \lambda_i)C_{i(p)} = \frac{\beta_i}{l^*} n_{(p)} + C_{i(0)}$$

In steady state, or when $t = 0$,

$$C_{i(0)} = \frac{\beta_i}{l^* \lambda_i} n_{(0)}$$

Therefore

$$(p + \lambda_i)C_{i(p)} = \frac{\beta_i}{l^*} n_{(p)} + \frac{\beta_i}{l^* \lambda_i} n_{(0)}$$

$$C_{i(p)} = \frac{1}{p + \lambda_i} \left\{ \frac{\beta_i}{l^*} n_{(p)} + \frac{\beta_i}{l^* \lambda_i} n_{(0)} \right\} \quad \dots\dots(4)$$

Substituting for $C_{i(p)}$ from (4) into (3)

$$\begin{aligned} & \left\{ p - \frac{\delta k - \beta}{l^*} \right\} n_{(p)} \\ &= \sum_{i=1}^6 \lambda_i \frac{1}{p + \lambda_i} \left\{ \frac{\beta_i}{l^*} n_{(p)} + \frac{\beta_i}{l^* \lambda_i} n_{(0)} \right\} + n_{(0)} \\ n_{(p)} & \left\{ p - \frac{\delta k - \beta}{l^*} - \sum_{i=1}^6 \frac{\lambda_i \beta_i}{p + \lambda_i l^*} \right\} \\ &= n_{(0)} \left\{ H \sum_{i=1}^6 \frac{1}{p + \lambda_i} \frac{\beta_i}{l^*} \right\} \end{aligned}$$

Therefore

$$\frac{n_{(p)}}{n_{(0)}} = \frac{1 + \sum_{i=1}^6 \frac{\beta_i}{l^*(p + \lambda_i)}}{p - \frac{\delta k - \beta}{l^*} - \sum_{i=1}^6 \frac{\lambda_i \beta_i}{p + \lambda_i l^*}}$$

Now

$$\sum_{i=1}^6 \frac{\beta_i \lambda_i}{l^* p + \lambda_i} = \frac{\beta_i}{l^*} - \sum_{i=1}^6 \frac{\beta_i p}{l^* p + \lambda_i}$$

Therefore

$$\frac{n_{(p)}}{n_{(0)}} = \frac{1 + \sum_{i=1}^6 \frac{\beta_i}{l^*(p + \lambda_i)}}{p - \frac{\delta k}{l^*} + \sum_{i=1}^6 \frac{\beta_i p}{l^* p + \lambda_i}}$$

Multiplying through by l^*

$$\frac{n_{(t)(p)}}{n_{(0)}} \frac{l^* + \sum_{i=1}^6 \frac{\beta_i}{p + \lambda_i}}{pl^* - \delta k + \sum_{i=1}^6 \beta_i \frac{p}{p + \lambda_i}} = \frac{M_{(p)}}{N_{(p)}}$$

Roots are given by $N_{(p)} = 0$.

Coefficients are given by:

$$\begin{aligned} \frac{M_{(p)}}{N_{(p)}} &= A = 0 \quad (\delta k \text{ constant}) \\ N_{(p)} &= l^* + \sum_{i=1}^6 \frac{\beta_i}{p + \lambda_i} - p \sum_{i=1}^6 \frac{\beta_i}{(p + \lambda_i)^2} \\ &= M_{(p)} - p \sum_{i=1}^6 \frac{\beta_i}{(p + \lambda_i)^2} \\ A &= \frac{M_{(p)}}{M_{(p)} - p \sum_{i=1}^6 \frac{\beta_i}{(p + \lambda_i)^2}} \\ \frac{1}{A} &= 1 - \frac{p \sum_{i=1}^6 \frac{\beta_i}{(p + \lambda_i)^2}}{l^* + \sum_{i=1}^6 \frac{\beta_i}{p + \lambda_i}} \end{aligned}$$

Also, from $N_{(p)}$

$$\delta k = p \left(l^* + \sum_{i=1}^6 \frac{\beta_i}{p + \lambda_i} \right)$$

$$\text{Reactor doubling time} = \frac{0.693}{p}$$

$$l^* = 6.5 \times 10^{-5}$$

Results: Since doubling times less than 5 seconds are not very often considered, only the first five poles will be taken into account.

Table 1

P (Positive poles)	δk	A	Doubling time (seconds)
2.04×10^{-2}	1.062×10^{-3}	1.485	33.97
4.5×10^{-2}	1.725×10^{-3}	1.82	15.4
7.0×10^{-2}	2.155×10^{-3}	2.068	9.9
1.2×10^{-1}	2.768×10^{-3}	2.4	5.775
1.75×10^{-1}	3.213×10^{-3}	2.719	3.96

Table 2

Response $A \exp pt$

t (seconds)	1	2	3	4	5	7.5	10	15	20	30	
0.1062	1.5	1.516	1.547	1.579	1.612	1.65	1.729	1.821	2.017	2.233	2.739
0.1725	1.861	1.904	1.991	2.083	2.179	2.279	2.551	2.854	3.574	4.476	7.02
0.2155	2.143	2.218	2.379	2.552	2.736	2.935	3.496	4.164	5.91	8.387	16.86
0.2768	2.549	2.706	3.051	3.44	3.878	4.373	5.903	7.969	14.52	26.45	87.83
0.3213	2.967	3.239	3.859	4.596	5.475	6.522	10.1	15.65	37.53	90.04	468.8

The values given in Tables 1 and 2 may be plotted for comparison with actual results.

Table 3

For checking the Kinetic Unit.

% δk	1st decade		2nd decade	
	Time to 10 in seconds	Time to 100 in seconds	Time for 2nd decade in seconds	
0.1062	93.48	206.35	112.87	
0.1725	37.6	89.03	51.43	
0.2155	22.51	55.4	32.89	
0.2768	11.9	31.08	19.18	
0.3213	7.44	20.6	13.16	

8. Appendix 2: Logarithmic Transformation of Reactor Kinetic Equations for Solution on General-purpose Computer

The equations in their standard form are:

$$\frac{dn}{dt} = \frac{\delta k - \beta}{l^*} n + \sum_{i=1}^6 \lambda_i C_i + S \quad \dots\dots(5)$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{l^*} n - \lambda_i C_i \quad \dots\dots(6)$$

Dividing eqn. (5) by n

$$\frac{d(\log n)}{dt} = \frac{\delta k - \beta}{l^*} + \sum_{i=1}^6 \lambda_i \frac{C_i}{n} + \frac{S}{n} \quad \dots\dots(7)$$

and eqn. (6) may be written as

$$\frac{d_r(C_i/n)}{dt} + \left(\frac{C_i}{n}\right) \frac{d(\log n)}{dt} = \frac{\beta_i}{l^*} - \frac{\lambda_i C_i}{n} \quad \dots\dots(8)$$

Both these equations can be programmed on general-purpose computers more easily than eqns. (5) and (6) and provide equal logarithmic accuracy over many decades.

By introducing a new variable

$$Y_i = \frac{C_i}{n} ,$$

eqns. (7) and (8) may be written as

$$\frac{d(\log n)}{dt} - \frac{\delta k - \beta}{l^*} - \sum_{i=1}^6 \lambda_i Y_i - \frac{S}{n} = 0 \quad \dots\dots(9)$$

and

$$\frac{dY_i}{dt} + Y_i \left[\lambda_i + \frac{d(\log n)}{dt} \right] - \frac{\beta_i}{l^*} = 0 \quad \dots\dots(10)$$

9. Appendix 3: Delayed Photoneutrons in a D₂O-U 235 Reactor

Table 4

Group	Half lifetime $T_{1/2}$ (seconds)	Decay constant λ_i (seconds ⁻¹)	Fraction of the total numbers of neutrons β_i
1	2.5	2.77×10^{-1}	78×10^{-6}
2	41	1.69×10^{-2}	24×10^{-6}
3	144	4.81×10^{-3}	8.4×10^{-6}
4	462	1.5×10^{-3}	4.0×10^{-6}
5	1620	4.27×10^{-4}	2.5×10^{-6}
6	5940	1.167×10^{-4}	2.8×10^{-6}

There are further groups where the half lifetime is so long and the yield so small that they can be neglected in the simulator.

Manuscript first received by the Institution on 6th May 1960 and in final form on 31st August 1960 (Paper No. 617).

1961 Convention News

“RADIO TECHNIQUES AND SPACE RESEARCH”—OXFORD, 5th-9th JULY

Registration Forms

A registration form for the 1961 Convention is enclosed with this *Journal*. Further forms may be obtained on application to the Institution at 9 Bedford Square, London, W.C.1.

Members intending to take part in the Convention are urged to make their registration as early as possible. Preference in accommodation will be allocated in strict order of receipt of registration forms.

Accommodation at Christ Church

Although, as stated in the January *Journal*, accommodation in Christ Church has been increased since the Institution's last visit in 1954, the college authorities have had to limit residents to 200. For this reason therefore early application is advised. Limited accommodation may also be available in other colleges.

The Institution is unable to make hotel reservations on behalf of delegates; a list of hotels in the Oxford area may however be obtained on request from the Institution.

Preprints

Preprints and digests of all papers selected for presentation will be sent to delegates who have registered *before* 21st June. The registration form enclosed describes procedure for delegates whose registrations are received after this date.

Preprints *will not* be available for other than delegates until after the Convention. Details regarding the purchase of sets or individual copies of the papers will be made in the *Journal* in due course. All papers presented at the Convention will be finally published in *J.Brit.I.R.E.* It is not intended to publish Convention papers as separate proceedings.

Convention Badges

Distinctive badges which will permit entry to the lecture theatres and demonstration rooms and to other functions associated with the Convention will be issued to all delegates who are attending the *whole* Convention. Admission tickets will be provided for other delegates appropriate to the sessions for which they have registered.

Social Functions at the Convention

The main social function during the Convention will be the Banquet in Christ Church Hall on the Friday evening. The Banquet will be presided over by Admiral of the Fleet the Earl Mountbatten

of Burma, K.G. Members will be particularly pleased to learn that Sir Cyril Hinshelwood, Past President of the Royal Society and Professor of Chemistry in the University of Oxford, has already accepted an invitation to be present.

Attendance at the Banquet will be restricted to a total of 300. Delegates resident in Colleges will automatically receive tickets and the balance will be distributed in strict order of application. Tickets will cost £3 5s. and will cover cocktails, dinner and wine.

Other social functions will be announced by the Convention Committee in due course. Delegates will, for example, have an opportunity of attending an evening performance by the Hallé Orchestra in Oxford. Visits to research and other establishments of interest to members are also being planned.

Convention Handbook

The 1961 Convention handbook giving the complete programme of technical sessions, discussion meetings, residential and social arrangements etc. will be available in June. A copy will be posted to all delegates.

The Convention Committee believe that there are several aspects of the Convention theme which lend themselves to informal discussion, particularly where the best means of realizing a practical goal is not yet resolved. Special discussion sessions are therefore being included in the programme. There will of course be ample time allocated for discussion on the formal papers. Details of the programme including synopses of the papers will be published in subsequent issues of the *Journal*.

Display features arranged in Christ Church will include films, equipment and components.

The Handbook will also show that the Clerk Maxwell Memorial Lecture, a traditional feature of Brit.I.R.E. Conventions, will be given on Thursday evening, 6th July.

Session Arrangements

The Chairmen appointed for the various Sessions and the provisional order of arrangements are as follows:

Session 1. *Wednesday afternoon, 5th July*

Introductory Session.

“Radio Techniques in Space Research.”

Chairman: The President of the Institution.

(continued overleaf)

Sessions 2 and 3.

Thursday morning and afternoon, 6th July

“Satellite Engineering.”

Chairman: L. H. Bedford, C.B.E., M.A., F.C.G.I.
(Past President).

Thursday evening, 6th July

The Fifth Clerk Maxwell Memorial Lecture.

Session 4. Friday morning, 7th July

“Extra-terrestrial Measurements.”

Chairman: I. Maddock, O.B.E., B.Sc. (Member)
(Chairman of the Convention Committee).

Session 5. Friday afternoon, 7th July

“Techniques in Radio Astronomy.”

Chairman: G. W. A. Dummer, M.B.E. (Member).

Friday evening, 7th July
Convention Banquet.

Sessions 6 and 7.

Saturday morning and afternoon, 8th July

“Communication Satellites.”

Chairman: Denis Taylor, PH.D., M.Sc. (Member).

Saturday evening, 8th July

Alternative arrangements will include an organ recital, film displays, discussion groups, etc.

Papers already approved for presentation

The Convention Committee has already approved a number of papers and the first list is given below. Synopses will be published in the April and subsequent Journals, as well as in the Convention Handbook.

- “The Use of Probing Electrodes in the Study of the Ionosphere.” Dr. R. L. F. Boyd (*University College London*).
- “Critical Engineering Factors in the Design and Development of Space Systems.”
James M. Bridges (*U.S. Department of Defense*).
- “Radio Tracking of Satellites.” Dr. B. G. Pressey (*Radio Research Station*).
- “The Reliability of Components in Satellites.” G. W. A. Dummer, M.B.E. (*Royal Radar Establishment*).
- “Techniques of Microminiaturization.” D. H. Roberts and D. S. Campbell (*Plessey*).
- “Power Supplies for Space Vehicles.” K. E. V. Willis (*National Research Development Corporation*).
- “Some Thermal Considerations on the use of Silicon Solar Cells in Earth Satellites.”
R. P. Howson, D. H. Roberts and B. L. H. Wilson (*Plessey*).
- “A Review of the Methods and Problems Involved in Launching Satellites.”
C. R. Hume, M.B.E., and R. A. Shute (*De Havilland Aircraft*).
- “Engineering Aspects of Satellites and their Launching Rockets.”
G. K. C. Pardoe (*De Havilland Aircraft Company*).
- “Cosmic Ray Measurements in the Scout Satellite.”
Professor H. Elliott (*Imperial College*) and D. W. Mayne (*McMichael Radio*).
- “X-Ray Measurements in the Upper Atmosphere.” K. Pound (*University of Leicester*).
- “X-Ray Spectrometer for Scout Satellite.” J. Ackroyd, R. I. Evans and P. Walker (*Bristol Aircraft*).
- “Some Observations of Synchronous Doppler Frequency Shift Measurements obtained at Spaced Receivers during a Transit of Russian Satellite 1958 δ (*Sputnik III*).”
F. A. Kitchen, R. N. Gould and W. R. Carter (*Admiralty Surface Weapons Establishment*).
- “Radio Astronomy from Satellites.” Dr. F. Graham Smith (*University of Cambridge*).
- “A Satellite Technique for performing a High Resolution Survey of the Radio Sky at Medium Wavelengths.”
Dr. R. Jennison (*Jodrell Bank Experimental Station*).
- “Meteor and Auroral Observations.” Dr. J. S. Hey (*Royal Radar Establishment*).
- “Ultra-violet Astronomy from Rockets and Satellites.” Dr. D. W. O. Heddle (*University College London*).
- “Overall System Requirements for Low Noise Performance.” C. R. Ditchfield (*Royal Radar Establishment*).
- “Some Types of Low Noise Amplifiers.” R. Hearn, R. J. Bennett and B. A. Wind (*Plessey*).
- “A Proposal for an Active Communication Satellite System Based on Inclined Elliptic Orbits.”
B. Buss and J. R. Millburn (*Hawker Siddeley Aviation*).
- “The Advantages of Attitude Stabilization and Station Keeping in Communications Satellite Orbits.”
Dr. W. F. Hilton (*Hawker Siddeley Aviation*).
- “Television Communications using Earth Satellite Vehicles.” L. F. Matthews (*Associated Television*).

The Synthesis of High-purity Oscillations Suitable for Single-sideband Receivers

By

P. S. CARNT, B.Sc.(Eng.)†

AND

E. RIBCHESTER, B.Sc.†

Presented at a Symposium on Stable Frequency Generation held in London on 25th May 1960.

Summary : An oscillator is controlled by a phase locked loop, its output frequency being mixed with a selected part of a 100 kc/s spectrum to form an i.f. in the 900–1000 kc/s region. This i.f. feeds one side of a phase detector, the other side being fed by an interpolating signal. The latter may be derived either by another similar stage operating at a lower frequency, or by any other suitable method, the required purity in this signal being only of the order of 40 dB. The a.p.c. loop will lock when the i.f. and the interpolating frequency are the same. In the locked condition an additional filter is switched into the loop by means of a quadrature phase detector, and this filter reduces the amplitude of spurious frequencies and noise in the output. The paper discusses factors affecting the resultant purity.

1. Introduction

This paper describes a synthesizer intended primarily for use with single-sideband receivers for which a high degree of purity is required, that is, greater than 80 dB. Only the part of the synthesizer concerned with the final purity has been considered in detail, and several alternative arrangements for the rest of the synthesizer are possible. These alternatives provide varying degrees of frequency accuracy, although all the alternatives can give the high purity of output which is characteristic of the part described herein. The particular output frequencies required were 1 kc/s points between 3 and 30 Mc/s with an accuracy equal to that of the 100 kc/s standard, and 100 c/s points in the same range with an accuracy of ± 5 c/s. It will be seen that the synthesizer provides an output whose frequency bears a locked relationship to an appropriate harmonic of a 100 kc/s standard and an interpolating signal which covers the range 900–1000 kc/s. The interpolating signal may also be derived from the 100 kc/s standard or if a less accurately known output frequency can be tolerated then another source covering the 900–1000 kc/s range may be used. This paper is only concerned with the means of providing the lock to the appropriate harmonic of the 100 kc/s standard.

In order to achieve the required purity, the phase-locked loop principle has been employed rather than conventional passive filter techniques, and the fact that it is possible to set the frequency of a free running

oscillator to within certain defined limits—for example, within ± 40 kc/s over the 3–30 Mc/s band—leads to considerable circuit economy. Figure 1 shows a block diagram of the synthesizer. The input frequencies required are a standard 100 kc/s source, and an interpolation signal which can be set as required anywhere in the range 900 to 1000 kc/s.

The purity of this interpolation signal need not exceed about 40 dB provided there are no spurious signals closer than about 1 kc/s to the required interpolation frequency.

2. General Description

The general principles of the synthesizer will be described first. From the 100 kc/s standard a 100 kc/s spectrum is produced which extends up to at least 30 Mc/s, and this spectrum is applied to a tuneable filter which selects some 10 or so 100 kc/s points of which only one is actually required. This spectrum filter is, in fact, an image frequency rejector. The filter output is then applied to a conventional mixer.

The required output is taken from an oscillator which is nominally free-running and whose frequency can be set to an accuracy of ± 40 kc/s over the band. Its output is applied via a buffer to the mixer, the purpose of the buffer being to prevent the spurious signals and spectrum components at the mixer from contaminating the oscillator output.

At the mixer a wanted i.f. in the band 900–1000 kc/s is produced and this can be the result of mixing the oscillator output with the relevant spectrum component either above or below the oscillator frequency.

† The General Electric Co. Ltd., Telecommunications and Engineering Laboratories, Hirst Research Centre, Wembley, England.

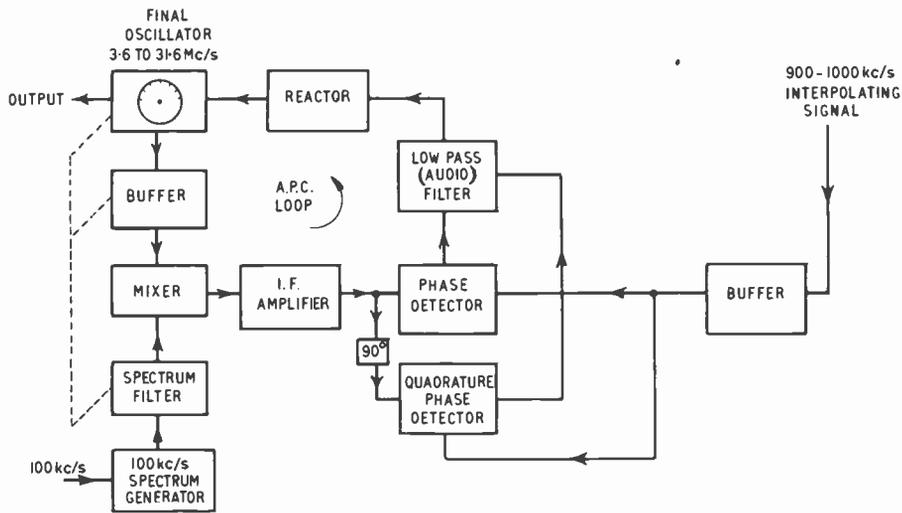


Fig. 1. Block diagram of synthesizer.

Since the spectrum components decrease in amplitude with increasing frequency, it is preferable to use the lower frequency spectrum component. For example, if the required frequency is 30.05 Mc/s, the relevant spectrum component would be 29.1 Mc/s for a 950 kc/s i.f. The alternative spectrum component would, of course, be 31 Mc/s.

In addition to the wanted i.f., the mixer output also contains components separated from it by 100 kc/s intervals. All components within the band 850 to 1050 kc/s are amplified in the i.f. amplifier, which has a bandwidth of at least 200 kc/s. Hence the i.f. amplifier accepts the wanted i.f. together with at least one spurious signal 100 kc/s away. The relatively large i.f. bandwidth is necessary for a reason which will be described later.

The i.f. amplifier output is applied to one side of a phase detector whose other side is fed with the interpolation signal—in the example quoted, this interpolation signal would be at 950 kc/s. The phase detector output therefore has frequency components corresponding to the beats between the 950 kc/s interpolation signal and all the i.f. components passed by the i.f. amplifier. Assuming for the moment that the spectrum filter has completely rejected the image frequency, the zero frequency phase-detector output corresponds to the wanted signal, and all spurious signals are spaced 100 kc/s from this. The low-pass filter removes the spurious signals and allows the zero frequency component to lock the oscillator to the required frequency by way of the reactance valve. Hence the oscillator frequency is locked to the appropriate spectrum component offset by the interpolation signal frequency which corresponds to the wanted i.f. It will be appreciated that the oscillator will lock to

that frequency which gives the lowest beat frequency between an i.f. and the interpolating frequency, so that the setting accuracy of the oscillator must be better than ± 50 kc/s otherwise the adjacent 100 kc/s harmonic could cause lock.

While it would appear that a low-pass cut-off frequency of just less than 50 kc/s would be satisfactory, there is a good reason for making the pass-band very much less than this. The smaller the pass-band of the low-pass filter, the better the purity for a given image rejection—it must be remembered that any a.c. signal appearing at the reactance valve grid, when the loop is locked, will produce spurious signals in the oscillator output. However, a narrow-band low-pass filter would normally lead to very long pull-in times, hence the two-mode loop or quadri-correlator which has been borrowed from N.T.S.C. colour television receivers.

The addition of a second phase detector operating in quadrature to the loop detector enables a d.c. voltage to be derived which is present only when the loop has locked. Therefore the low-pass filter can be given a relatively wide pass-band to enable the loop to lock quickly, and the d.c. voltage produced by the quadrature detector can then be made to change the components of the low-pass filter (by means of a relay, in this case), to give an extremely narrow pass-band. Theoretically, the pass-band can be reduced indefinitely by this technique but in practice microphony sets a lower limit.

3. Operation of the Synthesizer

To operate the synthesizer, the interpolation frequency and the oscillator dial are set as required, and a switch is then pressed which earths the grid of the

reactance valve. This is necessary in order to destroy any memory in the low-pass filter circuit, and to prevent spurious locking as the various settings are adjusted. Next, this switch is released, and the loop locks. Automatically the quadrature detector output alters the low-pass filter characteristics, and lights a lamp to indicate that lock has occurred. If a centre zero d.c. voltmeter is connected to the reactance valve grid, the operator can trim the oscillator frequency dial (which, of course, will not now change the frequency) until the reactance valve correction voltage is zero. This adjustment ensures that the free running and locked frequencies are the same, so that unlock caused by microphony, for example, is not so likely.

4. Purity Considerations

In Fig. 2, the wanted and image i.f. responses are shown on the 100 kc/s spectrum, with the spectrum filter attenuating the image. Now if the oscillator frequency is set to an exact 50 kc/s point, both i.f.s are equal and the image does not therefore interfere. But suppose the oscillator is set to a 48 kc/s point, then the image i.f. will correspond to a 52 kc/s point, that is, the wanted and unwanted i.f.s will differ by only 4 kc/s. Both will be accepted by the i.f.

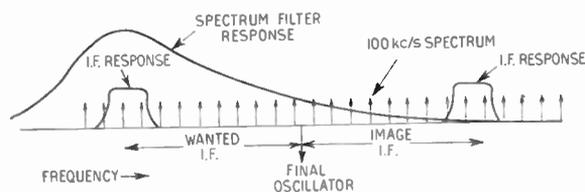


Fig. 2. Diagram to show rejection of image.

amplifier, and at the phase detector output the image i.f. will produce a 4 kc/s signal. However, if the low-pass filter is sufficiently narrow, this will be able to reject the spurious 4 kc/s. Of course, even higher purity can be achieved by increasing the image rejection of the spectrum filter.

5. Description of the Synthesizer Circuit

The various parts of the synthesizer will now be considered in greater detail.

5.1. Spectrum Generator and Filter

The spectrum generator uses a blocking oscillator to produce 100 kc/s pulses having a width of about 20 μ s. The amplitude of the harmonics is in the region 1–10 mV at 30 Mc/s and care must be taken not to use too large a pulse amplitude, otherwise 9th and 10th harmonics of the repetition rate can produce an i.f. directly.

The spectrum filter is a tuned anode, tuned grid stage with ganged capacitors, the tuned circuits having

Q s of about 70. This gives an image rejection of about 40 dB at 30 Mc/s.

5.2. Mixer and Buffer Amplifier

The hexode part of an X78 is used as the mixer, the spectrum being applied to the first control grid and the oscillator to the second control grid. This technique provides some isolation between oscillator output and spectrum, but further isolation is provided by the tuned buffer. This buffer can have appreciable gain so that an attenuated (and therefore better isolated) oscillator output can be used.

5.3. I.F. Amplifier

The i.f. amplifier provides an output of about 20 V peak at the phase detector from an i.f. of about 100 μ V from the mixer. Delayed a.g.c. is applied to cater for variation in amplitude of harmonics in the spectrum. The 6 dB bandwidth is approximately 200 kc/s about the centre frequency of 950 kc/s. This wide bandwidth is required so that if the interpolation frequency happens to be near 900 or 1000 kc/s there is sufficient bandwidth to accommodate the frequency deviation of the oscillator corresponding to the beatnote produced during pull-in.

5.4. Oscillator and Reactance Valve

The oscillator and reactance valve must obviously be designed to meet the dial setting and stability requirement of ± 40 kc/s or better. It would seem that this is possible, and in an experimental set-up which was used to confirm the feasibility of this type of synthesizer, a modification was carried out on a signal generator so that the triode internal modulation oscillator was converted into a reactance valve. The sensitivity of the reactance valve was about 25 kc/s per volt over the 20–30 Mc/s band.

5.5. Phase Detectors

Balanced double-diode phase detectors are used for both the loop and auxiliary detectors, with an i.f. feed of 20 V peak on one side, and a push-pull interpolation frequency feed of about 50 V peak on the other side. This type of detector gives an output proportional to the smaller of the two signals whose phases are being compared, so that in this case the sensitivity is about 20 volts per radian. The d.c. gain of the a.p.c. loop is therefore about 500 kc/s per radian, corresponding to a static phase error of ± 6 deg for a tuning error of ± 50 kc/s.

The auxiliary detector, operating in quadrature to the loop detector, gives a zero d.c. output voltage for the unlocked condition, and about +20 V for the locked condition. With a suitable added negative bias, this d.c. voltage is made to operate a valve with a relay in its anode circuit when lock has occurred. It is interesting to note that if the spectrum filter were

tuned to the higher end of the spectrum to allow lock to the image i.f., the auxiliary detector d.c. output voltage would be reversed in sign; thus the relay would not operate so that lock would not be indicated.

5.6. A.P.C. Loop Filter

Figure 3 shows the type of low-pass filter used in the a.p.c. loop, and a second stage of filtering is added by means of the relay when lock has occurred. The resistor xR is a damping resistor which enables the shape of the a.p.c. loop frequency response to be adjusted as required. It must be remembered that it is not only the output voltage to input voltage frequency characteristic of this filter which determines the loop performance; the loop gain must also be considered. The characteristic which is significant is the plot of output phase variation divided by input phase variation, versus frequency. In terms of this characteristic, the out-of-sync frequency response is 3 dB down at 1.5 kc/s, while the in-sync frequency response is 3 dB down at about 100 c/s. The out-of-sync design was arranged to give the most severe filtering consistent with a pull-in time of about 2 seconds, while the in-sync design was determined experimentally to be as severe as possible consistent with microphony effects.

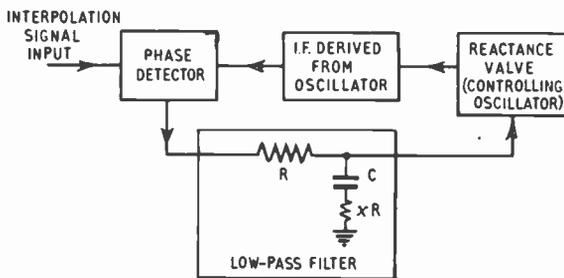


Fig. 3. Synthesizer a.p.c. loop.

$$m = \frac{\text{a.c. transmission of filter}}{\text{d.c. transmission of filter}} = \frac{x}{1+x}$$

Since $x \ll 1$, $m \approx x$.

6. Spurious Responses

As far as spurious responses are concerned, the only ones which appear to be significant (that is, less than 90 dB below the wanted signal) occur when the frequency is set close (less than 1 kc/s or so) to a 50 kc/s

point. The wanted and image i.f.s then differ by only 2 kc/s or less, and this difference frequency can appear as a small modulating voltage on the grid of the reactance valve, thereby producing frequency modulation of the output. This impurity can be reduced by increasing the image rejection of the spectrum filter. In an experimental model with an image rejection of only 40 dB at 30 Mc/s the deviation was measured as follows:—

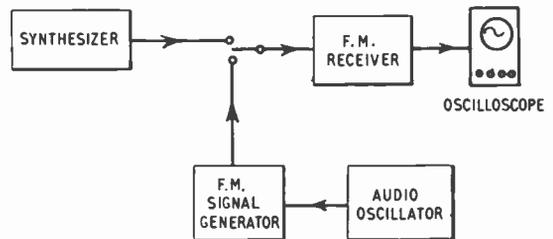


Fig. 4. Arrangement for measuring phase modulation of fina oscillator.

The synthesizer output at 30 Mc/s was connected to a frequency-modulation receiver whose audio output was displayed on an oscilloscope as in Fig. 4. The interpolation frequency was then adjusted in the neighbourhood of a 50 kc/s point until a maximum audio output was obtained. An f.m. signal generator was then substituted for the synthesizer, and a modulating audio oscillator was set to the same frequency as the beat obtained from the synthesizer. The deviation required to produce the same audio output was then measured.

In the experimental model it was found that the largest audio output occurred for a modulating frequency of 2 kc/s (that is, wanted and image i.f.s 2 kc/s apart), and the appropriate f.m. deviation was then found to be 3 c/s, corresponding to a total phase deviation of about $\frac{1}{8}$ deg. It should be emphasized that this deviation is small and that it occurs only in the region of 50 kc/s points.

7. Acknowledgment

The work described in this paper was carried out under an Admiralty contract.

Manuscript received by the Institution on 4th October 1960 (Paper No. 618).

Thin Polymeric Films for use as Dielectrics

Presented at the Symposium on New Components held in London on 26th–27th October 1960.

By

L. W. TURNER, B.Sc.†

Summary : The various techniques whereby polymeric materials can be converted into usable film form are discussed. The limitation of these methods are considered, in particular the well-known extrusion lay-flat process. A method of film preparation by casting on to a suitable carrier is described and assessed. Properties relevant to electrical applications are discussed for polystyrene, styrene copolymers, polycarbonates, celluloses and polyolefines.

1. Introduction

Polymeric materials are of such a wide range of types that it is not possible to generalize for the whole class, but amongst their number there are many materials of such electrical properties as to commend them to capacitor manufacturers, and new materials are regularly being brought forward for evaluation. Representative materials have high insulation resistance, low power factor, moderate or high heat resistance, moderate permittivity but—and this is hardly surprising—no material can be considered as ideal, sometimes because of inherent characteristics and sometimes because of technical limitations in the product-form.

Some polymeric materials (e.g. polystyrene and polyethylene terephthalate) have been in use for a considerable time as sheet or film-form dielectrics, but, by reason of the methods employed in manufacture, there are limitations to the minimum thickness available. Improvement in the potential capacitance/volume ratio appropriate to a type of capacitor can arise by increase in permittivity or by reduction in dielectric thickness. The latter approach mainly has been examined by the organization with which the author is associated, attention being given to the preparation of the films, not to capacitor design, manufacture or behaviour. A little attention has been given to the possibility of combining with the thickness reduction an increase in permittivity.

This examination has involved the assessment of the minimum thickness potential of existing processes and theoretical and practical consideration of any other processes thought to be worth the effort. The methods at present employed for the manufacture of polymeric films or foils for a wide variety of applications are:

- | | |
|--------------------------|-----------------------|
| (a) extrusion-stretching | (c) extrusion-casting |
| (b) extrusion-blowing | (d) solvent casting |
| (e) emulsion casting | |

† Yarsley Research Laboratories, Clayton Road, Chessington, Surrey.

2. Methods of Producing Film

The various methods listed above will now be considered briefly and their potentialities in respect of minimum thickness assessed. A brief account will be given, where appropriate, of practical investigations which have been made.

2.1. Extrusion-stretching

An extrusion machine is employed to heat, transfer and build up pressure within a melt of plastics material to force it through a tubular die. The tube coming from the die is then taken over a fan-tail mandrel, fitted with rollers around its edges, to give a lateral stretch, and at the same time a longitudinal stretch is given by a take-off mechanism operating at a greater rate than the material is moving from the die. The combined stretching processes yield a flat tube of biaxially-oriented material in which the molecular chains lie more or less randomly within planes. The edges are trimmed away to yield two continuous rolls of film.

The film has roughly a three-times stretch in both directions. Such a material has markedly different properties from unoriented material, principally in its ability to withstand bending and in general toughness. For this reason the method is of particular value with relatively brittle materials like polystyrene and, in fact, was developed in the war years in Germany to convert Polystyrol III into the film "Styroflex". The process is not easy to control, particularly in ensuring uniform thickness across the mandrel as stretching occurs, the obvious tendency of the material being to overstretch towards the edges.

An alternative form of process in which extruded sheet is drawn out laterally by a tentering mechanism has been developed in the U.S.A.

After considering such a process the conclusion was reached that the lower limit was probably about 3×10^{-4} in. or $7.5 \mu\text{m}$, and at this level quality would be difficult to maintain. While it was known that the process had been tried with some success for other

materials and was thereby shown to have useful versatility, it was concluded that a high degree of experience would be necessary to operate it even at the 7 μm level and that to attempt to go below this would be unfruitful.

2.2. Extrusion-blowing

Large tonnages of polyolefines are being converted into film by this process which also involves a two-way stretching of an extruded tube. However, the stretching mechanism is quite different, the stretched material being held as a closed "sausage" to maintain a small pressure of air within it. The air is led into the extruding tube through the mandrel of the extrusion die and stretches the material laterally by increasing its diameter. A longitudinal stretch is given by the speed of take-off. By feeding the blown tube to a pair of nip rollers through a pair of boards or sets of rollers inclined at a small angle it is gently eased out into a lay-flat roll. After the nip-roll, which serves to hold the air in the "sausage", the edges can be trimmed off and the two continuous films wound up separately, or left on to provide for bag making.

Again a three-times stretch is about the optimum for polythene of low and high density and for polypropylene. The method has the considerable advantage of symmetry at the blowing or stretching stage in theory, if not always in practice, and a uniform orientation and thickness should result. The disadvantage of the process is that the symmetry must eventually be lost when the "sausage" is flattened. When very thin film is being made this part of the process is difficult to perfect—folds or local stretching occur all too readily.

Partly because of the inherent symmetry in the process which should readily lead to uniformity and control, but also because of prior experience in this field, this process was selected as worthwhile for investigation from the minimum thickness point of view. Because of an existing interest in a special type of polystyrene¹ and a heat-resisting styrene copolymer, these materials were to be employed in the programme of work. More will be said about these styrene polymers below. Later the scope was increased so that polyolefinic materials could be examined.

Basically the process can be considered as an integration of a number of steps each of which needs to be controlled carefully if the optimum result is to be attained. These steps are:

- (a) pick-up of material by the extruder screw;
- (b) heating and homogenization of the melt and pressure build-up;
- (c) transfer to the tube die and extrusion as a tube;
- (d) blowing of the tube;
- (e) cooling of the blown tube;

- (f) folding;
- (g) haul-off.

Since the material is being stretched by two separate mechanisms, any lack of control in the above stages can affect differently the lateral and longitudinal variations in the film. For example, variations in extruder performance and haul-off speed will more certainly affect the longitudinal variations while the performance of the die will very greatly affect the lateral quality.

A small extruder, with a 1 in. screw, capable of operating over a wide range of speeds, was employed and the necessary die, cooling and take-off equipment designed and constructed. Particular attention was paid to the die since, for a film thickness of less than 5 μm (the ultimate target), uniformity of output of a very high order was essential, and the initial wall thickness of the tube had to be in the region of 5–10/1000 in. if excessive stretching was to be avoided. Even so it was realized that stretching would have to be high.

The polystyrene and styrene- α -methylstyrene copolymers mentioned proved difficult to handle largely because they were brittle when cold so that unblown tube could not (even at the small wall thicknesses here extruded) be taken between the nip rollers to commence the process satisfactorily. It is not felt that the process is inoperable with such materials (in all probability it is being employed by one company for the manufacture of packaging films in the 1–5/1000 in. range) but success was not achieved before a decision was taken to pass on to an examination of certain polyolefines. The conclusion was reached from the experimental work (tentatively at least) that the effort that would be called for with polystyrene and the copolymer was not worthwhile.

With polythene and polypropylene it became possible to begin to examine important process details and it was shown to be possible to prepare quite thin films by this blowing technique on a small scale. The lowest limit reached was with polypropylene when 4 μm film was made but its properties left a good deal to be desired. At such thicknesses polypropylene has a very soft handle and it stretched too readily on winding to be of great interest, as yet, to capacitor manufacturers. To achieve this low limit excessive longitudinal stretching had been necessary, making the film very easy to split along its length. High density polythene gave a crisper film with a handle rather like that of tissue paper but could not be taken below about 7.5 μm .

Other materials might well have proved to be capable of being handled by this technique but a parallel programme, in which the solvent process was being examined, was proving to be rather more interesting so attention was diverted to it.

2.3. Extrusion-Casting

Tending now to rival the extrusion-blowing process in the plastics industry, the extrusion-casting process is employed for handling the polyolefines, nylon and polyethylene terephthalate. This latter, as Melinex, Mylar or Hostaphan, is used quite extensively as a dielectric material. The method is applied particularly to those materials which soften sharply to a low viscosity fluid on being melted.

The process consists of extrusion through a slit die either on to a chilled highly polished roll or into a water-bath. The choice of process depends on the material, the application and the manufacturers' experience, and one machinery manufacturer makes his equipment versatile so that either technique can readily be followed. At the moment the chilled-roll method is the more widely used.

Since an extrusion die is employed, and by the nature of the process longitudinal draw-down only is possible, the minimum thickness is somewhat high. The manufacturers of polyethylene terephthalate film however can make, to reasonable quality limits, 6 μm film and this is achieved by after-treatment in which the material is stretched sequentially in two directions at a temperature much below that employed for extrusion. A British Patent² describes such a process and claims the advantages of at least a 2.75 : 1 stretch longitudinally and at least 3.3 : 1 laterally.

Assuming for the moment that as the thickness is reduced the material strength will be adequate to withstand the necessary tensions set up in the film during its passage through the equipment, it would be necessary to extrude a film of approximately 5/1000 in. in order to finish with one of about 0.5/1000 in. when the area increase by after-treatment is about 10 times. With this in mind it is realized that the process could not be taken down indefinitely and that the present limit of 6 μm represents a considerable achievement. Such a process was not considered further.

2.4. Solvent Casting

The method of casting from a solution is a simple one and has been applied for a long time in the manufacture of photographic and packaging films, especially those made from the cellulosic family of plastics materials: nitrocellulose, cellulose acetate and cellulose acetobutyrate. The method consists of preparing a solution in a suitable solvent to a viscosity in the right range to enable a layer of it to be spread or cast on to a surface where the solvent can be evaporated and the resulting film removed. Continuous machines employ moving surfaces, e.g. a copper band or the surface of a large drum.

Using a solvent technique has a big advantage in that filtration becomes possible so that (at least in part) the possibility of pin-holes or breakdown points being formed by dirt particles is reduced or even eliminated. The great disadvantage is that of having to evaporate solvents.

The normal thickness limit of the process would be in the region of 0.5/1000 in. (about 12 μm) set partly by the accuracy of the equipment but mainly by the necessity of having film of sufficient strength and stiffness (while it still contains some solvent) to permit its removal from the band and its passage through the drying chambers.

The idea was conceived of casting on to a supporting band, drying out the solvent while the film was still on this carrier and leaving it there or stripping it off as subsequent application demanded. High molecular weight polystyrene had been prepared as the result of another programme of research, and this was employed as the first material for examination. It was readily dissolved in a number of solvents and development of equipment was put in hand to enable films in the thickness range 1–6 μm to be made from this material. The fact that the polystyrene had a high molecular weight had a two-fold advantage:

- (a) Solutions of adequate viscosity could be prepared with quite low concentrations.³ This meant that it was not necessary to cast very thin layers of the solution in order to finish with dried film of 1–6 microns.
- (b) Polystyrene is a brittle material, but high molecular weight grades show improvement in toughness and handling quality over those grades normally marketed.

Coated papers had been used⁴ as carriers in some earlier film casting work but for the present programme it was decided that a "Melinex" base could be expected to prove much superior and it was therefore employed. The equipment, eventually developed into a prototype casting machine of good precision, is illustrated in Fig. 1. The solution, made up to the solids content and viscosity appropriate to the thickness of dry film required, freed from dissolved air and filtered, is laid on to the carrier by use of a conventional type of film spreader or by a coating-roller system as shown in the illustration. The film is dried by passage through an infra-red tunnel, then interleaved with tissue paper and wound up on the carrier.

2.4.1. Results with polystyrene and copolymers

It has been found possible to cast films satisfactorily from 0.5 μm to, say, 6 μm by this technique. These limiting values need some comment.

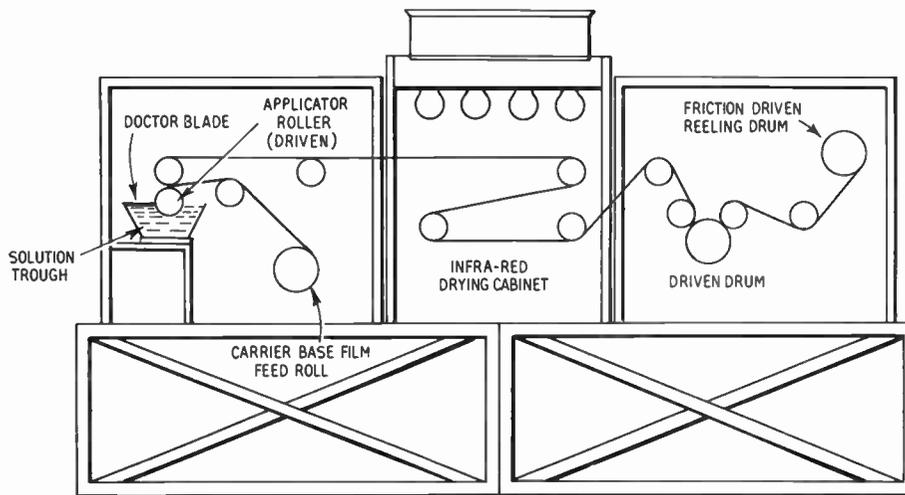


Fig. 1. Schematic diagram of film coating and casting machine.

- (a) The lower limit is approximate and depends on the material since the question as to whether it can be stripped off for use, depends on the relative values of the film strength and the adhesion to the base. At about $0.5 \mu\text{m}$ separation becomes impossible for most materials from a "Melinex" base.
- (b) Much thicker films than $6 \mu\text{m}$ have been prepared by the carrier technique but drying can only occur from one side, and this is known to give rise to difficulty in the case of such films. Conventional casting processes (e.g. drum machines) are more suitable for films of $6 \mu\text{m}$ upwards.

The choice of solvent is of some importance, not because of difficulty with the "Melinex" base which resists solvents adequately for normal purposes, but because of the influence the solvent has on the properties of the final film. The extent to which the polymer molecules are extended in solution varies with the nature of the solvent and this carries over to a certain extent into the finished film. The degree of interlacing or entanglement of the polymer chains can vary in this way with effect upon the final strength and toughness.

In contrast with biaxially-stretched polystyrene, cast film has very little orientation and this has two important results:

- (a) The nature of the polystyrene when unorientated is such that cast films are basically brittle. Only because of exceptional thinness can they be rolled. Use of high molecular weight polystyrene improves the situation but does not wholly remove the effect. Winding of such films into capacitors then presents some difficulty.

- (b) As the film is heated above its softening point, large shrinkages do not occur. The heat treatment possible with a capacitor using biaxially-oriented polystyrene does not bring about the desired tightening action. Determinations have shown that the shrinkage of cast films is, at most, about 10% in the longitudinal direction.

The mechanical properties of the styrene copolymers do not differ markedly from those of polystyrene with the result that films made from them have the same tendency to brittleness in the unorientated state.

It was found to be possible to add barium titanate, in a finely divided form, to the dope to give a film of somewhat increased permittivity, but marked increase only becomes possible with proportions of filler that seriously increase the brittleness of the film.

2.4.2. Other materials

At this point it was obvious that other materials ought also to be considered and both cellulose triacetate and polycarbonate were tried with very interesting results, since both materials have better toughness in the unstretched condition. Polycarbonate gave particularly promising results and film in the range $0.5\text{--}0.6 \mu\text{m}$ was again possible. The properties were found to be such that film within this range of thicknesses could be wound round tiny mandrels without cracking, which had not always been possible with polystyrene and styrene copolymer films.

2.4.3. Polyolefines

So far the materials mentioned have been soluble in acceptable solvents (i.e. solvents commonly available with correct volatility etc.) but this is not so for

polyethylene and polypropylene. Exploratory experiments have shown, however, that thin films can be prepared with modification to the technique. The crystalline polyolefines can be dissolved in hydrocarbons at elevated temperatures and can be cast on to a suitable carrier—aluminium foil is preferable—if the temperature is kept above the melting point of the polymer to avoid precipitation of it during drying. Care must be taken to avoid oxidation, and separation from the carrier is not so simple as in the previously described instances. The lower limit of operation is therefore not so low as for polystyrene or polycarbonate but on a fully developed machine 2–6 μm film is considered to be a production possibility.

2.5. Emulsion Casting

Some polymeric materials cannot be either melted or dissolved, but if aqueous emulsions of the materials can be prepared, and if the particles dried out from the emulsion can be sintered to a continuous film, a carrier process is again a possibility.

Using aluminium foil as the carrier it has been found that polytetrafluoroethylene (p.t.f.e.) can be converted into film by this technique. The emulsion can be rolled on to the carrier base, the water dried out from the film leaving a layer of fine white particles

which can be sintered into a continuous film at temperatures in the region of 400° C. The emulsifying agents are burned out at this temperature. Film of 4–10 μm can be made in this way.

3. Properties of Film Forming Materials

The properties of the materials mentioned in the previous section will now be reviewed. The amount of information directly relating to thin films is small and for comparative purposes properties are given, where necessary, for bulk material. Usually these refer to standard test-pieces but the dimensions are many times greater than the thickness of the films. Tensile strength, breakdown voltage and other properties will depend on the film thickness. Data are contained in Table 1.

Since polycarbonate films are of particular interest, a further comparison is made of this material with polystyrene for permittivity and power factor over a range of temperatures and frequencies. These data appear in Tables 2 and 3.

4. Further Polymers with Film-forming Potential

This brief survey would be very incomplete without some reference to materials which may be of interest in the future. There is no doubt that they are under active consideration in many laboratories.

Table 1
Properties of film forming materials

Material	Density g/cm ³	Tensile strength lb/in. ²	Elonga- tion %	Tensile modulus lb/in. ²	Softening point °C	Water absorp- tion %	Permitti- vity 50 c/s	Power factor 50 c/s	Volume resistivity ohm cm	Dielectric strength kV/mil
Polystyrene	1.05	6.7 × 10 ³	2	4 × 10 ⁵	106	—	2.55	0.0003	> 10 ¹⁶	9†
Styrene α methyl styrene copolymer	1.05	8 × 10 ³	2	4 × 10 ⁵	130	—	2.54	0.0003	—	—
Cellulose triacetate	1.30	11 × 10 ³	30	3.5 × 10 ⁵	—	—	3.9	0.019	1 × 10 ¹⁶	1.2
Polycarbonate	1.24	9.4 × 10 ³	80	3.3 × 10 ⁵	165	0.36	3.0	0.0007	4 × 10 ¹⁵	8†
Low density polythene	0.92	1.5 × 10 ³	600	1.8 × 10 ⁴	88	—	2.25	0.0002	> 10 ¹⁶	9†
High density polythene	0.96	4.2 × 10 ³	400	2.0 × 10 ⁵	122	—	2.35	0.0001	> 10 ¹⁶	9†
Polypropylene	0.90	5.0 × 10 ³	600	1.6 × 10 ⁵	> 140	—	2.1	0.0002	> 10 ¹⁶	—
Polyethylene terephthalate	1.38	20 × 10 ³	75	5.5 × 10 ⁵	—	0.50	3.2	0.003	10 ¹³	9†
Polytetrafluoro- ethylene	2.2	1 × 10 ³	150	6 × 10 ⁴	—	—	2.1	< 0.0005	1 × 10 ¹⁵	6†

†Determined on 12 μm film.

Table 2
Variation in power factor and permittivity with temperature

Temperature	Polystyrene (measured at 1 Mc/s)		Polycarbonate (measured at 800 c/s)	
	Permittivity	Power factor	Permittivity	Power factor
20	2.54	0.0004	3.1	0.0010
60	2.54	0.0004	3.0	0.007
120	—	0.0009	3.0	0.0007
150	—	0.0030	3.1	0.0012

Table 3
Variation in power factor and permittivity with frequency (temperature 20° C)

Frequency c/s	Polystyrene		Polycarbonate	
	Permittivity	Power factor	Permittivity	Power factor
60	—	0.0004	3.3	0.0008
10 ³	—	—	3.0	0.0010
10 ⁴	2.57	0.0004	3.2	0.0045
10 ⁶	—	—	2.8	0.0100
10 ¹⁰	2.54	0.0004	—	—

4.1. Isotactic Polystyrene

Mention has been made of the brittleness of unorientated polystyrene and it is only natural that consideration should have been given to the possibility of improvement of the material in this regard. No doubt all are familiar with the moulding granules and sheet materials made from a rubber-toughened form that has been marketed for some years, but as far as one knows little attention has been given to such a material for dielectric applications because the presence of the rubber impairs those electrical properties for which polystyrene is so well known. Plasticization, by addition of a proportion of a relatively low molecular weight, is not good practice with polystyrene since the material becomes "short" in its behaviour.

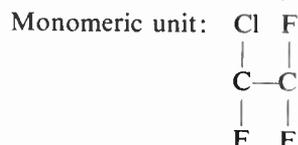
Now, however, that isotactic crystallizable materials such as polystyrene (in which the benzene ring can be made to take up a regular position) can be prepared from asymmetric monomers the situation may well

change. Isotactic polystyrene has a high softening point, films can be made from it under certain circumstances and there may be interesting results from plasticization.

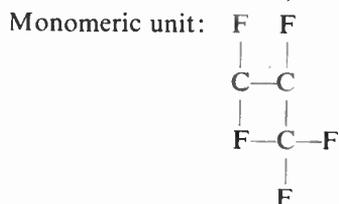
4.2. Other Fluorine-containing Polymers

Three other fluorine-containing polymers merit some mention in such a review as this:

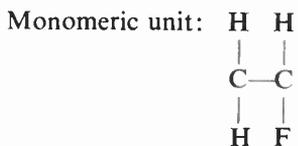
- (1) Polymonochlorotrifluoroethylene (P.T.C.F.E.; trade names: Hostafion, Kel-F).



- (2) Fluorinated ethylene-propylene copolymer (F.E.P. or Teflon F.E.P.).



- (3) Polyvinyl fluoride (P.V.F. Trade name: Teslar).



The first of these is well known and its properties make it of considerable interest in electrical applications, since they approach those of p.t.f.e., but the material is more readily handled being a thermoplastic.

The second also is related to p.t.f.e. in its properties and has thermoplastic workability. It has a somewhat higher dielectric constant.

The third listed above is interesting because it has a higher-than-usual dielectric constant.

Some properties of these materials are listed in Table 4.

5. Double Cast Films and Other Forms

While the casting process basically is a good one from the point of view of preparing thin films free from pin-holes, success in this direction depends on strict care in certain respects, a prominent point being care in keeping dust away from the base, the solution and from the running process. A high degree of protection can be given by the use of double-cast films, made by employing two different materials for the

Table 4

Properties of some fluorine-containing polymers

Material	Density gm/cm ³	Heat resis- tance °F	Per- mitti- vity 60 c/s	Power factor 60 c/s	Volume resis- tivity ohm cm	Break- down voltage kV/ mil
P.T.F.E.	2.1–2.3	500	2.0	0.0002	10 ¹⁹	—
P.T.C.F.E.	2.1	390	2.65	0.015	10 ¹⁸	—
F.E.P.	2.15	> 400	2.1	0.0002	> 10 ¹⁷	4
P.V.F.	1.37	250	7.5	0.0005	10 ¹⁰	3

first and second coats, and in certain cases this is a possibility. Success depends on ability to choose solvents for the second casting that will not disturb the first, and in view of the sensitivity of films of 1–6 μm thickness such a choice is limited. It has been found

to put together films of polystyrene and nitrocellulose in this way and other combinations are possible.

Mention has been made of employing metal foils as the carrier; it is an obvious extension to employ the carrier as part of the capacitor when the casting process becomes a coating process. In such instances the mechanical properties of the film become less important in themselves. Aluminium down to 6 μm and other metals can be coated on the film casting equipment described above.

6. References

1. W. Mikucki, "New high-softening dielectric materials", *Brit. Commun. Electronics*, 7, pp. 40–3, January 1960.
2. British Patent No. 838,708 (I.C.I. Limited.)
3. British Patent No. 588,531 (E. Schaefer & Erinoid Limited.)
4. D. A. McLean and H. G. Wehe, "Miniature lacquer film capacitors", *Proc. Inst. Radio Engrs*, 42, pp. 1799–1805, December 1954.

Manuscript received by the Institution on 6th October 1960 (Paper No. 619)

DISCUSSION

Dr. T. E. Shen: In the conventional principle of capacitor design a multi-layer dielectric is always used to avoid the excessive weakening of electric strength due to conducting particles and pin holes. Although in the advent of plastic film capacitor and metallizing construction, and due to the increasing demand of miniaturization, the above principle is not always adhered to, it remains good practice to follow whenever possible. In a low voltage capacitor employing unsupported film dielectric the use of multi-layer dielectric often causes great increase in size due to the limitation of the thinnest dielectric available. In a capacitor employing supported dielectric films this difficulty can be overcome by the application of multi-layer coating on the support base. As the film is mechanically supported there is no limitation in thickness due to lack of mechanical strength, and therefore, each coating can be made as thin as desirable. This situation can be regarded as an important advantage of supported dielectric film.

In the case of multi-layer cast film from solution, it is stated in the paper that different plastic materials have to be used in conjunction with a careful choice of solvent to ensure the solvent used in the second coating will not dissolve the first plastic layer. This requirement severely limits the number of layers and the choice of materials and their resultant electrical properties. As some of the plastic materials used for film making can form a saturated solution with certain solvents, it is proposed that an alternative principle may be adapted in making multi-layer cast films by employing saturated solution of the same material in successive cast layers, each layer being dried separately before the next layer is applied. As the solution is saturated, its solvent will not attack the material in the previous

layer. Would the author consider such an approach practicable in making multi-layer cast film of some of the plastic materials?

The proposal in the above question refers to the film being made of a thermoplastic material. In the case of thermosetting material the use of a saturated solution would not be necessary. As the thermosetting material in solid form after curing is usually not soluble in the same material in liquid form before curing, there should be no problem in making a multi-layer cast film by the successive application and curing of the individual layers. As some of the thermosetting resins, such as epoxy resins, have suitable electrical properties for a capacitor dielectric and are available in surface coating grades, would the author consider this as an attractive approach in producing a multi-layer cast film with good electrical strength?

One of the supported plastic film which is available in low thickness and yet demonstrates good electrical strength is made from Desmodur-Desmophen lacquer, which is a thermosetting material. Would the author consider the success of this material is likely to be due to the application of the multi-layer application principle?

In the vacuum metallization process on polycarbonate and polystyrene films difficulty is often experienced which is believed to be caused by vapour emission from the plastic film. As the polycarbonate films are usually made by the solvent casting technique, would the author consider that the vapour emission from this film is due to some solvent left in the film? The polystyrene film is usually made by the extrusion technique, and the presence of any solvent is,

therefore, highly unlikely. Would the author consider that some vapour can be produced from styrene monomer or dimer which is left in the polystyrene film after the film forming process. Can the author suggest any method to overcome the difficulty caused by the vapour emission?

Mr. E. P. Appleby : Could Mr. Turner offer any comments on the possibility of applying any of his processes or modification to such processes in order to obtain "Melinex" film (in small quantities) of thickness in the order of 5 micron.

AUTHOR'S REPLY

Dr. Shen has proposed two interesting ideas relating to multi-layer thin-film casting. The first, of employing a saturated solution, is probably not applicable to all materials likely to be of interest for their electrical characteristics. Crystalline polymers tend to behave in this way though the conditions are critical and there is separation of molecular weight species since low molecular weight materials are more soluble.

The second suggestion is more likely to be a feasible operation and the example quoted of a thermo-setting lacquer, which might conceivably be a useful dielectric, is worth further examination since it lends itself so well to the multi-layer technique.

The vapour emission from polycarbonate film during metallization is most likely to be due to traces of solvent and moisture and not to any changes in the polycarbonate

or residual reactants. All polystyrene contains some monomer, etc., which would be lost during vacuum treatment. Extrusion does not necessarily reduce the monomer content and may in certain circumstances cause an increase. The only method by which vapour emission could be overcome would be to warm the film in a vacuum prior to the metallization process, that is, by an efficient pre-drying process.

Replying to Mr. Appleby, it is briefly mentioned in the paper that "Melinex" is melt cast and the commercial limit of thickness at the moment is 6 μm . Melinex is not soluble under normal conditions and is, therefore, not capable of being worked by the technique of solvent casting. An amorphous form of polyethylene terephthalate is available as "Videne"; its properties are different: it is soluble and it has lower temperature resistances.

Problems in the Design of Numerical Control Equipment for Machine Tools

By

K. J. COPPIN,

B.Sc., A.R.C.S. (*Associate Member*)†

Presented at the South Western Section's Convention on "Aviation Electronics and its Industrial Applications", held in Bristol on 7th-8th October 1960.

Summary : The requirements of general-purpose equipment are examined from the points of view of utilization, economic considerations and maintenance factors. The relative merits of analogue and digital systems are examined. The choice of servo type and programming medium are considered. The results achieved with an established equipment are reviewed, its defects examined and some possible improvements suggested.

1. Introduction

Over the past ten years, and more particularly the past five, there has been growing interest in the application of electronic methods to problems of measurement as they affect industry. Despite the fact that a large and increasing proportion of our total production uses mass production techniques, in which direct measurement plays very little part, there are still many industrial processes for which, by reason of the capital outlay involved, or the nature of the product, these techniques are unsuitable. The aim of numerical control methods may broadly be defined as increase of productivity in processes involving direct measurement of the operations of production, or of the finished product.

Although there is nothing inherently difficult in the process of length measurement to the order of accuracy required by most industrial operations, repeated measurement is a tedious function, inducing operator fatigue, boredom, and finally, error. In some cases, the precision required, or the number of measurements to be made in producing the component, is so high that the percentage of scrap due to simple errors of measurement reaches disastrous proportions. The expenditure in man-hours per correct component may also become excessively high. Numerically controlled equipment aims to overcome these difficulties by relieving the operator of all, or most, responsibility for measurement, by arranging for this to be done by electronic apparatus working from instructions in direct numerical form. The purpose of this paper is to consider the influence on the design of such equipment of various factors arising from the use for which it is intended.

† Ekco Electronics Ltd., Malmesbury, Wiltshire.

2. Utilization

2.1. *Special-purpose Equipment*

Probably the first, and certainly the most complex, numerically controlled equipments to be made available to industry were three-dimensional profile milling machines. At first sight, it may seem odd that the most complex and refined equipment came first, but the operating consideration was simply that of greatest need. Various industries, the aircraft industry in particular, required components, the complexity of which was such that the cost of manufacture by conventional means was prohibitive, so that new techniques must be produced if progress were to continue. Since the entire project involved breaking new ground, the machines, as well as the control equipment, could be designed directly for the purpose intended. Although in the process it was discovered that existing methods of machine tool design left much to be desired, there was no unwillingness to improve where improvement was needed, because here was, not a supplier seeking a market, but a market seeking a supplier.

2.2. *General-purpose Equipment*

On the other hand, those designers who have ventured into the field of general-purpose equipment have had a much more uphill battle. Works managers, their appetites whetted by reading of what was being achieved by these special-purpose machines, began to dream of factories in which the most complex operation was performed in minimum time, without scrap, simply by attaching a mysterious "black box" to any of their existing machines which was (or more often, once had been) capable of carrying out the type of operation required. But, of course, they were not prepared to set a machine aside for one

particular class of work. They had not enough work of that type to keep the machine occupied full time, and therefore, if they were to consider buying one, the little black box must be at least as much of a Jack-of-all-trades as the unfortunate machine operator, who was expected to become as proficient in handling it as he had been hitherto in operating micrometers, slide rules and other purely mechanical aids. And, of course, it must pay for itself in a year, at most, and last for at least ten.

3. Economic Factors

3.1. *Special-purpose Equipment*

Economically, again the designer of special-purpose equipment has had things more or less his own way. The problem thrown up by industry must be solved, or progress is halted. It does not really matter whether the problem is solved by the extension of existing techniques, or the introduction of new ones. Certainly the research and development will be costly; certainly that cost will be reflected in the cost of the not-so-little black box. Possibly, even when the design is complete, only a small number of mammoth undertakings will have either sufficient work to justify the installation of such a machine, or sufficient money to pay for it. Perhaps a few may be able to install one and hire its services part-time to the less fortunate. In any event, the hurly-burly of competitive selling need not concern him, nor need considerations of design for quantity production.

3.2. *General-purpose Equipment*

Equipment designed for general application, however, is subject to much more careful scrutiny from the economic standpoint. By its very nature, it is expected to have a wide field of application, and must be designed in such a way that, if successful, it can be produced at least in moderate quantities, without undue strain on the designers' production organization. If it is to be applied in the wide field envisaged, its capital cost must be such, in relation to its value to the customer, as not to exclude it from consideration. If it is to be general purpose, too, some market research will be required to discover what advantages the customer expects to achieve by its use, and what features will therefore have the greatest sales appeal. If he is concerned with reduction of scrap, reliability will be his prime demand. If he is seeking increase of production, increased speed of operation will be his yardstick, though increase of production necessarily implies reliability also. If he is in difficulties over finding adequate supplies of skilled labour for his undertaking, his criterion will be simplicity of operation, in order that he may be able to lower his requirements for operator skill. Whatever may be the reason which leads him to contemplate the purchase of the black box, his first hope will be that his capital

commitment begins and ends with that. He may, if he is very enlightened, appreciate that machines primarily designed for hand operation may have undesirable characteristics from the point of view of automatic control, and he may be persuaded to buy new plant in addition. In the majority of cases, however, the designer will be faced with the desirability of making his black box operate, with at least a modicum of success, in conjunction with an existing machine.

4. Maintenance Factors

4.1. *Maintenance by Supplier*

In any equipment, whether special or general purpose, the problem of servicing and maintenance must be considered. In the case of special-purpose equipment, the supplier may be forced by the sheer complexity of the installation to undertake the necessary maintenance under the contract to the customer, although he may be able to limit the calls on his services by designing on a "building block" basis, and supplying the customer with spare "blocks". The supplier of general-purpose equipment will normally have a free choice. Provided his anticipated sales justify it, he can set up a day-and-night maintenance organization, in which case he is free to employ designs based on the technique of on-the-spot repair, rather than servicing by substitution at the site, followed by repair elsewhere. Until, however, his machines are in sufficiently widespread use to justify the setting-up of a generous service coverage, this arrangement will almost inevitably entail substantial amounts of idle time on the machine, while a service engineer is located and directed to the site.

4.2. *Maintenance by Customer*

The author believes that the aim of system design should be to bring all routine maintenance, and the greatest possible proportion of servicing, within the scope of facilities which the customer may be expected to possess, or have at his disposal, locally. Since, in heavy industry particularly, the customer is unlikely to have electronic technicians in his employment, and may not even have labour accustomed to using a small soldering iron, this implies the method of "servicing by substitution". The machine is made operational in the minimum of time by replacement of a defective sub-assembly by a serviceable spare, the defective item being repaired by the suppliers' service organization. The breakdown of equipment into individually replaceable sub-assemblies is not without its disadvantages, however. The plugs and sockets which are used for connection of these sub-assemblies represent an additional potential source of failure, and often impose restrictions on design by imposing limitations on the number and layout of inter-unit connections.

Granted, as a pre-requisite, the simplification of the equipment to the point at which as much as possible of the maintenance can be done by the customer's personnel—after a course of instruction at the supplier's works if necessary—there would appear to be a case for calling on the assistance of an already widespread organization, that of radio and television servicing, to deal with more obscure faults. Its personnel have the necessary skills, and at least some background in electronics, and could as readily be agents in this field as in those with which they already deal.

5. Choice Between Analogue and Digital Systems

So far, we have considered what may be described as "external" factors. The next consideration is one of "internal" choice. In any control system there are two fundamental elements, the "master" equipment which provides the command signals, and the "slave" equipment which carries out the commands. If the system is to be "closed loop", that is, if the slave element is to be capable, not only of receiving commands and operating on them, but also of reporting progress back to the control station, it must contain some form of transducer, whereby the movements it makes are caused to generate characteristic signals. These signals may be of two basic types—analogue or digital. There is still controversy regarding satisfactory definitions, but for the present purpose it will suffice to say that if variations of the physical quantity to be measured are represented to the control system as variations in the *magnitude* of some other physical quantity, the system is *analogue*. If, on the other hand, the variations are presented to the control system as variations in the *number* of signals generated, regardless of magnitude, the system is *digital*.

5.1. Type of Work and Accuracy

Since an analogue system merely substitutes measurement of some other physical quantity for measurement of length, the accuracy of the system, assuming a perfect transducer, will be that with which the analogue quantity can be measured. Since in the case of current or voltage, the analogues commonly used, this accuracy cannot readily be made greater than 1 part in 10^3 , systems which require accuracies greater than this will need at least two analogue arrangements in cascade, and difficulties may arise at the point of transfer of control from one arrangement to the other. Digital systems, on the other hand, can be built for any accuracy required. The smallest quantity to be measured is represented by one digit, and the store made large enough to accommodate the number of these contained in the total range of movement.

5.2. Availability of Programming Services

Where analogue systems are employed, the choice of scale is to a large extent arbitrary, so that such systems can readily be devised to accept information fed to them in the decimal form in which it normally appears on drawings or in conventional calculations. Most electronic computers, and allied counting devices, on which a digital system will be based, operate in the binary scale, so that, in general, programming services for preparing machine instructions in binary or other appropriate code must be made available if digital methods are to be employed.

5.3. Relative Merits of the Two Systems

Whereas the accuracy of analogue systems is limited by accuracy of measurement, and cannot readily be improved, the accuracy of a digital system is purely that of counting. If a machine is to have an accuracy of 0.0001 in, however, at a traverse speed of, say, 60 in/min, the count rate required is 10 000 per second, and it is by no means simple to ensure accurate counting at this speed. It is also not easy to detect the cause of false counting if it occurs, and supply failure can completely disrupt the program of a digital system, whereas an analogue system can easily be designed, in such an event, to carry on from where it left off, when power is restored.

Broadly, it may be stated that where the work program is complex enough to require a computer, digital methods may well prove advantageous, but for simpler operations, and certainly if customer servicing is envisaged, analogue methods are to be preferred, despite the artifices which must be resorted to to overcome the basic accuracy limitation.

6. Choice of Servo Type

6.1. Influence of the End Product

We shall only concern ourselves here with the choice between proportional and "on/off" or "bang-bang" servos. The type of motive power—electric, hydraulic, pneumatic—will be disregarded. In the field of contouring equipment, where ability to vary the velocity of each motion of the machine in order to be able to make cuts at any angle to the machine axes is an essential requirement, the proportional servo is the obvious choice (though not quite an inevitable one: a Russian system uses stepping motors, the steps being so small that the resulting discontinuities are not objectionable). In non-contouring applications, "on/off" servos are by no means excluded.

6.2. Influence of the Machine

If it is proposed to take the ideal solution of integrating the control system and the machine into a logical entity, designed to carry out one function or group of applied functions and no other, so that the

power requirements and machine characteristics are known, a correctly matched proportional servo will undoubtedly give the best performance. Where the problem is one of designing a general-purpose arrangement, intended to carry out a variety of functions on a range of machines having widely different characteristics, the "on/off" servo is a more suitable choice. If the use of servo-amplifiers is avoided, as it can be in this arrangement, a large range of power requirements can be catered for with the same basic design, and a system which is designed to have heavy inherent damping will function satisfactorily in the presence of most of the mechanical defects associated with conventional machine tool design.

7. Choice of Programming Medium

It is assumed that the user will expect the system to be capable of carrying out a number of consecutive operations, without requiring the operator to feed it with fresh information as each operation is completed, and to this end some information storage medium will be required. Currently available for the purpose are punched and magnetic film or tape, and punched cards. The factors involved in making the choice between them are:

- (i) Availability of medium and programming services.
- (ii) Speed of read-out required.
- (iii) Type of application.

In the case of contouring machines, and systems using digital control generally, the choice is limited, by the high rate of read-out required, to film or tape. While, in the case of punched tape or film, it may be possible for the system to be organized to accept some standard code for which perforators and readers are commercially available, so that the customer *may* be able to prepare his own program, the use of magnetic tape in general means that the supplier must be prepared to provide tape preparation facilities or equipment, for customer hire.

In the case of equipment designed to carry out point-by-point operations only, however, punched cards also form an acceptable medium. Some manufacturers have used them on the basis of "one card, one operation", others, like the author's company, have made arrangements for the card to contain the instructions for a moderate number of consecutive operations. Whereas tape is normally punched according to some pre-arranged code, and cannot easily be read by direct inspection, the information on punched cards is normally presented in direct decimal form, and can be verified visually without difficulty. Perforating equipment suitable for some purposes is commercially available, and special-purpose per-

forators can be provided (and used by the customer to prepare his own program), without undue expense.

8. Organization Factors

Whereas in the case of special-purpose equipment special techniques will be accepted if demanded, the customer will expect that general-purpose equipment will fit in with established techniques to the greatest possible extent and any changes in technique demanded must be reasonable and convenient. In fact, the mere intention of designing a general-purpose black box for use in conjunction with existing machines implies the acceptance of most current techniques. There is one established practice, however, which is a bugbear to designers of analogue systems, though of less concern to those who use digital methods. This is expecting to be able to use any point on the table working surface as datum, instead of leaving the reference point undisturbed in one corner.

The author is perfectly well aware of all the arguments in favour of current practice, and of the draughtsman's device of using more than one datum in the same component to overcome difficulties with cumulative tolerances. This procedure is unnecessary with numerically controlled machines, which work in a manner which does not give rise to cumulative tolerances, and the datum could be taken care of in the planning office when preparing the program. If only users realized what they pay in cost and complexity for retaining this quite unnecessary facility, they would quickly dispense with it.

Where an equipment carries out positioning functions only, no new techniques are involved, except in that, as has already been stated, the use of a constant datum would make equipment design simpler. Where the system is intended to program other operations, such as selection of tool feeds and speeds, or even of the tool itself, the planning office will acquire additional functions, but otherwise the use of general-purpose numerically controlled equipment raises no special problems.

9. Programming of Non-positioning Functions

So far, we have considered only the various factors which influence the design of a system for moving the work on the work-table to the position at which some cutting operation is to be carried out. At this stage in the production program, the alternatives are:

- (i) selection of the correct tool, feed, and speed, and performance of the cutting operation, by the machine operator;
- (ii) execution of these functions by the system itself, the operator functioning only as machine minder and loader.

The choice between these two methods, is, in fact,

dictated rather more by the type of machine being controlled, and the type of work being carried out, than by increase in complexity of the control equipment. If the programming medium provides facilities for giving instructions to the operator at a certain point to use a certain tool, feed rate, and spindle speed, it is a relatively simple matter to arrange that these instructions are fed instead to selector devices built into the machine itself. The problem is to decide at what stage the additional cost and complexity of these devices outweigh their usefulness.

Although selection of spindle feeds and speeds by remote control is purely a matter of replacing manual selection of gear ratios by power selection, and tool stroke can be controlled either by pre-set stops, or the addition of another measuring system, no real gain has been achieved if it is still necessary for the operator to select and insert the correct tool. Tool changes can only be made without operator intervention by the use of turrets or of multi-spindle machines. Turrets are open to objection on the score that they reduce spindle rigidity, and so impair accuracy, and also complicate arrangements for depth control. Multi-spindle machines, because change of tool means change of working point, complicate the preparation of the program, because these changes must be taken into account in preparing the positioning instructions.

In general, special-purpose equipment can be designed to incorporate facilities for such of these additional functions as may be specified. General-purpose equipment, on the other hand, should provide for them as optional extras to allow for the wide variations of user requirements.

10. A Complete Design

10.1. Theoretical Specification

At the Institution's Convention on "Electronics in Automation" in June 1957, the author presented a paper† in which the design of the Ekco numerical control system, with which he was directly concerned, was discussed in some detail. As the present paper is concerned with the "why" of design rather than the "how", it is not proposed to recapitulate in respect of technical detail here, except to indicate the extent to which the "why" dictated the "how".

The intention was to produce a general-purpose equipment, suitable for use on existing machines, and designed for point-by-point positioning applications alone. Originally, control by manual dial setting only was provided, but control by punched card was soon added, and is now incorporated as standard, as are automatic arrangements for monitoring for correct functioning. The lead-screw was

to be used as the measuring element, owing to the difficulty of fitting separate scales on many existing machines. The accuracy was to be of the order of 0.0002 in, and analogue methods of control were favoured because it was felt that these were more easily understood, and it was hoped that the customer would carry out his own maintenance. Important sub-assemblies were to be separately replaceable, to facilitate this.

The position transducer was to be a potentiometer, mechanically coupled to the lead-screw, so as to make one revolution per 0.1 in. of work-table movement, the voltage derived from the travelling contact of this potentiometer being a direct analogue of the work-table position within that range. Granted a voltage measurement accuracy of 1 part in 10^3 , the system should therefore resolve to 0.0001 in, but owing to "drift" and non-linearity effects, it was not expected to achieve better than 0.0002 in. in practice. A decimal scale was to be employed, and the range extended to 100 in. by adding a three-decade mechanical counter to record complete revolutions of the potentiometer. By associating a potentiometer with each dial of the counter, voltages could be obtained which were direct analogues of the positions of the dials, and could therefore signal their reading to the control circuits.

In order to minimize the effects of machine characteristics, an "on/off" servo was to be employed. The minimum of two operating speeds necessary to achieve both stability and a reasonable cycle time, would be obtained by using two motors differentially coupled to the load, as the magnetic clutches available at the time were not considered sufficiently reliable. Uni-directional final approach would be employed to overcome backlash effects, and datum shifting facilities would be provided by an independent motor and differential. To avoid ambiguity and conflict of information, the "command" potentials and the "response" potentials from the associated transducer elements would be compared sequentially, starting with those from the most significant digit of the counter and working downwards. The clearance signal would be equality of "command" and "response" potentials. All sequence and control functions would be carried out by d.c. relays.

The programming medium was to be punched card. Systems in current use were considered and rejected on various grounds, and a special card providing storage for 25 operational instructions was devised, together with reader and perforator. Provision was to be made for signals relating to other machine functions to be given to the operator, and for the control of power operation of these functions if desired. Facilities for the connection of any interlocks required for safety purposes were to be provided.

† "A 'basic' system of position control for the traversing tables of machine tools", *J. Brit. I.R.E.*, 17, pp. 563-78, October 1957.

10.2. Practical Achievement

At the present time, some three years after the system proposed first became commercially available, about 24 are in service. In view of the relatively low capital cost, this is a somewhat discouraging figure. To some extent it is explainable in terms of credit squeezes, recessions in the aircraft industry and the machine tool industry, and of conservatism on the part of management. The latter arises, not only from reluctance to try new ideas, but also from failure to recognize the correct field of application. Time precludes detailed examination of this point, but the

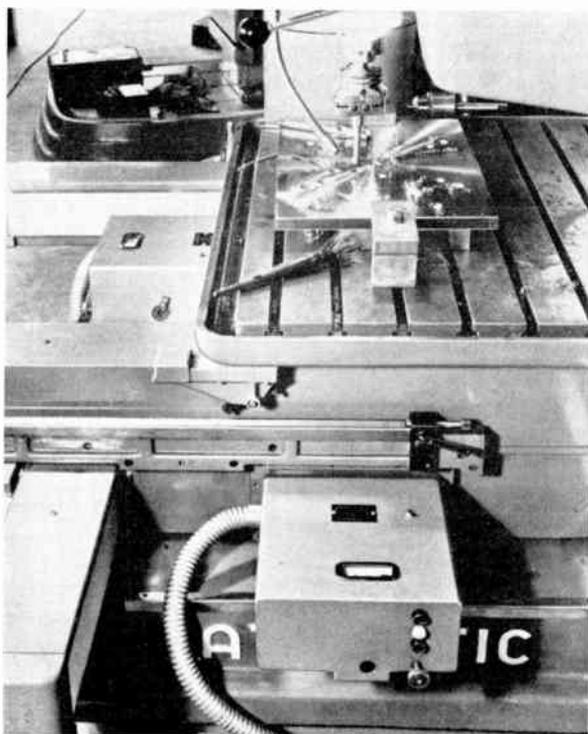


Fig. 1. The Ekco machine tool equipment in use on a co-ordinate table, showing the two traverse units.

basic error resided in the belief that numerically controlled general-purpose machines could be fitted into mass production organization, whereas this is, and seems likely to remain, the field of specialized machines, often of the transfer type. The great field of usefulness of numerically-controlled equipment is in increasing speed and flexibility in small batch production. Because of problems of planning, user reports contain accounts of service which range from 24 hours per day to 24 hours per month—the latter resulting from the fact that the system has speeded up a particular operation, which previously involved hours of tedious marking-out, to such an extent that bottlenecks have been created at later stages.

10.3. Defects of the System

Apart from the causes of limited use outlined in the preceding paragraph, there is some customer resistance resulting from real or imagined weaknesses in the system itself. Chief among these have been its speed limitations. Originally, on the advice of lead-screw manufacturers, the fast traverse rate was limited to 24 in/min, and considerations of stability restricted the slow approach speed to about $\frac{1}{2}$ in/min. With the advent of re-circulating ball screws, the upper speed restriction was removed, and the measuring system was recently rearranged to operate on the basis of 0.2 in. movement per revolution of the final potentiometer, instead of 0.1 in. By this means, the operating speed was doubled, whilst still preserving an acceptable order of accuracy. In practice, the time per operation proved to be much less than half that formerly required, because the new arrangement eliminates a complete stage from the original sequence, besides doubling the speed of those which remain.

After the first six equipments had been installed, it became apparent also that reliability was not as good as had been anticipated, the basic cause being that the control system was based on the procedure of comparing "command" and "response" signals for absence of potential difference, rather than equality of magnitude. Now a voltmeter can read zero either because there is no potential difference or because it is disconnected, and the faults reported were, in fact, due to temporary disconnections resulting from imperfections in rubbing contacts. Improved contact materials, and duplication of current paths where practicable, have considerably reduced the risk of failures due to this cause, but as a further precaution, all systems in current production are fitted with an additional monitor which not only checks that the potentials of points A and B are equal, but also verifies that they differ from a common reference potential by the same amount.

So, over the years, the system has evolved, and with its evolution, the original notion that it could be serviced by the works electrician, even given access to replacement sub-units, has been perforce abandoned, and a service organization has been created. Oddly, the lack of valves and other mysterious electronic devices has increased, rather than decreased, the service difficulties. Whereas a valve has one input and one output, and can be readily changed if suspect, a relay may have more than one input and a multitude of outputs, so that, for every ten engineers who can be persuaded to probe the mysteries of a box full of valves, only one can be found who will explore a box full of relays.

Oddly, too, the programming arrangements, heavily criticized as they were initially for failing to use standard punched cards, have, in the event, won

over their opponents, and, apart from possible changes in the material from which the card is produced, seem destined to form the nucleus of any future development.

10.4. *Re-thinking*

It is doubtful whether any product ever reached the market—doubtful even if it had left the drawing board—before the designer had discovered some aspect of it which he wished to improve, and the system with which the author has been concerned has occasioned a whole multitude of second thoughts. Second thoughts are not always best, however, and despite spells of deviationist thinking, most of the ideas incorporated in the existing system still hold their own against projected alternatives.

Given the opportunity to “try again”, however, the author would certainly make the black box bigger. Cramping not only hampers servicing, it also increases the necessity for service by increasing the risk of breakdown. Operating speeds would be increased to about 100 in/min, and differentials would be replaced by clutches. Differentials are costly to produce and low in mechanical efficiency, whilst clutches have greatly improved in reliability. Backlash would be eliminated from the system, so that it could be used on backlash-free machines for a limited range of milling operations. Detachable sub-assemblies would be eliminated, since in practice they did not fulfil their purpose of making customer servicing possible, and they place hampering restrictions on design.

Relay programmers would be replaced by uni-selectors, which are, after all, only power-operated multi-way switches, and should be as easy as switches to understand. Their contacts, too, lie in logically related groups which should make servicing easier. Facilities would be provided for control of motor speed, to permit step-by-step milling as in current Russian practice. For technical reasons beyond the scope of this paper, line-finder arrangements would replace potentiometers as transducers in the counter mechanisms.

Because competitors would almost undoubtedly incorporate them, the author would reluctantly retain datum shifting facilities, with all their attendant complications. The facilities for programming, and interlocking with, other functions of the machine are already provided in basic form. What more might be done in this respect—indeed, whether anything more is done at all—must depend on what the customer wants and is willing to buy.

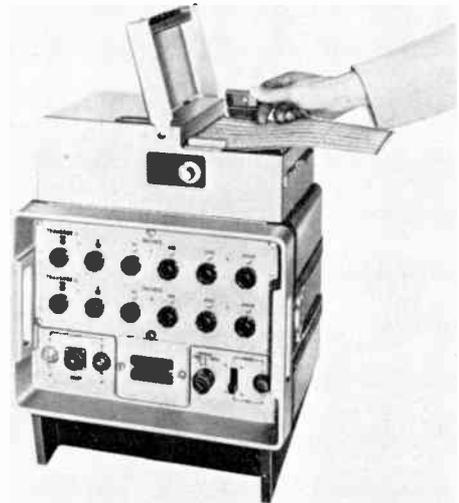


Fig. 2. Control unit and card reader of Ekco machine tool control equipment.

11. Acknowledgments

The author is indebted to the Directors of Ekco Electronics Ltd. for permission to publish this paper.

Manuscript received by the Institution on 15th September 1960 (Paper No. 620).

APPLICANTS FOR ELECTION AND TRANSFER

As a result of its meeting on 28th February the Membership Committee recommended to the Council the following elections and transfers.

In accordance with a resolution of Council, and in the absence of any objections, the election and transfer of the candidates to the class indicated will be confirmed fourteen days after the date of circulation of this list. Any objections or communications concerning these elections should be addressed to the General Secretary for submission to the Council.

Transfer from Associate Member to Member

DUNLOP, Wg. Cdr. Patrick John, R.A.F. *R.A.F. Scharfoldendorf, B.F.P.O. 33.*
WILLIAMS, George Amphlett. *London, W.2.*

Direct Election to Associate Member

EVANS, Brian Richard, B.Sc., M.Sc. *Wolverhampton, Staffs.*
HOLFORD, Harry Burgess, B.Sc.(Eng.). *Chelmsford, Essex.*
HOLLAND, Michael John. *Glasgow, W.5.*
HUMPHREYS, Stephen Frederick. *Edgware, Middx.*
JACKSON, Derek Ronald. *Hornchurch, Essex.*
KEMP, Graham Gilbert, B.Sc. *Harpenden, Herts.*
KIRK, Sidney Arthur. *London, E.17.*
PETERSEN, David, B.Sc. *Letchworth, Herts.*
SALMON, Kenneth James. *Upper Hutt, New Zealand.*
SMITH, Frederick Alexander. *Lingfield, Surrey.*
WOOLLAND, John Samuel. *Uxbridge, Middx.*

Transfer from Associate to Associate Member

BROOMFIELD, Captain Bertie, R.N. *Torrington, N. Devon.*
MOWBRAY, Wg. Cdr. Frederick James, R.A.F. *Amesbury, Wilts.*

Transfer from Graduate to Associate Member

CACHIA, Saviour. *Hayes, Middx.*
HADJIDEMETRIOU, Demetrious. *Leopoldville, Congo.*
HEYWOOD, Charles Leslie, M.Sc., B.Sc. *Twickenham, Middx.*
QUINN, Peter George. *Bushey, Herts.*
ROSE, Milton, B.Sc. *London, N.W.9.*
STRANGE, Norman Edward. *Kingston-upon-Thames, Surrey.*

Transfer from Student to Associate Member

CUSSONS, Ashley Roy. *Dorking, Surrey.*
PLAYFORD, Victor James. *Wantage, Berks.*
RIOUAL, Louis Auguste, B.Sc. *Brest, France.*

Direct Election to Associate

MONTAGUE, Capt. William Alexander, R.Sigs. *B.A.O.R.*
WEBB, Peter Ralph Charles. *Lincoln.*

Transfer from Associate to Graduate

BURTON, Ernest Douglas. *Reading, Berks.*

Direct Election to Graduate

AXTELL, Richard Thomas. *Harmondsworth, Middx.*
BARFIELD, Edward George. *Great Malvern, Worcs.*
BOULTER, Brian Alfred. *Great Yarmouth, Norfolk.*
BRENNAN, Francis Michael. *Dublin.*
COCHRAN, Major James Gordon, B.Sc., R.A. *Cobham, Surrey.*
CUSHING, Brian Michael. *Chelmsford, Essex.*
EDWARDS, Brian John. *London, W.3.*
FAIRFIELD, James Henry. *Basingstoke, Hants.*
GARRETT, John Arthur. *Wells, Somerset.*
GULLIVER, Anthony John. *Bristol.*
HELEY, Trevor Paul. *Dunstable, Beds.*
JARVIS, William Anthony. *Rickmansworth, Herts.*
JENKINS, William Alfred. *Sidcup, Kent.*
JEPHTNA, Anthony. *Reading, Berks.*
LONG, Michael James. *Lyme Regis, Dorset.*
MOELWYN-HUGHES, Ifan Gruffydd, B.Sc. *Wembley, Middx.*
NEWMAN, Geoffrey Charles, B.Sc. *North Wembley, Middx.*
RICHARDS, Dermot Aelfred. *Godalming, Surrey.*
RING, Terence. *Basingstoke, Hants.*
SMITH, Carlyle Fitzgerald. *Coventry, Warwicks.*
SMITH, Sidney Maurice. *Hatfield, Herts.*
SMITH, William George. *Ruislip, Middx.*
WATERFIELD, Charles Jeffrey. *Chelmsford, Essex.*
WHATLEY, Peter John. *Kings Langley, Herts.*
*WILLIAMS, David Lloyd McNeil, B.Sc. *Carlisle, Cumberland.*
WILLIAMS, Douglas Mowbray. *Colchester, Essex.*
WILTSHIRE, Royston George. *New Malden, Surrey.*
WOOLLETT, Arthur Anthony Thomas. *Basingstoke, Hants.*

Transfer from Student to Graduate

ANDERSON, Edward Philip Talbot. *Cardiff.*
BAIGENT, John Andrew Mortimer. *Hounslow, Middx.*
BRAITHWAITE, Clive. *Amphill, Beds.*
BREEZE, Alan George. *Lymington, Hants.*
CORY, Frederick John. *Chippenham, Wilts.*
GUPTA, Makhan Lal. *Agra, India.*
JACKSON, Michael Clifford. *Reading, Berks.*
LEE, Han Chi, B.Sc. *Hong Kong.*
MARSHALL, Laurel Everleigh. *Kingston, Jamaica.*
OGU, Edwin N. P. *London, W.2.*
ONIANWA, Christopher Afamefune. *London, N.19.*
SMITH, Alan. *Belfast, N. Ireland.*
STOKES, Roy. *Rowston, Herts.*
TALWAR, Satish Kumar. *Agra, India.*
USMAN, Mirza Mohd. *Bahrain, Persian Gulf.*

STUDENTSHIP REGISTRATIONS

The following students were registered at the 4th January and 31st January meetings of the Committee. The names of a further 26 students registered at the 28th February meeting will be published later.

LEA, Arnold Trevor. *Worcester.*
LOCKHART, Reginald. *Bath.*
LUCKHURST, Barry. *Welling, Kent.*
McFADZEAN, Gordon. *Edinburgh.*
MASON, Leonard. *Kampala, Uganda.*
NEWMAN, Brian, B.Sc. *Chepstow.*
NG HONG YEW. *Singapore.*
NUTT, Alan David. *Australia.*
OAIYA, Frederic. *Southampton.*
PARK, Kenneth. *Shepton Mallet.*
PAYNTER, John. *New Zealand.*
RENN, Gilbert. *Geneva.*
ROCKLEY, Graham Charles. *New Plymouth, New Zealand.*
SCAFE, Roy Barrington. *Jamaica.*
TAYLOR, John Livesey. *Bolton.*
TEN BROEKE, Bernardus J. *Den Haag, Holland.*
TERRILL, Kenneth Phillip. *Harrow.*
THOMAS, Philip Wilfred. *Bristol.*
Van Der MEER, Herman. *Arnhem, Holland.*
VIR RAVINDER KUMAR. *London, E.15.*
WARD, James. *Glasgow.*
WARDLE, Derek. *Fareham, Hampshire.*
WILLCOCKS, Michael W. *Crawham Park, Essex.*
WONG, Yiu Wah. *Hong Kong.*
WORRELL, Brian Frank. *London, N.W.9.*

AKHLAGHI, Ali. *Iran.*
ALDER, James Gordon. *Cheltenham, Glos.*
AMOS, Reginald George, B.Sc. *Bristol.*
ARMSTRONG, John Patrick. *Basingstoke.*
BEADLE, John Alan, B.Sc. *Betchworth, Surrey*
BREACH, Frank T. *East Molesey, Surrey.*
BURTON, Herbert Frederick. *Lincoln.*
CHILTON, George Arthur A. *Wolverton, Bucks*
COLLIER, Michael Henry. *Axminster, Devon.*
CORCORAN, Thomas Francis. *Birmingham II.*
EMELUGO, Samuel Chukwumeke. *Lagos.*
FENSOME, David A. *Potters Bar, Middlesex.*
FOUBISTER, David. *Edinburgh 9.*
KATZ Zvi. *Haifa, Israel.*
KEANE, John, R., B.Sc. *Woodley, Berks.*
MacDONALD, Calum Archibald. *Isle of Mull.*
McGREAL, David Edgar. *Alberta, Canada.*
MEINTJES, Jeffrey Ayton. *London, E.4.*
MILBORROW, Reginald Sydney. *Reading.*
MILNER, Ramon Kevin. *Malaya.*
SER CHOON NG, B.Sc. *Singapore 12.*
NORTON, Richard H. *Wolverton, Bucks.*
PETTIFER, John. *London, S.E.24.*
PIROOZMANDI, Rouhollah. *South Iran.*
SINCLAIR, William Tullock L. *Daventry.*
SMITH, Edward James. *Cheddar, Somerset.*
*STOKES, John Francis A. *Wembley, Middlesex.*

TAYLOR, Ronald G. *Henley on Thames.*
TUCKER, Jeremy M. C. *London, N.W.11.*
ADAMS, Leonard. *London, N.W.7.*
AKANNI, Olubodunrin. *London, S.W.8.*
*ALI, A. Majeed M. *Basrah, Iraq.*
AMARASINGHAM, Y. B.Sc. *London, W.4.*
AUDUS, Michael Francis, B.Sc. *Abingdon.*
BALCOMBE, David James. *East Croydon.*
BELL, Herbert Frederick. *Whitehaven.*
BENNY, William R. *Ohakea, New Zealand.*
BONNER, Peter. *Bexleyheath, Kent.*
BURNETT-HALL, Richard H., B.A.(Cantab). *London, N.10.*
CLARKE, John Reginald. *Wantage, Berks.*
CORNISH, Frederick Douglas. *Plymouth.*
CRAWFORD, Brian Thomas. *Plymouth.*
DAWSON, Albert T. *Albrighton, Staffs.*
DICKENSON, Ronald. *Cheadle, Ches.*
FRIEND, Dermot Neville, B.Sc. *Coventry.*
GOH, Yee Yen. *Kuala Lumpur.*
HAKIM, Maurice Isaac. *Coventry, Warwicks.*
HALLIDAY, Ezekiel Tamuno. *Chelmsford.*
HARTLEY, William. *London, S.W.15.*
HEGHOYAN, Manas. *London, W.4.*
HILL, Albert Arthur. *London, E.8.*
HOOD, William. *Edinburgh, 3.*

* Reinstatements

An Equipment for Automatically Processing Time Multiplexed Telemetry Data

By

N. PURNELL, B.Sc.†

AND

T. T. WALTERS‡

First presented at a meeting of the South Western Section held in Bristol on 27th January, 1960 and subsequently at a meeting of the West Midlands Section in Wolverhampton on 11th January 1961.

Summary: An equipment is described for processing magnetic tape recordings of frequency-modulated time-multiplexed telemetry data. Details are given of the way in which the input signals are derived and the method by which the recordings are made. The equipment produces two forms of output: analogue graphs on paper film and digital records on punched cards. The performance achieved and the methods of checking this performance are detailed.

1. Introduction

The development of a guided missile system involves the examination and interpretation of several million data points. The conversion of such data into a form suitable for processing by a general purpose digital computer can present serious problems when tackled by manual analysis methods.

The introduction of magnetic tape recording for this type of data offered a solution requiring the construction of the equipment described in this paper. The only input facility available, for the DEUCE computers used for system evaluation, is punched cards. The output of the equipment described could therefore only be in digital form on punched cards.

Since space and weight in missiles is limited, it follows that many of the measurements, in practice those which present a data processing problem, cannot be made with great accuracy. A small number of high accuracy measurements can, however, be made and manual data processing methods can be afforded for dealing with these.

Manipulation of the data to provide gain and level correction, and linearization, is more convenient when the data is in an analogue form. The limited accuracy required, and the wide previous experience of analogue techniques, confirmed the decision to convert the data to an analogue form, although the final requirement is for a digital output.

2. Input

The input to the equipment is a replay of a magnetic tape recording derived from the received output of a telemetry sender. In this sender a carrier is amplitude-modulated by a sub-carrier in the range 130 to 180 kc/s. A 24-way rotary switch is used to time-

multiplex the sub-carrier. One segment of the switch is used for synchronization purposes and always produces a sub-carrier frequency a little above the band normally used for information channels.

The remaining switch positions are used for the transmission of data and, depending on the values of the parameters involved, will produce sub-carrier frequencies in the range given above. Some channels may be used for standard or reference levels, or alternatively a number of reference levels may be telemetered on one channel by use of a low-speed sub-multiplexing switch.‡

As received, the sub-carrier frequencies are inconveniently high for tape recording, and a beat frequency is generated between this signal and the output of a crystal-controlled oscillator. The difference frequency is filtered out and applied to one track of a multi-track high-speed tape recorder. It is this tape record which is used to provide the input to the equipment.

The output of a crystal-controlled 100 kc/s oscillator is recorded on one of the remaining tape tracks as a time reference. A discontinuity is introduced into this signal to mark the "instant of fire".

3. Outputs

The primary output is in the form of Hollerith 80-column × 12-row punched cards. Each row contains two 8-digit binary-coded parameter samples and two binary numbers of up to 20 digits giving the times at which these samples were taken, from instant of fire,

‡ Descriptions of telemetry equipment typical of that used to supply data to this processing equipment are given in two recent papers: W. M. Rae, "Engineering aspects of missile telemetry equipment—an airborne sender for 24-channel telemetry", and F. F. Thomas, "455 Mc/s telemetry ground equipment", *J. Brit.I.R.E.*, 21, pp. 57-67 and 69-77, January 1961.

† Bristol Aircraft Ltd., Filton House, Bristol.

in binary milliseconds. The tape is played through once for each channel for which cards are required, and each "pack" of cards produced relates to one parameter only.

A graphical output is obtained by use of a 25-channel galvanometer trace recorder, producing a record on 6 in. wide paper film. Up to 6 parameters may be presented on one film record, together with a set of time ordinates derived from the 100 kc/s reference, and a marker for the "instant-of-fire pulse".

A digital-to-analogue converter has been constructed which, in conjunction with the card punch, provides the facility for converting the parameter values punched on any set of cards, to an analogue voltage suitable for display on the galvanometer trace recorder.

4.3. Sync. Separator

The voltage histogram from the frequency discriminator has a synchronization channel producing a voltage level outside the range occupied by the remaining 23. This level is recognized by an amplitude discriminating circuit in the sync. separator, and its appearance used to trigger a pulse generating circuit.

4.4. Channel Separation Equipment

The voltage histogram consists of 24 d.c. levels which correspond to the state of the 24 channels sampled by the time-multiplexing switch in the missile. The purpose of the channel separator is to separate or "strobe out" individual channels. For each separated channel, a memory circuit stores the last input voltage until reset by the next sample. The pulse which allows

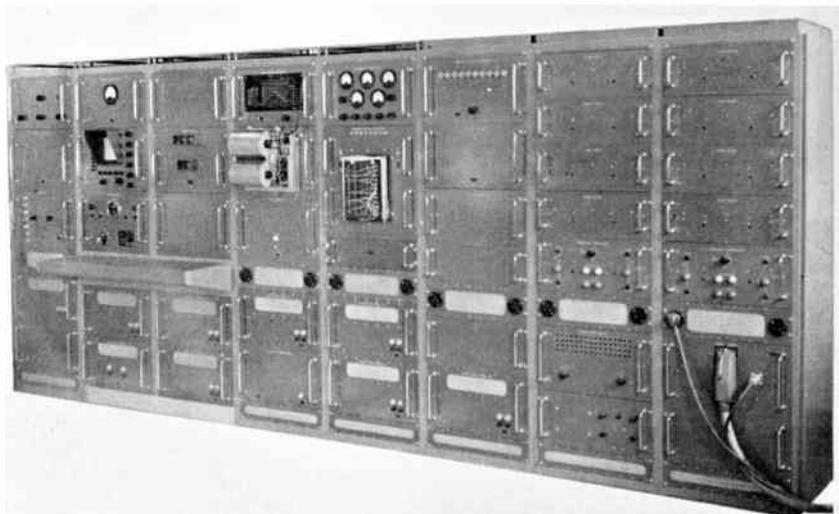


Fig. 1. The complete equipment. Tape replay deck and card punch are not included.

4. Outline of System

A photograph of the complete equipment is shown in Fig. 1, and a block diagram in Fig. 2. This shows the interconnection of all units, and should be referred to when reading the detailed description of units.

4.1. Tape Replay Deck

The player used with this equipment is a $\frac{1}{2}$ in. multi-track machine running at 15 in./sec.

4.2. Frequency Discriminator

The frequency-modulated information appears on one of the output sockets of the tape replay deck and is connected to the input of the frequency discriminator. The output from this unit is a direct voltage accurately proportional to input frequency and is referred to as the "voltage histogram".

a particular memory circuit to reset is known as the strobe pulse and is also used to brighten the trace of the histogram display tube to indicate which channel is being separated.

Six separating circuits are provided in the equipment so that up to six data channels can be recorded simultaneously on the galvanometer trace recorder.

4.5. Histogram Display Unit

This unit incorporates a double-gun cathode ray tube with a time base initiated by the sync. pulse. The voltage histogram is displayed on one trace and a square wave derived from the 100 kc/s reference signal on the other.

Six potentiometers are provided on this unit to adjust the positions of the six strobe pulses on the voltage histogram.

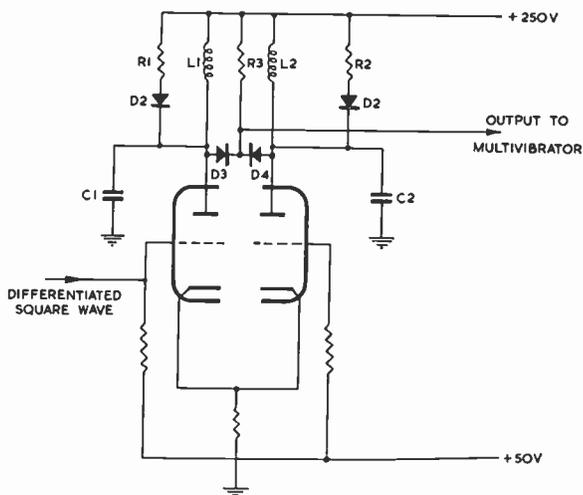


Fig. 6. Damped ringing stage of the frequency discriminator.

4.14. Digital-to-Analogue Converter

This unit takes an 8-line binary input from the card punch, and uses the changing voltages on the lines to operate 8 relays. Each relay short-circuits or open-circuits one resistor in a series chain carrying a constant current. The output is taken from the ends of this chain, and fed to one galvanometer in the galvanometer trace recorder as a means of checking the validity of the punched information. Figure 3(b) shows a portion of a film record produced in this way, the original analogue record, Fig. 3(a), being shown for comparison purposes.

5. Detailed Description of Units

5.1. Frequency Discriminator

A block diagram of this unit is given in Fig. 5. The input signal produced by the tape replay deck is connected to the first of two squaring amplifiers, the output from the second being a square wave of unity mark/space ratio.

The square wave is differentiated and connected to the grid of a double triode having tuned circuits as anode loads. The circuit diagram of this stage is shown in Fig. 6. In the absence of the damping resistors R1 and R2, each triode valve would produce a train of damped oscillations on the arrival of each input pulse. The damping resistors and the diodes D1 and D2 however, permit only a single positive half cycle of ringing, negative half cycles being heavily damped by the resistors R1 and R2. When the input signal to this stage steps positively the tuned circuit, L2, C2, executes a half cycle of ringing and when the input signal steps negatively L1 and C1 perform in the same way. The signals at the two anodes are added together

in the common resistor R3 via the isolating diodes D3 and D4. The output from the stage thus consists of a series of positive pulses, one for each half cycle of input frequency, whose shape depends on the properties of the two tuned circuits and not on the shape of the original waveform from the tape playback amplifier.

These positive pulses are differentiated and the resulting negative-going portions clipped by a diode. The positive pulses are almost constant in shape and area over a wide range of input frequency and amplitude, and are used to trigger a monostable multivibrator. It is essential that the rectangular pulses produced by this stage are constant in amplitude and width, and special precautions are taken to achieve this. The circuit consists of two triodes with feedback derived from a common cathode resistor. Coupling between the valves is via a cathode follower and the output waveform is clamped between two d.c. voltage levels to ensure constant amplitude.

The output from the multivibrator is connected to the first of two low-pass filters. Integration of the pulses takes place within the filter and the d.c. level adjustment is performed here, by adding a steady voltage derived from a neon stabilizer.

The d.c. output from the first filter is amplified, filtered again and finally amplified to produce the required sensitivity. The filter constants are chosen so that signals at multivibrator frequency are heavily attenuated, but level response over approximately 0.6 of a channel width is achieved.

5.1.1. Performance of the frequency discriminator

Input amplitudes between 0.25 V and 50 V peak-to-peak at constant frequency result in constant discriminator output voltage.

The output ripple and noise is less than 0.1% of the normal output voltage range.

In the working frequency range the maximum non-linearity, i.e. the maximum departure from the mean straight line, expressed as a percentage of the full output voltage range is less than 0.3%.

Under operating conditions in the equipment the drift observed in 24 hours was 0.4% of the full output voltage range.

5.2. Sync. Separator

This unit consists of a comparator whose inputs are respectively the voltage histogram and a fixed reference voltage. The overall level of the voltage histogram is set so that the comparator is operated only when the synchronization channel is present.

The operation of the comparator is used to generate a sync. pulse which forms the output of the unit.

5.3. Channel Separation Unit

5.3.1. Time-base and reference voltage generators

A total of six channels can be separated or "strobed out" by this unit, a block diagram of which is given in Fig. 7. The portions shown in the upper part of the diagram supply two outputs which are common to six identical separating circuits. Only one of these circuits is shown in full schematic form.

The sync. pulse is used to trigger a monostable multivibrator circuit with a short time-constant. The trailing edge of the output pulse from this stage is used to fire a gas-filled triode which momentarily applies a short circuit to the capacitor C1. This capacitor completes a feedback loop round the high-gain amplifier A. The input to the amplifier is a negative voltage and its output voltage therefore rises with a constant slope.

The arrival of each sync. pulse restores this voltage to zero so that the output of the amplifier A is a time-base waveform which provides one of the two inputs required for the six separating circuits. This waveform is also used as a time-base for the cathode-ray tube in the display unit.

The capacitor C2 charges to the peak voltage reached by the time-base waveform through the upper diode shown in Fig. 7, and a unity gain amplifier holds

this voltage until the arrival of the next sync. pulse. When this occurs the leading edge of the multivibrator output generates a negative pulse which partially discharges C2 through the lower diode. This arrangement allows the voltage across C2 to follow an increase of sync. repetition frequency and hence a reduced time-base amplitude. The peak time-base voltage forms the other common input to the six separating circuits and is known as the reference voltage.

5.3.2. Separating circuits

The reference voltage supplies six helical potentiometers whose settings determine the particular channels to be separated. For convenience, these potentiometers are situated in the histogram display unit but properly form part of the separation circuits. They are known as "strobe-setting" potentiometers. In the following discussion one separating circuit only will be considered, the others being identical.

The voltage on the wiper of the strobe-setting potentiometer is compared with the rising time-base waveform in a comparator. The output voltage of the comparator steps positively as equality of the two inputs is reached. This voltage step is sharpened by a Schmitt trigger circuit and is used to trigger a monostable multivibrator.

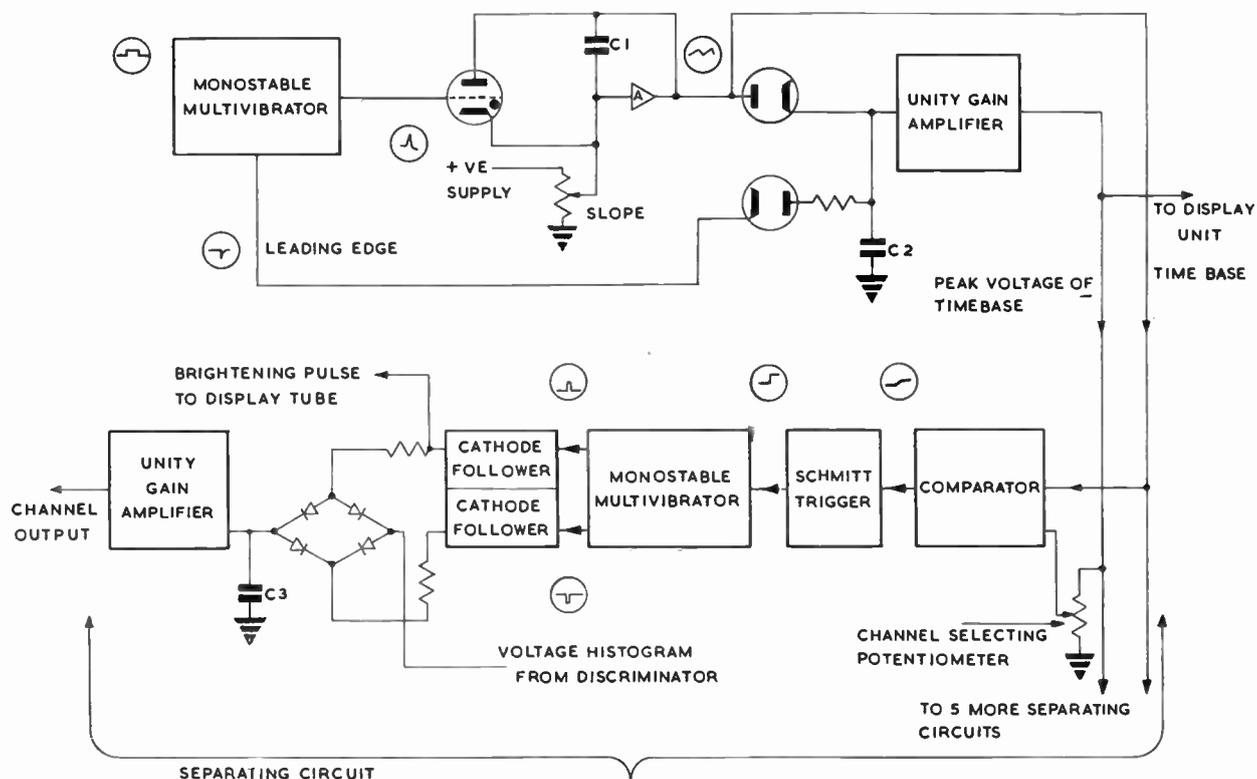


Fig. 7. Block diagram of the channel separator.

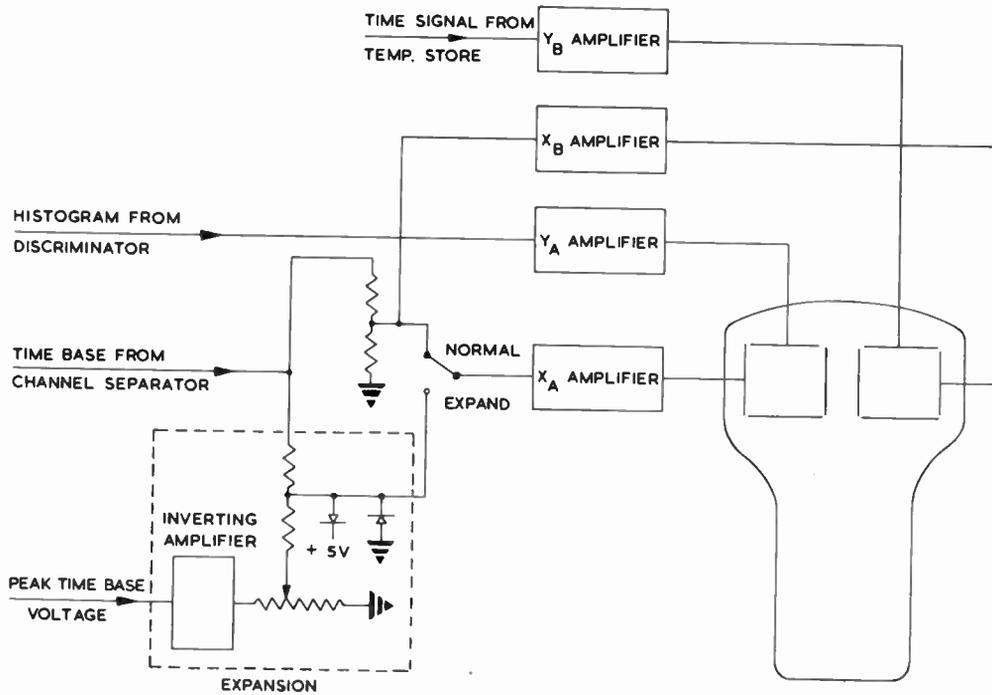


Fig. 8. Block diagram of the histogram display unit.

At the moment of equality of the comparator input voltages, short positive and negative pulses are obtained from the multivibrator and these are connected through cathode followers to a four-diode gate. It will be observed that for a given position of the strobe-setting potentiometer the multivibrator pulses will occur at a fixed fraction of the time between sync. pulses.

While the pulses from the cathode followers are present, all four diodes are conducting and there is a low-impedance path from the line carrying the voltage histogram signal to the capacitor C3. This low-impedance path is present for approximately one-quarter of a channel width, and it allows C3 to charge to the level of the voltage histogram at that time.

This voltage is stored by the capacitor and unity gain amplifier between strobing pulses. The final channel output is therefore a series of discrete voltage levels which are reset to the new value of the channel at each histogram cycle.

5.4. Histogram Display Unit

This unit incorporates a double-gun cathode-ray tube on which is displayed the voltage histogram and a square wave derived from the 100 kc/s timing reference signal. A block diagram of the unit is shown in Fig. 8.

The voltage histogram is brightened by pulses derived from the channel separators, and the square wave timing signal has a marker indicating the time of occurrence of the "read time" pulse generated in the pulse generator unit. All four pairs of deflection plates are supplied from amplifiers incorporating gain and shift controls.

The brightening pulses produced by the six channel separators are added and used to modulate the grid potential of the tube assembly displaying the voltage histogram. To assist in accurate setting of the brightening pulses, any desired portion of the voltage histogram trace may be expanded.

The time-base developed in the channel separator supplies the X deflection for the square wave timing signal and, when the NORMAL-EXPAND switch is set to normal, the X deflection for the voltage histogram. For this purpose the time-base is connected to a potential divider and reduced in amplitude.

The peak value of the time-base is held in the channel separator and this voltage is used in the histogram display unit as a reference for the expansion circuitry. It is first inverted so that it becomes a negative voltage, equal and opposite to that of the peak time-base amplitude. The output from the inverting stage is connected to a chain of 24 resistors shown as a potentiometer in Fig. 11. Depending on the portion

of the voltage histogram that is to be expanded, an appropriate fraction of the voltage is tapped off the resistor chain and connected through two high value resistors to the line carrying the time-base waveform. When the time-base reaches a reference voltage equal and opposite to that tapped from the resistor chain, the voltage at the junction of these two resistors passes zero and the cathode-ray tube trace commences to move. As the full time-base amplitude is now in use, the spot moves rapidly across the screen, giving an expansion of the portion of voltage histogram present at the time. Two diodes limit the excursion of the expanded waveform to a safe value.

The use of the peak time-base voltage as a reference ensures that when the time-base amplitude changes, due to changes in the missile switch-motor speed, there is no change in the portion of the voltage histogram which is expanded.

5.5. Galvanometer Trace Recorder

The unit is a commercially available 25-channel galvanometer trace recorder. The galvanometers used are critically damped and have a response which extends up to about 200 c/s.

The camera is built into a rack-mounted tray which incorporates suitable drive amplifiers with zero-shift

and sensitivity controls. A number of film speeds are available, which can be selected by changing gears and/or manipulating a 10 : 1 reduction switch.

5.6. Sub-channel Separator

The five standard reference signals which are transmitted for overall gain and level correction are normally accommodated by a single channel. This channel is used to telemeter the output of a low-speed, twelve-position switch in the missile, which samples the five standards in a prearranged sequence.

The purpose of the sub-channel separator is to separate the individual standard voltages from the output of the standards channel and to present these voltages on individual continuous low impedance outputs.

It is by no means always the case that any of the five standards occurs once only per cycle of the low-speed switch, and hence amplitude selection as a means of synchronization is denied. The method of synchronization used is that of recognizing a pattern of five consecutive voltage steps, and driving a twelve-position switch in contact-to-contact synchronism with the airborne switch.

A block diagram of the unit is given in Fig. 9. The circuit may conveniently be divided into three parts,

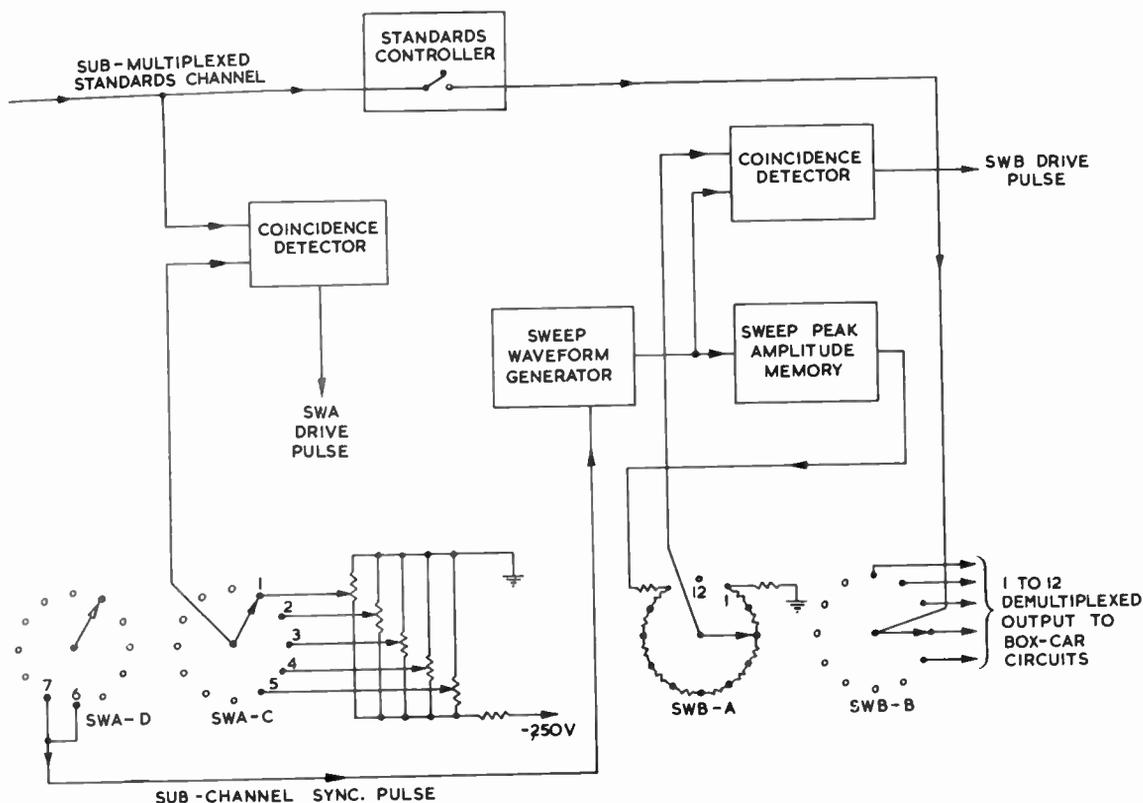


Fig. 9. Block diagram of the sub-channel separator.

“sync. generator”, “strobing circuits” and “standards controller”.

5.6.1. Sync. generator

This “looks for” a known pattern of standard voltage steps and when this pattern occurs, a sync. signal is developed at the end of the pattern.

The five potentiometers connected to SWA-C are first set to give voltages approximately equal and opposite to five consecutive voltages produced by the channel employed for the standards. When the two inputs to the coincidence detector are equal or nearly equal, but opposite in sign, a relay releases and energizes the drive coil of SWA. If the inputs are not equal and opposite, there is no path for the drive coil in the coincidence detector.

Assume that SWA is at position 1. When standard 1 appears on the submultiplexed data channel input, the coincidence detector will have equal and opposite inputs and hence will energize the drive coil of SWA. This will advance the switch to position 2 and so alter the input to the coincidence detector, so that the coil of SWA is de-energized. SWA will now wait at position 2 until standard 2 appears, when it will advance to position 3. This process continues for standards 3, 4 and 5.

When standard 5 appears, SWA will move to position 6. At positions 6 and 7, SWA is unstable as it is energized through its interrupter. It therefore moves quickly past positions 6 and 7 to position 8, and is then stepped slowly over positions 8 to 12 to position 1 where it waits until the next time standard 1 appears.

“Sub-channel sync.” signals are taken from positions 6 and 7 of SWA-D, and SWA-E.

5.6.2. Strobing circuits

The sync. signal generated by SWA-D is used to initiate a linear sweep waveform. A second 12-position switch SWB waits on position 12 until it is moved to position 1 by the sub-channel sync. pulse, after which it moves one step every time this sweep waveform reaches equality with the voltage picked off a 12-resistor chain connected round one of its wafers. The chain is supplied by a d.c. voltage equal to the previous maximum excursion of the sweep waveform, and as this is reset by the sub-channel sync. signals, the stepping speed of SWB is automatically adjusted so that SWB runs in step-to-step synchronism with the missile sub-multiplexing switch. SWB-B is used to demultiplex the incoming signal on to separate output lines, circuits similar to those used in the channel separator being employed to “box car” the output samples.

5.6.3. Standards controller

This unit prevents the acceptance of erroneous values of the standards which may arise, for example, when there is a temporary loss of synchronizing pulses on the voltage histogram. When this occurs there may be a gap in the pattern sought by SWA and up to three complete cycles of SWA may be necessary before SWB is again in proper synchronism. The standards controller prevents the incorrect routing of the standard values during these three cycles.

The unit functions by comparing the proposed new value of a standard with the previously recorded value; if the difference is less than 5% the switch shown in Fig. 9 closes and the new value is accepted. If the proposed new value differs by more than 5% from the previously recorded value, the switch remains open and the new value is rejected.

In order to start the operation there is an overriding manual control which closes the switch until the correct standard levels have been established.

5.7. Analogue-to-Digital Converter †

This unit performs three prime functions.

- (1) The conversion of the analogue voltage representing each data sample to an 8-digit binary number.
- (2) The automatic continuous correction of this number by reference to the five standard levels.
- (3) Compensation for the transducer characteristic so that the binary number produced by the unit is a linear representation of the original quantity.

A subsidiary function of the unit is the production of a reconstituted analogue record by summing the binary outputs in a digital-to-analogue converter. The reconstituted analogue voltage will thus be linearized and corrected for gain and level variations and allows linearized records to be produced by the galvanometer trace recorder.

A simplified block diagram of the unit is shown in Fig. 10. The five standards are connected by means of a plug-board to five points on a resistor chain. An electronic switch steps up the chain, producing a staircase waveform in which the amplitudes of the steps are dependent on the voltage gradients in the resistor chain, due to the connections of the standards. This staircase waveform is compared with the data input voltage. When equality is reached, a signal from the

† G. C. Henderson, “A special purpose analogue-digital converter”, *Electronic Engng*, 32, pp. 602–8, October 1960. (A paper based on this article and entitled “Cavalcade—an analogue-digital converter for data handling” was read at the South Western Section Convention on “Aviation Electronics and Its Industrial Applications” in Bristol.)

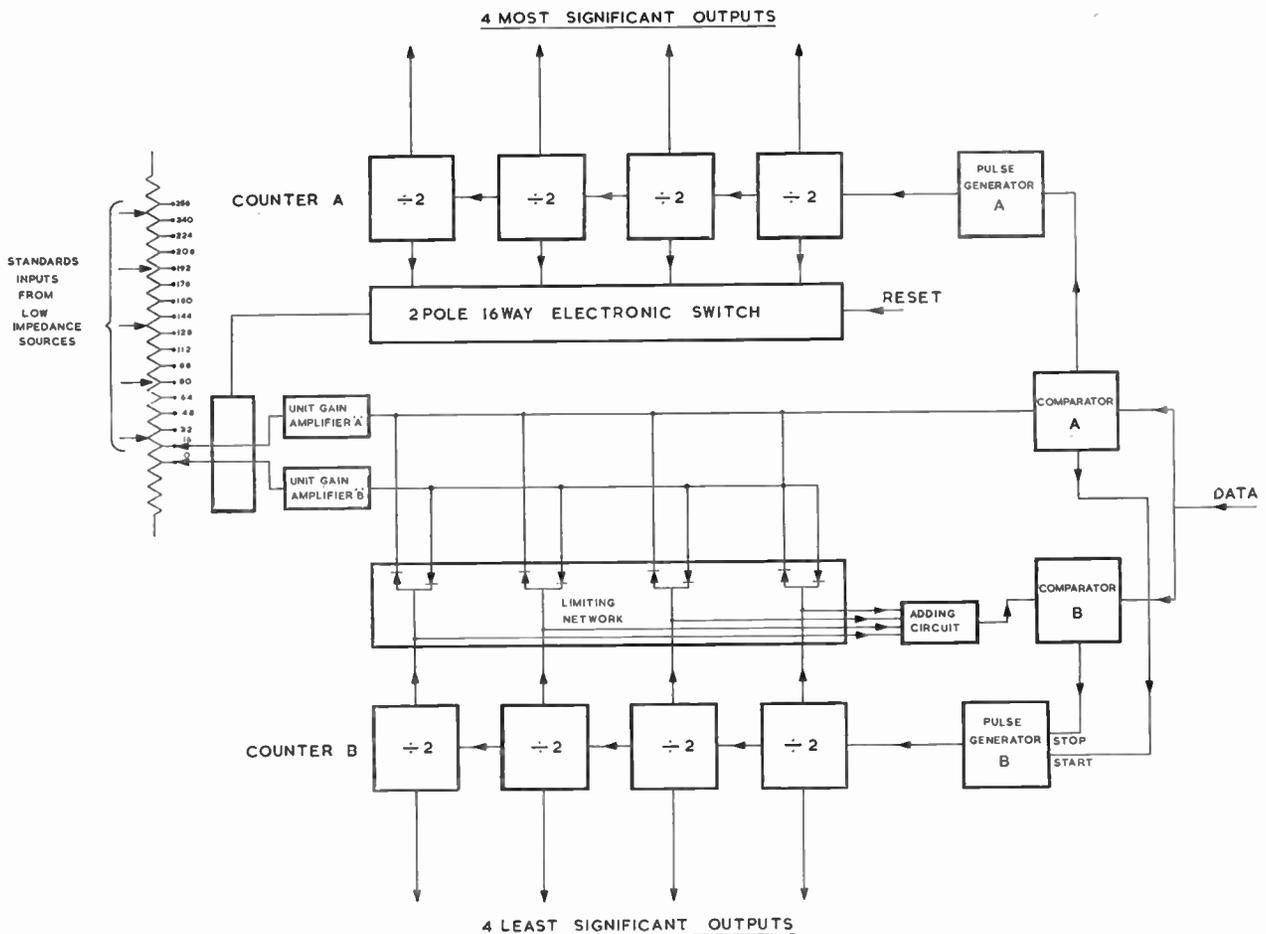


Fig. 10. Block diagram of the analogue-to-digital converter.

comparator stops the stepping action and a binary counter records the number of steps taken. The reading given by the binary counter is then a digital representation of the data input voltage.

5.7.1. Details of operation

An accuracy of $\frac{1}{2}\%$ is required from the unit so that 8 binary digits are needed. It would appear, therefore, that 256 tappings must be made on the resistor chain and that a single-pole, 256-way, electronic switch would be required. In fact, only 17 tappings are taken from the resistor chain, and a "high-gear" and "low-gear" operation takes place using a 2-pole, 16-way, electronic switch.

At the start of the operation all the counters are at zero, the comparators are in their "off" position, and the electronic switch is at the bottom of the chain.

Pulse generator A then supplies input signals to the four-stage counter A causing both poles of the electronic switch to step up the resistor chain. Pulse generator B is not allowed to function until comparator A has operated.

When the upper pole of the switch reaches a point in the resistor chain where the potential is equal to or greater than that of the data input, comparator A operates, stopping pulse generator A and starting pulse generator B.

Pulse generator B supplies counter B with pulses, but in this case the outputs from the counter are limited between the voltages present on the two poles of the electronic switch. After suitably adding the limited outputs from counter B, a staircase is produced in which the height of each step is one sixteenth of the potential difference between the poles of the electronic switch.

When equality is reached between this staircase voltage and the data voltage, comparator B operates and stops pulse generator B, thus completing the action.

The state of the binary stages in counter A reveals the number of "large steps", and that of the binary stages in counter B the number of small steps, which have been taken. As a small step is $\frac{1}{16}$ th of a large

step, the data input voltage may be represented by any of 256 binary numbers. Counter A supplies the four most significant digits and counter B the four least significant.

It will be seen that if an overall change in gain or level occurs, affecting the standards and data voltages in the same proportion, this will not affect the *number* of steps recorded although the heights of the steps will be different.

5.7.2. Sender non-linearity correction

In Fig. 10 the standards are shown connected at equal intervals to the resistor chain. This is not necessary to the operation and in fact suitable placing of the five standards in the resistor chain introduces a non-linearity in the conversion which can easily be made the inverse of the sum of transducer and modulator non-linearity.

To obtain a better approximation to a non-linear transducer characteristic, six auxiliary standards are generated in the unit. Four of these are termed internal auxiliary standards and give voltages mid-way between the five existing standard voltages. The other two auxiliary standards are external to the existing standards, and produce voltages greater and lower respectively than the outer main standards, by an amount equal to the potential difference between the outer main standards and their adjacent main standards. For example, if the original five standards are represented by voltages of 20, 30, 40, 50 and 60 V, six auxiliary standards are generated having voltages of 10, 25, 35, 45, 55 and 70 V. For simplicity, the auxiliary standards are not shown in Fig. 10.

To correct a transducer characteristic we require a calibration curve for the transducer taken before flight, showing modulator frequency plotted against input quantity, and a set of frequencies which were those given by the five standards at the time of the transducer calibration (Fig. 11). The transducer input quantity is first rescaled bearing in mind that the digital number finally produced must lie between 0 and 255. The five standard frequencies and their calculated auxiliary frequencies are marked on the frequency ordinate and horizontal lines produced from these points to meet the curve. Perpendiculars are then dropped from the points of intersection to the rescaled input quantity axis. The number indicated by the foot of any perpendicular gives a numerical indication of where that standard should be connected in the resistor chain. The connection to the resistor chain is by means of a plug board into which each standard can be plugged with a positional accuracy of half of one digit, and which is scaled with numbers corresponding to the numbers on the rescaled input quantity axis. All that is necessary, therefore, is to connect the 11 standards to sockets on the plug board bearing the numbers

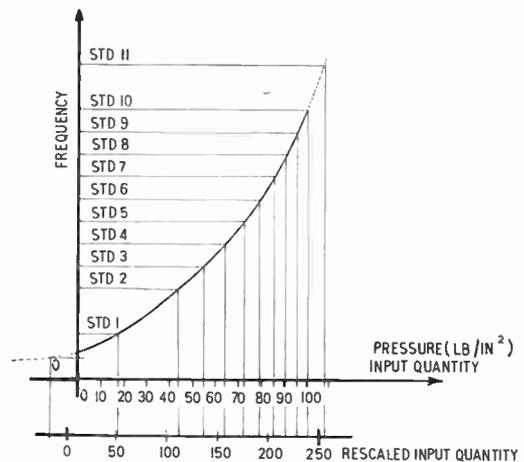


Fig. 11. Calibration graphs.

indicated by the feet of the perpendiculars on the rescaled input quantity axis.

5.8. Time Counter and Elapsed-time Counter

This unit receives the 100 kc/s timing signal recorded on the centre track of the tape and divides it to provide pulses at suitable frequencies to the camera and pulse generator. It also contains a transistorized 20-stage binary counter, the outputs of which are ultimately used as a measure of the time in milliseconds, from the "instant of fire", at which each data sample occurs. The instant of fire is recorded on the tape as a discontinuity in the timing signal; this discontinuity is recognized and a pulse is generated which resets to zero the 20-stage counter and the significant frequency dividers.

The elapsed time counter incorporates an in-line numerical display indicating seconds in tens and units. It continually counts 1-second pulses derived from the 100 kc/s timing signal unless manually zeroed by the operator.

A block diagram of the unit is given in Fig. 12. The 100-kc/s timing reference signal is initially amplified by the tape playback amplifier and is then connected to two tuned amplifiers. The upper tuned amplifier selects and squares the continuous timing reference signal while the lower tuned amplifier recognizes the discontinuity which occurs at the instant of fire. A pulse is generated which operates a latching bistable circuit preventing the acceptance of spurious discontinuities in the event of unexpected irregularities of the timing signal while the missile is in flight.

The operation of the latching circuit gives rise to a number of effects:

- (1) The 20-stage binary counter is reset to zero.
- (2) The significant frequency-dividing stages are reset to zero.
- (3) A marker galvanometer in the galvanometer trace recorder is deflected.

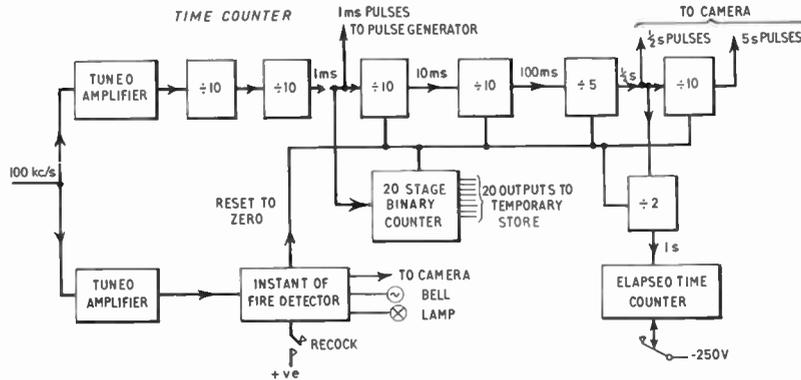


Fig. 12. Block diagram of the time counter.

- (4) A lamp glows on the front panel of the unit indicating that the bistable circuit is latched. This forms a reminder to the operator that he must manually reset the circuit before the instant-of-fire detector can be used again.
- (5) A bell rings for a short time warning the operator that if he wishes the elapsed time counter to register time from the instant of fire, he must zero that unit by depressing the push-button provided. Five seconds are allowed for him to do this without inaccuracies occurring in the indicated time. He therefore has sufficient time to note the number of pre-flight seconds before resetting the elapsed time counter to zero.

The above functions ensure that:

- (1) The times punched on the cards are measured from the instant of fire.
- (2) The time ordinates recorded by the galvanometer trace recorder date from the instant of fire.
- (3) The instant of fire is easily identified on the film record produced by the galvanometer trace recorder.

5.9. Temporary Store

This unit is effectively two buffer stages, one between the time counter and the main store, and one between the analogue-to-digital converter and the main store.

In the case of the time counter outputs, the time counter is never stationary for the period necessary to set up a main store row (about 10 ms), and also the time counter output stages are incapable of operating a main store relay.

Although the analogue-to-digital converter outputs are stationary for the required time, it was found convenient to use extra temporary store stages rather than incorporate suitable relay drive output devices in the converter itself.

The unit consists of one bistable transistor circuit for each binary digit. Each stage can be triggered by the output of an "and" gate, the inputs to this gate being a "read" pulse from the pulse generator, and a digit signal on the input line from the time counter or analogue-to-digital converter.

A "reset" line is common to all stages. Figure 13 shows the circuit of one stage. VT1 and VT2 form the AND gate, VT1 being shared by several stages. Normally, the bases of VT1 and VT2 are near earth potential, VT2 and VT4 are cut off, and VT3 is conducting.

When negative signals are applied to the bases of VT1 and VT2, VT2 collector will step positively to near earth potential, producing a positive pulse at the base of VT3 via MR1, which initiates the cumulative changeover action leaving VT3 cut off and VT4 conducting. VT4 will now supply an earth to the particular main store relay to which its collector is connected at this instant.

MR3 allows the stage to be reset even when the main store relay is latched in, the 220-ohm resistor serving as a protection against an overload condition which can occur during checks.

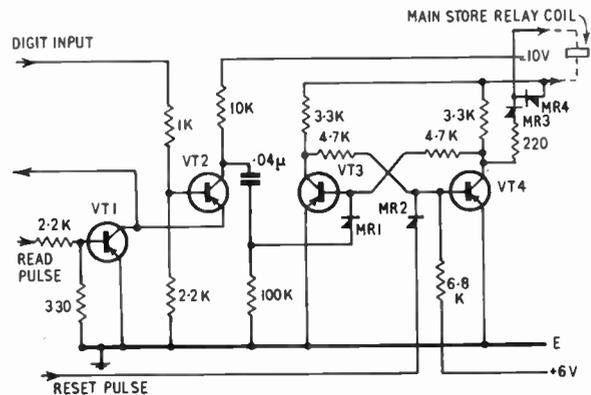


Fig. 13. Circuit of the temporary store—one stage.

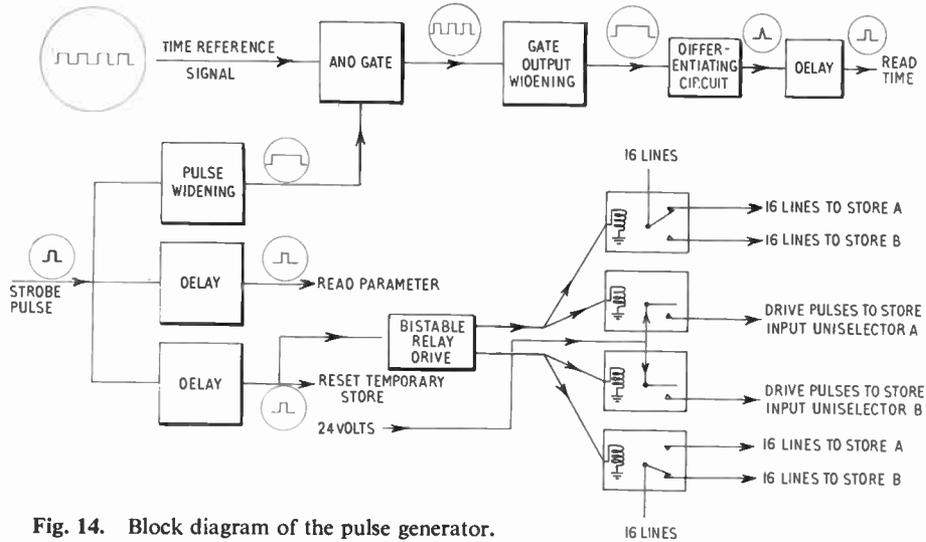


Fig. 14. Block diagram of the pulse generator.

MR4 limits the back e.m.f. which occurs across the main store relay coil when its supply is broken.

The stage is reset by a positive pulse on the base of VT4 via MR2.

5.10 Pulse Generator

Figure 14 shows a block diagram of this unit, the functions of which are as follows:

- (1) Generation of the "read time" pulse. This pulse must occur during the first stationary period of the time counter, after the appearance of the strobe pulse.
- (2) Generation of the "read data" pulse. This must lag behind the strobe pulse by a period sufficient for the completion of the analogue-to-digital conversion cycle.
- (3) Generation of the temporary store reset pulse. This pulse must lag behind the "read data" pulse by a period sufficient for the operation and latching of the main store relays.

(4) Operation of the changeover relays, which switch the 32 information lines to stores A and B alternately.

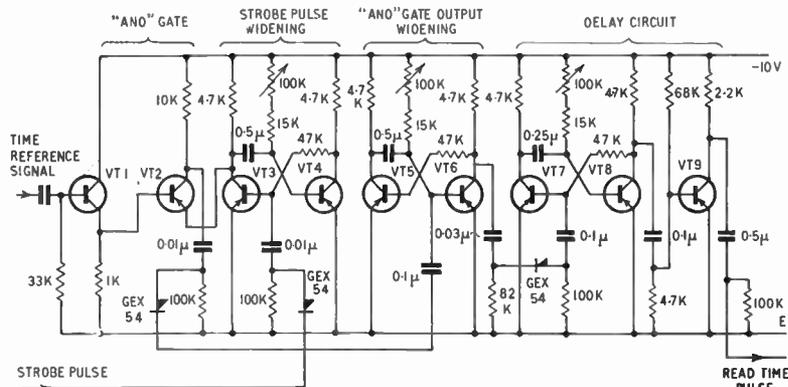
(5) Generation of the pulses which advance the main store input uniselectors.

The unit is supplied with the frequency-divided time reference signal and with the strobe pulse appropriate to the channel from which a digital output is required.

To generate "read time" pulse, the circuit shown in Fig. 15 is employed. The negative-going strobe pulse is applied to a pulse-widening circuit consisting of VT3 and VT4, a widened and inverted pulse appearing at the collector of VT3. This is applied to the emitter of the gate transistor VT2, allowing it to conduct and amplify a few cycles of the time reference signal. This signal is applied to the base of VT2 via the emitter follower VT1.

The gated portion of the timing signal is applied to another pulse-widening circuit VT5 and VT6, which operates on the first negative-going edge of the gated waveform.

Fig. 15. Circuit diagram of the "read_time" pulse generator.



The new widened pulse is differentiated and operates a delay circuit, VT7, VT8, VT9, the delay being sufficient to ensure that the resulting pulse always occurs during positive half-cycles of the time reference signal. Similar techniques are used to delay the strobe pulse in order to produce the "read data" and temporary store "reset" pulses.

The "reset" pulse is also used to operate a bistable transistor circuit, having two power output stages driving groups of relays. These groups are energized alternately, their states changing with the arrival of each reset pulse. Each group consists of eight relays operating double pole changeover contacts, switching 16 information lines between stores A and B, and one relay operating a heavy-duty single make contact, switching 24 volts to the input unselector drive coils in one of the stores.

Reference to Fig. 16 will show that the input unselectors and the changeover relays only operate between "reset" and "read" pulses at the temporary store.

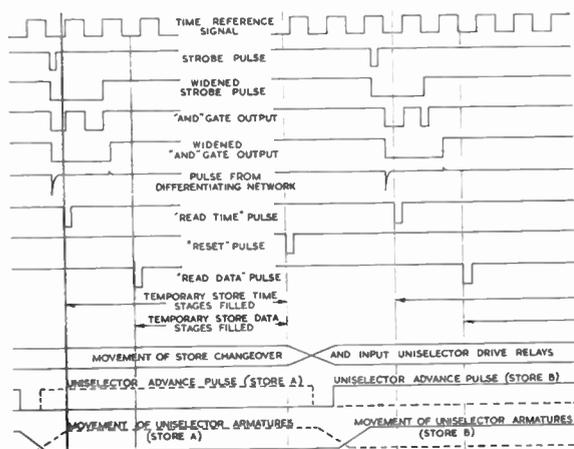


Fig. 16. Waveforms in the pulse generator.

5.11. Main Store Blocks

There are eight store blocks in the complete equipment, four in store A, four in store B. Individual blocks form eight-column, twelve-row stores, so that the entire main store has 64 twelve-row columns. Each block consists fundamentally of two eight-pole, twelve-way switches, one for input and one for output, respectively setting up and monitoring the state of 96 conditionally latched relays.

Figure 17 is a simplified diagram of one store block. Digital information is fed into the store on eight lines. Presence of a digit on any line is indicated by its connection to a low impedance source within one or two volts of earth level. Absence of a digit is indicated by a relatively high impedance connection between this line and the -24 volt supply.

Each of the eight lines is connected to the wiper of one bank of the input 8-pole 12-way switch. This switch, and the similar one used for the output circuits, is a 9-bank 25-way unselector. In both cases, on each of the eight banks used for information, contact 1 is connected to contact 14, contact 2 to 15, etc., up to 12 to 25. Contacts 13 on these banks are left blank, and an arrangement is provided to make the wiper step quickly past this position.

Thus the switch is effectively a 12-way device, and as it rotates the eight information inputs are connected first to the eight contacts 1, then the eight contacts 2, etc.

The 96 information storing relays are arranged, electrically, in twelve rows of eight relays. Each relay operates a double-pole changeover contact set and has four external connections:

- (1) The coil return line, which is always connected to a 24-V supply line common to all 96 relays.
- (2) A conditional earth line for latching purposes, common to all 8 relays in a particular row.
- (3) An operating signal line, from one contact of one bank of the input unselector.
- (4) An output connection feeding -24 V to one contact of one bank of the output unselector, when the relay is energized.

The output unselector samples the output of the 96 relays, row by row, and feeds the information out on eight lines to the punch output unit.

5.11.1. Unselector stepping arrangements

The input unselectors in store A are advanced while the input unselectors in store B are stationary, and one row of store B is being filled. Then store B input unselectors are advanced while store A input selectors are stationary filling the next row of store A. This process continues until the stores are $\frac{7}{12}$ ths full, when the card punch is started, and the output unselectors in both stores move in synchronism feeding the stored information to the card punch and clearing the stores. In the worst case the last store row is only just filled before the output unselectors read and clear it.

The arrangements for advancing the store block unselectors are similar, and closely related, to those for the equivalent unselectors in the sequence controller units. It is therefore convenient to deal with all of these facilities at the end of the description of the sequence controllers.

The ninth bank of each unselector in the store blocks is employed for synchronization of stepping, feeding of motoring pulses, and detection and correction of asynchronous operation.

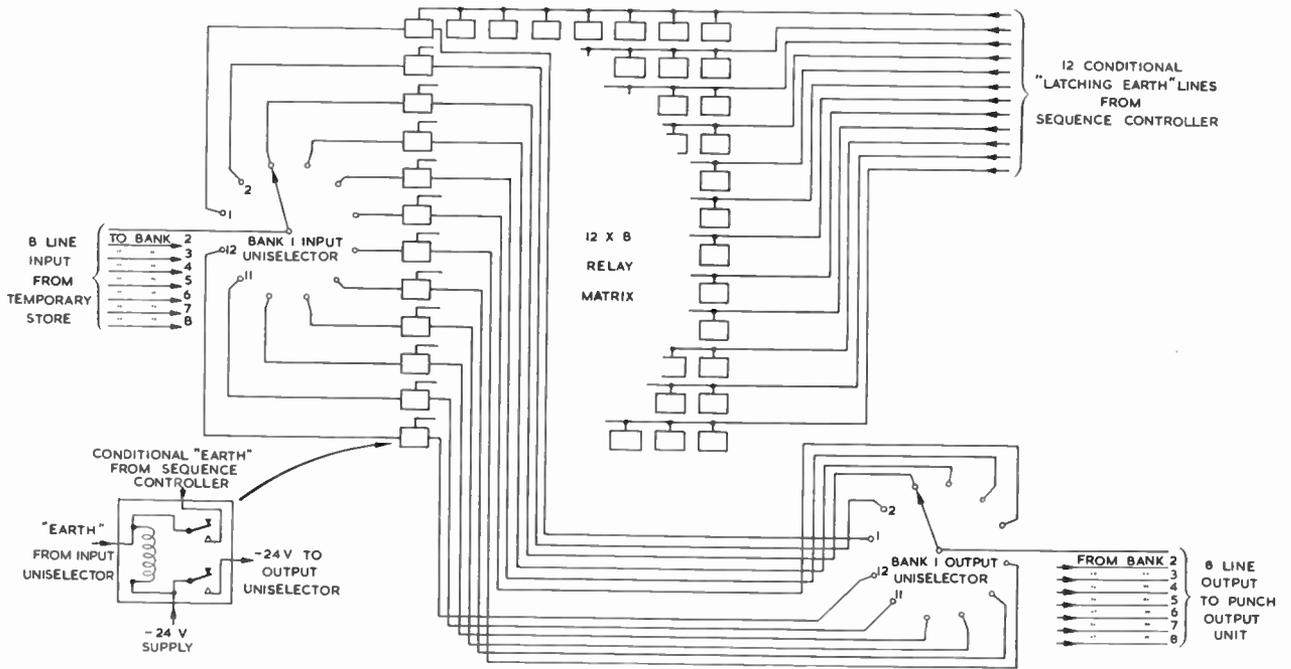


Fig. 17. Simplified diagram of one store block.

5.12. Sequence Controllers

There are two sequence controllers, one associated with store A, and one with store B. Each sequence controller has the following functions in its own store.

- (a) Detection, indication, and rectification of asynchronism in the input uniselectors.
- (b) Supply of "end of card" or "homing" signals to the output uniselectors, ensuring an "in-step" start to each punch-out cycle.
- (c) Provision for co-ordinated step-by-step manual advancement of the input uniselectors.
- (d) Provision of co-ordinated step-by-step manual advancement of the output uniselectors.
- (e) Supply of a "start punching" signal to the card punch when the stores are $\frac{1}{2}$ ths full.
- (f) Provision of clearing facilities for the store rows that have been read on any particular punch-out cycle.
- (g) Provision of visual indication when the input uniselectors are on contacts 1 or 14.
- (h) Provision of visual indication when the output uniselectors are on contacts 1 or 14.

In addition the sequence controllers co-ordinate the operation of the input uniselectors in stores A and B, so that store A is always half a step ahead of store B.

5.12.1. Uniselector stepping arrangements

Each sequence controller has an input and output

uniselector, which run respectively in step-by-step synchronism with the four input and four output uniselectors in the four associated store blocks. All the input uniselectors are advanced by pulses generated by the pulse generator and all the output uniselectors by pulses produced by cam-operated contacts in the card punch.

As all these uniselectors are running at near their maximum pulsed operating speeds and, in addition, have to jump rapidly over contact 13 in every case, errors in the form of lost steps and, very occasionally, gained steps occur from time to time on individual uniselectors.

The techniques developed for overcoming these faults are based on withholding the supply, which is needed for the rapid step over contact 13, from any uniselector which has gained a step; and supplying power for an additional rapid step over contacts 12 and 25 for any uniselector which has lagged one or more steps. The necessary supply switching is carried out on banks of the sequence controller uniselectors, and an extension of these techniques is used to ensure that store A is always half a step ahead of store B. As soon as any one uniselector drops out of step with the remainder, a visual indication is given, and a relay is operated which allows a hole to be punched on the card opposite each row of suspect information. Because of the high stepping speed, some difficulty was experienced in the design of these units, and although the resulting equipment is entirely electro-

mechanical, the final circuitry is of a fairly sophisticated nature.

5.12.2. Reliability

A recent test has demonstrated that an average of about one in five hundred samples is wasted because of faulty uniselector or store relay operation.

5.13. Store State Display

This unit is used mainly as a service and maintenance facility but a little experience will enable an observer to deduce useful information about machine performance during normal operation. Sixty-four lamps are arranged in four rows on the front panel, each lamp being connected to the wiper of one bank of an output uniselector in store A or B. Thus, as the output uniselectors read and clear the stores, a picture of the store contents is presented on the matrix of lamps.

5.14. Punch Output Unit

Each of the 64 output lines from the main store controls one relay in the punch output unit. The relays are used as single pole make switches, one side of all the contact sets being commoned.

As soon as the appropriate card row is stationary under the punch knives, the punch will generate a 40-V pulse. This pulse is applied to the common side of all the single pole make contacts, the other 64 poles being returned to the card punch and connected to punch magnets. During this time the output uniselectors will have been stationary on one row of the main store and any store relay, which is latched in, will have energized the appropriate relay in the punch output unit. This relay will return the 40 V pulse to one punch magnet, producing one hole in this row of the card.

5.15. Card Punch

The machine used is a modified I.B.M. Type 513 (see Fig. 18). In its modified form the machine consists of a card transport mechanism, transferring cards edgewise from a magazine to a stacker. *En route* the cards pass

- (a) a set of 80 punch knives.
- (b) a set of 80 "read" brushes.

The card motion is intermittent, each of the 12 rows remaining stationary under the punch knives and the read brushes for the time needed to punch holes.

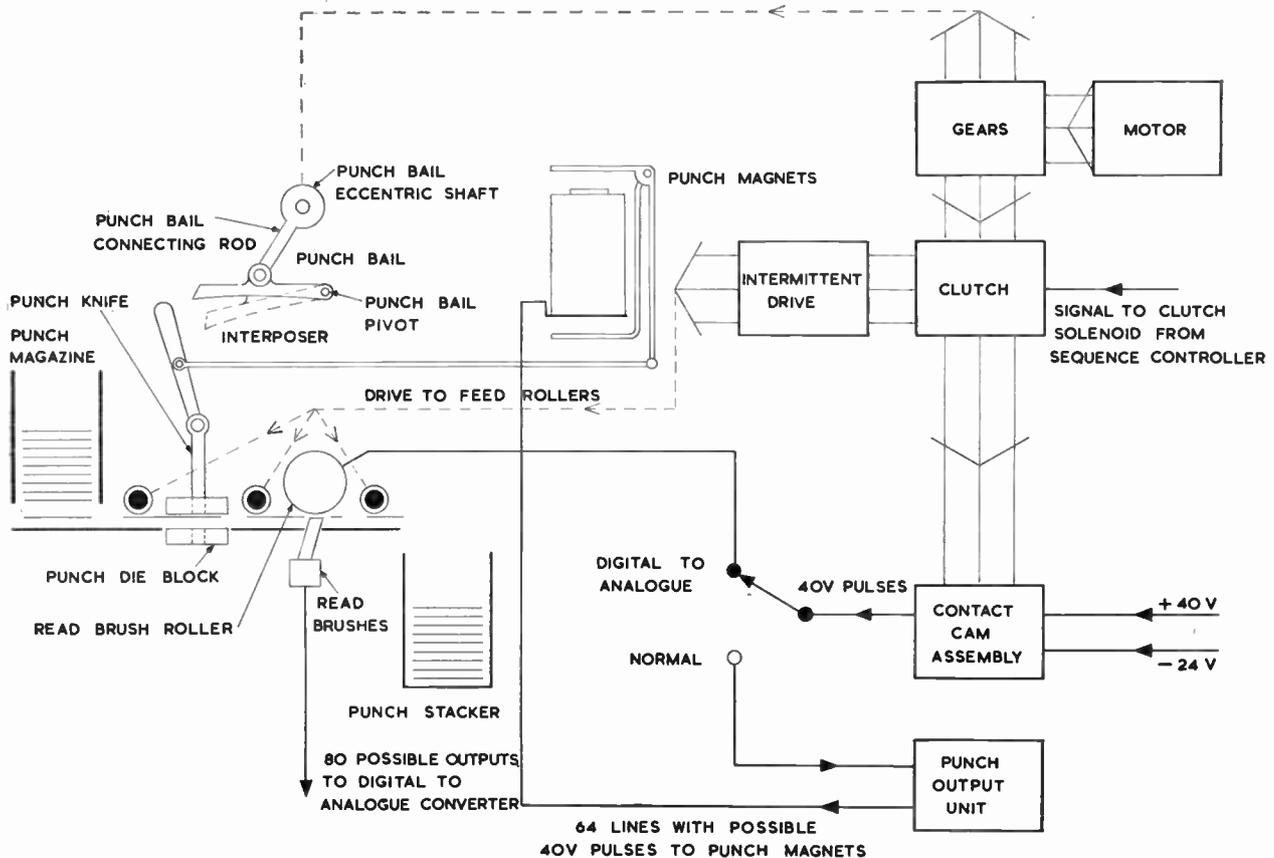


Fig. 18. The I.B.M. card punch Type 513.

Part of the drive gearing rotates continuously and the card transport mechanism is connected to this, when required, by a solenoid-operated dog clutch. Once this clutch has been engaged, the card transport mechanism will move one card cycle, i.e. one new card will leave the magazine and take up a position at the entrance to the punch knife station, the card which formerly occupied this position will pass under the punch knives and move to the entrance to the "read" brush station, and one card will pass under the "read" brushes and move towards the stacker.

A set of cams is geared permanently to the card transport mechanism and these are used to operate contacts, which supply:

- (a) 40-V pulses to the punch magnets via the punch output unit, or
- (b) 40-V pulses to the digital-to-analogue converter via the punch brush roller.
- (c) 24-V stepping pulses to the 10 output uniselectors.
- (d) Signals for the various protective and interlock circuits provided in the original machine.

The geometry of the solenoid operated clutch mechanism is such that the machine must wait 0 or any integral number of half card cycles between cards. Normally, the sequence controller energizes the clutch solenoid so that the machine waits one complete card cycle between cards. After several cards have been filled at this rate, the store filling begins to catch up with the store clearing, at which stage the "start punch" signal will arrive sufficiently early for the machine to wait only one half of a card cycle between cards. In this way the discrepancies in tape replay speed and card punching speed are accommodated.

6. Engineering

A standardized form of chassis construction is employed throughout the equipment.

The main features of this construction are:

- (1) The units can be withdrawn on telescopic runners, and remain operational in the extended position.
- (2) As far as possible, all wiring and small components are on the outsides of the units for ease of servicing.
- (3) The units are in box form, the centres being unobstructed except for valves and similar components. A chimney is thus formed, when all the units are in position, in which convection currents ensure a continuous flow of cooling air.

- (4) Wiring to each unit is originated on a set of terminal blocks on the frame of each rack and is conveyed via a hinged support assembly to appropriate plugs and sockets on the rear of each unit. A tabular documentation system for rack and support assembly wiring eliminates cumbersome drawing procedures and greatly facilitates the work of the service engineer.
- (5) Stocks of prefabricated chassis members, tag strips, etc., in a range of standard sizes, are held in store. Introduction of this system has resulted in a greatly reduced manufacturing time for many types of electronic assemblies.

7. Conclusions

This equipment has now been in service for more than twelve months, during which time a high utilization factor has been achieved. "Lost" machine time averages to a little over one hour per working day, about 40 minutes of this time is occupied by a routine daily performance check, the remainder being due to development of fault conditions during operation. It has been found possible to set-up the equipment and produce punched cards representing a complete telemetry record, containing up to a quarter of a million data points, in one day.

Practical tests show that the accuracy achieved is at least as good as that which can be achieved by manual reduction methods, and is probably better than the accuracy figure attained in manual working by a fatigued or bored operator. Various additional features have been incorporated to allow the equipment to be used for the reduction of other types of time-multiplexed data.

In particular, a digital graph plotter, handling an 8-line binary input at over 20 points per second, is to be incorporated. A prototype model is already in operation. Other proposals which are being actively investigated include the supply of a series of inputs to an analogue computer, for flight simulation, direct from the channel separator outputs, and the inclusion of a punched paper tape output facility.

8. Acknowledgments

The authors would like to express their appreciation of the help given by Mr. J. H. Russell and the encouragement of Bristol Aircraft Limited in the preparation of this paper.

Manuscript first received by the Institution on 15th March 1960 and in revised form on 27th September 1960 (Paper No. 621).

The Relative Magnitudes of Modulation Products in Rectifier Modulators and some Effects of Feedback

By

D. P. HOWSON, M.Sc.†

Summary: The various modulation products occurring in series, shunt and ring modulators are evaluated for square-wave switching of the rectifiers. It is assumed throughout that the modulator terminations are resistive, but not necessarily the same, at the frequencies of the modulation products; their value at other frequencies is, of course, immaterial. The case when the square-wave function has unequal mark/space ratio is discussed for each of the modulators when the terminations are constant resistances. Graphs are given of the ratios of the most important products for three common classes of termination. Finally, two feedback modulator circuits for use with rectifier modulators are examined, and it is shown that a knowledge of the relative magnitudes of the modulation products in these circuits enables effective designs to be made.

List of Symbols

$g(t) = \frac{1}{r(t)}$	r_0	constant term $\cos \omega_p t$ in Fourier expansion of $r(t)$.
$g_A(t) = \frac{1}{R + r(t)}$	r_n	coefficient of $\cos n\omega_p t$ in Fourier expansion of $r(t)$.
g_0	R	sum of source and load resistance.
constant term $\cos \omega_p t$ in Fourier expansion of $g(t)$.	R_0	value of R at frequency ω_q .
g_n	$R_{n\pm}$	value of R at frequency $n\omega_p \pm \omega_q$.
coefficient of $\cos n\omega_p t$ in Fourier expansion of $g(t)$.	R_s	source resistance.
h_0	R_R	load resistance.
insertion loss at frequency ω_q .	$s : 1-s$	mark/space ratio for square wave.
h_0'	v	load voltage.
insertion loss at frequency $\omega_p - \omega_q$.	V	source e.m.f.
h_1	$\rho = \sqrt{r_b r_f}$	
conversion loss for product $\omega_p - \omega_q$.	ω_p	switching or carrier frequency.
i_0	ω_q	signal frequency.
current at frequency ω_q .	$n\omega_p \pm \omega_q$	frequencies of modulation products.
$i_{n\pm}$		
product current at frequency $n\omega_p \pm \omega_q$.		
$r(t)$		
rectifier resistance.		
r_b		
reverse resistance of rectifier.		
r_f		
forward resistance of rectifier.		
$n = \sqrt{r_b/r_f}$		

1. Introduction

Previous papers on rectifier modulators have tended to devote themselves to the formulation of the conversion loss for particular circuit configurations. Whilst this factor is important, when the choice of a modulator circuit is to be made it is by no means the only consideration. In particular, it is useful to know the magnitudes of the unwanted products that will be produced by the modulator, so that adequate measures may be taken for their suppression. In addition, knowledge of these magnitudes enables the modulator to be tested more thoroughly, giving more confidence that it is working as intended. Therefore the present

paper was written in an attempt to provide more information than has been available hitherto, concerning these unwanted products. Throughout the paper the assumptions have been made,

- (i) that the circuits are linear, i.e. that the rectifier switching is controlled entirely by the carrier waveform,
- (ii) that the circuit impedances are resistive, although by the use of selective circuits these resistances may take different values at different product frequencies; they may also be zero or infinite at some frequencies.

The significance of these assumptions is discussed in Reference 1.

† Electrical Engineering Department, University of Birmingham

Throughout this paper it has been assumed that the applied signal frequency is ω_p , the carrier or switching frequency is ω_q , and the wanted modulation product $\omega_p - \omega_q$. This latter has been chosen in preference to $\omega_p + \omega_q$, which was used in Reference 1, since it lies between the two unwanted products ω_q and $\omega_p + \omega_q$, which are usually of the largest magnitude. Thus in general the design of a filter to pass $\omega_p - \omega_q$ will be more difficult than the design of one to pass $\omega_p + \omega_q$, and therefore the information provided in the following sections will be of more value. Obviously calculation of the unwanted products for $\omega_p + \omega_q$ as the wanted product could proceed in a similar manner to the following calculations.

2. Modulator with Square-wave Switching—Square-wave with Equal/Mark Space Ratio

Some of the properties of modulators with a square-wave resistance function of this type were discussed in References 1 and 2, and the present section is an extension of this work. Consequently, the detailed mathematics of the previous papers will not be reproduced here, the relevant equations and results being quoted where necessary. Throughout this section, the properties of the three common types of rectifier modulator—series, shunt and ring—are discussed via the medium of a single common circuit, as shown in Fig. 1. This, and the theoretical justification for it, were explained in Reference 1, and the notation used here is the same as that of the previous paper.

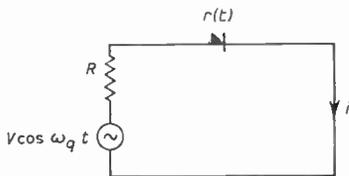


Fig. 1. Equivalent circuit for series, shunt and ring modulators.¹

$$R = R_s + R_R \text{ in series modulator}$$

$$R = \frac{R_s R_R}{R_s + R_R} \text{ in shunt modulator}$$

2.1. Terminations of Constant Resistance at All Odd-order Product Frequencies

From reference 1, equations (14), (18) and (19), we have

$$i_{n\pm} = \frac{-\frac{1}{2} V r_n}{(R+r_0)(R_0+r_0) - \frac{\pi^2 r_1^2}{16}} \dots\dots(1a)$$

and $i_{1\pm} : i_{3\pm} : i_{5\pm} \dots = 1 : \frac{1}{3} : \frac{1}{5} \dots\dots(1b)$

where R is the constant-resistance termination at all odd-order frequencies, and since $r(t)$ is a square-wave,

$r_n = r_1/n$. It was also shown in reference 1 that with this terminating condition, even-order modulation products (except of zero order, i.e. ω_q) are absent, and so the value of the terminations at even-order frequencies is immaterial.

Whatever the value of the resistive termination relative to the rectifier resistance, i.e. whatever the value of the conversion loss, the above-mentioned products are in the same ratio. However, i_0 is related to $i_{1\pm}$ by eqn. (14), reference 1, which gives

$$i_0 = \frac{-(R+r_0)i_{1\pm}}{\frac{1}{2}r_1} \dots\dots(2)$$

so that i_0 is a minimum with respect to $i_{1\pm}$ when R tends to zero. It might be expected, therefore, that, in the case where $\omega_p - \omega_q$ is the wanted product, and suppression of ω_q was proving troublesome, some relief might be afforded by making R tend to zero, at the expense of increased conversion loss. Actually it can be shown that the improvement is $20 \log \left(1 + \frac{2}{n} \right)$, which is negligible for normal values of n .

2.2. Terminations Constant at All Even-order Product Frequencies

Here, the relevant equations from reference 1 are numbers (4), (6), (31), in which we put the resistance at even-order frequencies equal to a constant, R :

$$V = i_0(R+r_0) + \frac{1}{2} \sum_{m=1,3,\dots}^{\infty} (i_{m+} + i_{m-})r_m \dots\dots(3)$$

$$0 = i_{l\pm}(R+r_0) + \frac{1}{2} \sum_{m=1,3,\dots}^{\infty} (i_{m\pm}r_{|m-l|} + i_{m\mp}r_{m+l}) \dots\dots(4)$$

$$i_{n\pm} = \frac{-\frac{1}{2} V r_n}{(R_{n\pm} + r_0)(R+r_0) - \frac{\pi^2 r_1^2}{16}} \dots\dots(5)$$

It is clear that substitution of (5) into (3) gives i_0 in terms of V , and substitution into (4) gives $i_{l\pm}$ in terms of V . Likewise it is clear that in general the evaluation of the infinite summations cannot be made. However, the practical modulator circuits included under this heading are relatively simple to evaluate.

Consider as an example the circuit in which $R = R_s$ for all products, except for $R_{1-} = R_s + R_R$. This case corresponds to a series modulator with a constant input resistance R_s , but a parallel tuned output circuit, resonant at $\omega_p - \omega_q$, at which frequency its dynamic resistance is R_R . At other product frequencies its impedance is negligible.

From eqn. (5), therefore, it is clear that

$$i_{1+} : i_{3\pm} : i_{5\pm} \dots = 1 : \frac{1}{3} : \frac{1}{5} \dots\dots(6)$$

since $i_{n\pm}$ is proportional to r_n except for term i_{1-} .

Further,

$$\frac{i_{1-}}{i_{1+}} = \frac{(R_s+r_0)^2 - \frac{\pi^2 r_1^2}{16}}{(R_s+R_R+r_0)(R_s+r_0) - \frac{\pi^2 r_1^2}{16}} = \frac{K_0}{K_1} \dots(7)$$

so that, the larger the dynamic resistance of the tuned circuit in the example chosen the larger the unwanted product i_{1+} is, relative to the wanted product i_{1-} .

Defining K_0 and K_1 as above, then (3) reduces to

$$V' = i_0(R_s+r_0) - \frac{1}{4}V \left[\frac{1}{K_0} \sum_{m=1,3,\dots}^{\infty} 2r_m^2 - r_1^2 \left(\frac{1}{K_0} - \frac{1}{K_1} \right) \right] \dots\dots(8)$$

i.e.

$$i_0 = \frac{V}{(R_s+r_0)} \left[1 - \frac{r_1^2(1-\pi^2/4)}{4K_0} + \frac{r_1^2}{4K_1} \right] \dots\dots(9)$$

$$= V \left[\frac{(R_s+r_0)}{K_0} - \frac{\pi^2 r_1^2}{4(R_s+r_0)} \cdot \left(\frac{1}{K_0} - \frac{1}{K_1} \right) \right] \dots(10)$$

Thus the larger the dynamic resistance of the tuned circuit, the smaller the unwanted product at i_0 , absolutely.

We have now to determine whether the unwanted product at i_0 is actually smaller relative to i_{1-} the wanted product.

From (5) and (9) we obtain:

$$\frac{i_{1-}}{i_0} = \frac{-2r_1(R_s+r_0)K_0}{4K_0K_1 + r_1^2(\pi^2/4 - 1)K_1 + r_1^2K_0} \dots\dots(11)$$

and thus, as K_1 increases, here also the unwanted product increases relative to i_{1-} .

These results are those that would be expected intuitively, namely that as the resistance at the wanted product frequency is increased, the current at that frequency decreases relative to all other product currents, including that at the signal frequency. Although the very nature of the output impedance ensures that this will not be an embarrassment as long as the circuit is truly linear, any intermodulation in the circuit could easily, in such a case, produce appreciable spurious currents at the wanted product frequency.

2.3. Terminations Zero or Infinite at All but Two Frequencies

These terminations are such that only voltages or currents at frequencies ω_q and $\omega_p - \omega_q$ occur in the circuit, $\omega_p - \omega_q$ being the wanted product frequency. Take the case of the series modulator where $R_s + R_R$ tends to zero for all frequencies but ω_q and $\omega_p - \omega_q$. Then if the output resistance R_R tends to zero for all

frequencies but $\omega_p - \omega_q$ only a voltage at frequency $\omega_p - \omega_q$ will be developed across it, and similarly if the input resistance R_s tends to zero for all frequencies but ω_q only a voltage frequency ω_q will be developed across it. But nevertheless currents at all product frequencies will flow in the circuit. The magnitudes of these may be quickly obtained by using the equation

$$i = V_1 g(t) \dots\dots(12)$$

where V_1 is the voltage across $r(t)$, and $g(t) = 1/r(t)$.

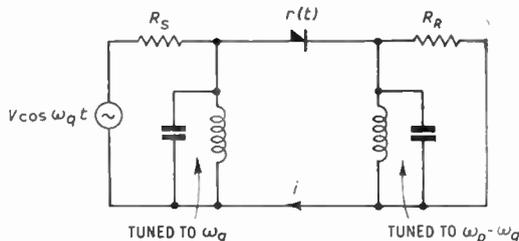


Fig. 2. A series modulator approximating to the type discussed in Section 2.3.

Figure 2 shows a possible practical circuit giving these conditions.

Equation (12) may be rewritten

$$i = [V - i(R_s + R_R)]g(t) \dots\dots(13)$$

$$= [(V - i_0 R_s) - i_{1-} R_R]g(t) \dots\dots(14)$$

since R_s and R_R are zero for currents other than i_0 and i_{1-} respectively. Writing this out for the various product frequencies, and bearing in mind that $g(t)$ contains only odd harmonics of ω_p , apart from a constant term, we obtain:

$$i_{1-} = \frac{-\frac{1}{2}g_1 V}{(1 + g_0 R_s)(1 + g_0 R_R) - \frac{1}{4}g_1^2 R_s R_R} \dots(15)$$

$$i_0 = \frac{(g_0^2 - \frac{1}{4}g_1^2)R_R + g_0}{\frac{1}{2}g_1} \cdot i_{1-} \dots\dots(16)$$

$$i_{2-} = -\frac{1}{2}g_1 R_R i_{1-} \dots\dots(17)$$

$$i_{1+} = (1 + g_0 R_R) i_{1-} \dots\dots(18)$$

$$\text{and } i_{1+} : i_{3\pm} : i_{5\pm} :: 1 : \frac{1}{3} : \frac{1}{5} \dots\dots(19)$$

$$i_{2-} : i_{4-}, i_{2+} : i_{6-}, i_{4+} :: 1 : \frac{1}{3} : \frac{1}{5} \dots(20)$$

All the currents in the circuit loop are therefore evaluable. It is of interest to note that the value of R_s only affects the absolute values of the currents, and not their relationships, one with the other. If R_R is increased, however, all the unwanted product currents are increased, as would be expected, relative to i_{1-} .

Exactly dual results may be obtained for the case in which $R_s + R_R \rightarrow \infty$ for all frequencies but ω_q and $\omega_p - \omega_q$ where only the currents i_0 and i_{1-} exist, but all the voltages occur across the circuit impedance.

3. Square-wave Resistance Function. Unequal Mark/Space Ratio

It will often happen that the rectifiers in a modulator circuit are so switched that the resistance function, although square-wave, has not quite equal mark and space durations. Further, it has been shown³ that greater efficiency can be obtained in one modulator circuit (that of Fig. 2) by allowing the mark/space relationship to diverge considerably from equality. Therefore it is useful to consider the effect of these variations on the product currents in the loop.

The general expression for $r(t)$, when the ratio of "mark" to "mark + space" is s , is given by

$$r(t) = r_f + s(r_b - r_f) + \frac{2}{\pi}(r_b - r_f) \cdot \sum_{n=1}^{\infty} \frac{\sin n\pi s}{n} \cos n\omega_p t \quad \dots\dots(21)$$

When $s = \frac{1}{2}$ this reduces to the result used previously. If, however, we consider s to be very close to $\frac{1}{2}$, so that $s = \frac{1}{2} \pm \delta$

$$\sin n\pi s \rightarrow \sin \left(n \frac{\pi}{2} \pm n\pi\delta \right)$$

This, for odd n , tends to ± 1 , as long as δ is small, for small values of n . For even n , it is equal to $\pm \sin n\pi\delta$, which tends to $n\pi\delta$ when $\delta \ll \frac{1}{2}$, and for small values of n .

Now in a modulator with constant resistance terminations,

$$i = \frac{V}{R + r(t)} = Vg_A(t) \quad \dots\dots(22)$$

where $g_A(t)$ is a square wave inverse in form to $r(t)$. Thus the current in such a circuit, for a slight variation of mark/space from 1 : 1, will be, from the above considerations,

- (a) a set of odd-order products, and a current at signal frequency, differing but little from those obtained in an equal mark/space modulator;
- (b) a set of even-order product currents, the lower orders of which will have approximately equal amplitudes, directly proportional to the variation of the mark/space ratio.

The other case of interest is when the mark/space ratio becomes either very large or very small. It is clear that in these cases $g_A(t)$ will consist of either a train of short rectangular pulses, or of a constant minus such a train. These will have a Fourier series representation such that the lower harmonics of $\omega_p t$ will all have approximately the same amplitude, just as the even-order products did in the last case to be examined. Thus all the lower order modulation products will have about the same amplitude, and only i_0 will be different in the two cases, being larger when the

mark/space ratio tends to zero. The actual general relationship is

$$i_0 = \frac{(r_b + R) - s(r_b + r_f + 2R)}{r_b - r_f} \cdot \frac{i_{1-}}{\sin \pi s} \quad \dots\dots(23)$$

so that as s tends to 0 or ∞ , i_0/i_{1-} tends to ∞ , since the process of modulation collapses, in the limit, in either case.

In the circuit referred to by Peterson and Hussey,³ however, when s tends to zero, i_0/i_{1-} does not become infinite, and, indeed, approaches unity. However, to achieve this desirable result, the terminating resistances R must also tend to zero. With any finite terminating resistance, the conversion loss becomes very large, since i_0/i_{1-} tends to ∞ when s tends to zero. This is understandable, indicating the breakdown of the modulating process in the practical circuit. However, if this circuit is analysed with finite terminating resistances, Peterson and Hussey found that some reduction in conversion loss could be obtained if s were less than one half although the conversion loss increased again as s approached zero. Along with the reduction in conversion loss it may be shown that there is a relative increase in the magnitude of the unwanted product i_0 .

It should be noted, as explained in Ref. 4, that the ring modulator cannot be represented by the same equivalent circuit as the series and shunt modulators when the carrier waveform has unequal mark/space ratio, since even- and odd-order modulation products occur in both the input and output loops. It is of interest to examine the current distribution in this modulator under such conditions, and one example that may be readily analysed is that in which the terminations are constant resistances R . It is clear that only a current at frequency ω_q flows in the input loop, since, although the rectifiers conduct with unequal intervals, the net effect on the input loop is merely that of changing over the connections to the output resistor, so that the input impedance of the modulator is a constant resistance R . The currents in the output loop, assuming ideal rectifiers, are given by

$$i \cdot \phi(t), \text{ where } i \text{ is the input loop current } \dots\dots(24)$$

and
$$\phi(t) = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{\sin n\pi s}{n} \cos n\omega_p t \quad \dots\dots(25)$$

so that they are of the same form as the current in the single loop circuit discussed above. Thus, a slight deviation from equality in the mark/space ratio of the carrier oscillator feeding such a ring modulator, will merely result in even-order modulation products occurring in the output loop, the lower orders of which will have approximately equal amplitudes. The conversion loss of the modulator will, to a first approximation, be unchanged.

Similar results may be obtained for other terminations of the ring modulator—for instance, if $R_s = R$ at ω_q , ∞ at all other frequencies, $R_R = R$ at $\omega_p - \omega_q$, ∞ at all other frequencies, it is easily shown that unwanted modulation-product voltages appear across the input and output terminations. These are odd-order products across the input termination, and even-order products across the output termination, and in each case, the lower order products will have approximately equal amplitude.

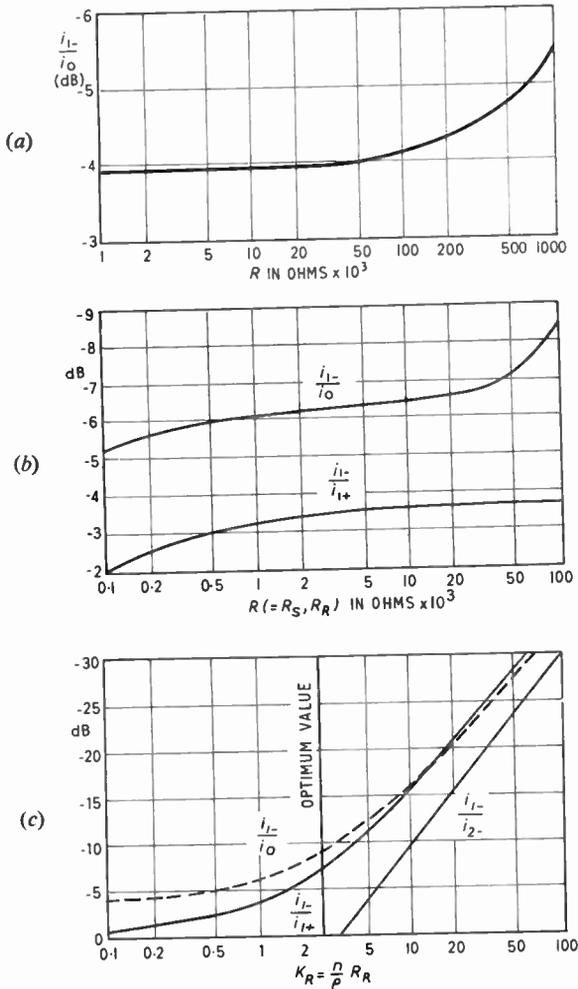


Fig. 3. The ratios of wanted to unwanted current products for a range of terminating resistances.

- (a) Ratio for modulators of the type discussed in Section 2.1.
- (b) Ratios for modulator of the type discussed in Section 2.2.
- (c) Ratios for modulators of the type discussed in Section 2.3.

4. Calculations of some Product Current Ratios

In order to illustrate the conclusions reached in Section 2, graphs have been drawn of the ratios of wanted to unwanted product current magnitudes, for varying values of load impedance. This has been done for the cases mentioned in Sections 2.1, 2.2 and 2.3,

but in only one case, that of Section 2.3, was it possible to produce a universal curve. In the other two examples, therefore, the values of the forward and reverse resistances of the rectifiers were arbitrarily chosen as 100 Ω and 1 M Ω , and a range of terminating resistance $R (= R_s = R_R)$ sufficiently wide, it is hoped, to cover all practical cases, was taken. The results for other cases with differing rectifier resistances, may usually be deduced from these curves.

In the case of Section 2.1 (terminations constant at all odd-order product-frequencies), only one curve was drawn (Fig. 3(a))—that of the ratio of i_{1-}/i_0 —since $i_{1-} = i_{1+}$, and no even-order products are produced in this modulator. In the case of Section 2.2 (terminations constant at all even-order product-frequencies), two curves were drawn (Fig. 3(b))—those of i_{1-}/i_0 and i_{1-}/i_{1+} —but the curve for i_{1-}/i_{2-} was not drawn, as the lower even-order products are generally significantly smaller than the neighbouring odd-order products, in this form of modulator. Finally, for the modulator described in Section 2.3, in which R_s and R_R are zero except at frequencies ω_q and $\omega_p - \omega_q$ respectively, it was found possible to produce a universal set of curves (Fig. 3(c)), and so the three relationships i_{1-}/i_0 , i_{1-}/i_{1+} , i_{1-}/i_{2-} were plotted. In this modulator it should be noted that the variation in these quantities is considerably greater than in the previous two circuits.

5. An Application of the Previous Work to a Study of Feedback Rectifier Modulators

In References 5 and 6, two types of feedback modulator are discussed, in which the conversion loss (or gain) is stabilized against variations in the modulating elements by the application of negative feedback. Both could be applied to circuits containing rectifier modulators, as shown in Fig. 4(a) and 4(b). A variation of the feedback modulator of Fig. 4(b) may be postulated, as shown in Fig. 4(c), which appears to have significant advantages in that (a) the amplifier in the circuit need accept only one frequency and may therefore be tuned, and (b) there is no need to suppress the feedback of frequency ω_q (possibly for fear of oscillation) as has been done in the published circuit details for the arrangement of Fig. 4(b).⁵ However, when all is said and done, the criterion of the effectiveness of the feedback rectifier modulator is how well the conversion loss is stabilized against changes in the forward and reverse resistances of the rectifiers. The circuit of Fig. 4(a) has been analysed in Reference 6, and depends essentially on the two modulators varying in the same manner; but the other circuits depend on rather different principles which are relevant to the present paper.

The stability of the conversion loss of the feedback modulator of Fig. 4(b) depends on the condition

$$h'_0 = Kh_1 \dots (26)$$

where K is a constant, h_0' = insertion loss of the basic modulator unit at frequency $\omega_p - \omega_q$, and h_1 = conversion loss for the product $\omega_p - \omega_q$.

For the feedback modulator of Fig. 4(c) the condition is

$$h_0 = kh_1 \quad \dots\dots(27)$$

where k is a constant, and h_0 = insertion loss of the basic modulator unit at frequency ω_q .

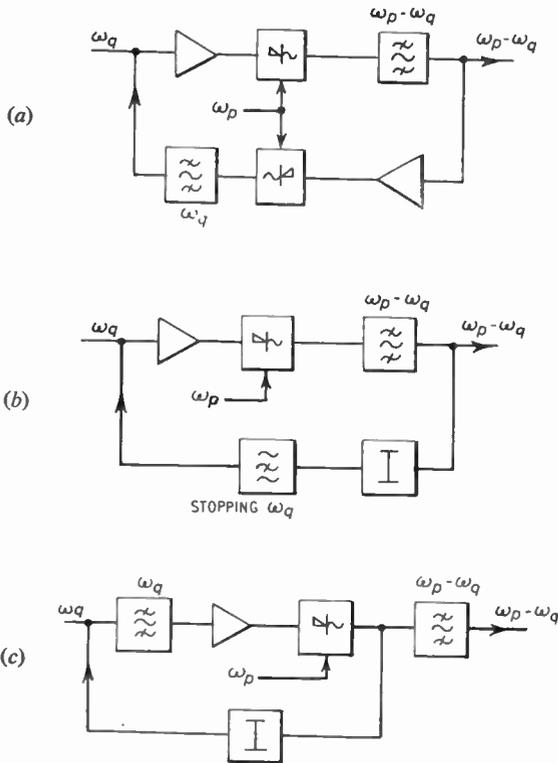


Fig. 4. Three configurations of rectifier modulator circuits with feedback.

- (a) Feedback modulator circuit using two identical modulators. (After Tucker.⁶)
- (b) Modulator circuit feeding back a component at frequency $\omega_p - \omega_q$. (After Boggs.⁵)
- (c) Modulator circuit feeding back a component at the signal frequency, ω_q .

Now if the basic modulator unit is free of frequency dependence, h_0 and h_0' are equal; in any case, both arrangements of negative feedback evidently depend for stability on essentially the same requirement. It is also clear that since both arrangements depend on an applied frequency producing a component at its own frequency in the output of the basic modulator unit, the ring modulator is useless for this application, and only the shunt and series modulators can be used. The quantities h_0 , h_0' and h_1 may then be replaced in

the conditions (26) and (27) by ratios of voltages and/or currents (according to which is involved in the feedback connection) thus:

For Fig. 4(b):
$$h_0 \propto \frac{V}{i_0'}$$

where i_0' is the current at frequency $\omega_p - \omega_q$ which would flow if the input frequency were made $\omega_p - \omega_q$ instead of ω_q ; in most practical cases this is the same as the current at frequency ω_q due to an input at ω_q if the values of the terminating resistances at ω_q and $\omega_p - \omega_q$ were interchanged.

Also
$$h_1 \propto \frac{V}{i_{1-}}$$

so that
$$K = \frac{h_0'}{h_1} \propto \frac{i_{1-}}{i_0'} = \text{constant} \quad \dots\dots(26a)$$

For Fig. 4(c):

$$k = \frac{h_0}{h_1} \propto \frac{i_{1-}}{i_0} = \text{constant} \quad \dots\dots(27a)$$

Consider now two particular examples so that the utility of the feedback arrangements may be assessed. Firstly, let the basic modulator unit be fed from a constant-resistance source, so that the circuit may be taken as that discussed in Section 2.2. This would correspond to Fig. 4(b) as drawn, since the modulator termination shown there is not constant at all odd-order frequencies, but is constant at all even-order frequencies. Then from eqn. (5) we obtain

$$\frac{i_{1-}}{V} = \frac{-\frac{1}{2}r_1}{(2R+r_0)(R+r_0) - \frac{\pi^2 r_1^2}{16}} \quad \dots\dots(28)$$

To obtain i_0' we have to consider the output component at the same frequency as the input when the output termination is tuned to this frequency instead of to a sideband; this condition (applying to the feedback current) is of the type discussed in Section 2.1. From eqns. (1) and (2), we obtain

$$\frac{i_0'}{V} = \frac{-(R+r_0)}{(R+r_0)(2R+r_0) - \frac{\pi^2 r_1^2}{16}} \quad \dots\dots(29)$$

Thus from (28) and (29) we obtain

$$K = \frac{r_1}{2(R+r_0)} = \text{constant} \quad \dots\dots(30)$$

As $r_0 \approx \frac{\pi}{4}r_1$ for rectifiers with a high ratio of reverse to forward resistance, (30) will apply only when $R \ll r_0$. (Note, however, that for a high reverse-forward ratio, the loss is nearly independent of r_f). This restriction is such that, if the modulator is designed for optimum conversion loss, the change of conversion loss for a given change of rectifier resist-

ances is little different in the modulator alone and in the complete feedback modulator. It is therefore clearly necessary, if a satisfactory circuit is desired, to make R small, accept a higher conversion loss in the rectifier modulator, and counteract this with increased gain in the amplifier within the loop. This can be seen from the figures in Table 1, where the performances of two versions of the feedback modulator of Fig. 4(b) are compared with that of the modulator without feedback. A forward rectifier resistance of 100Ω , and a reverse resistance of $1 \text{ M}\Omega$ are assumed. The conversion loss of the modulator is worsened by 0.6 dB by choosing the non-optimum terminations.

Table 1

Change in conversion loss without feedback		Minimum change in conversion loss with feedback		
rectifier resistance	optimum terminations	$\frac{1}{10}$ th optimum terminations	optimum terminations	$\frac{1}{20}$ th optimum terminations
$r_f \times 10$	+ 0.7 dB	+ 5.0 dB	0 dB	0 dB
$r_f \div 10$	- 0.05	- 0.7	0	0
$r_b \times 10$	- 0.05	0	- 0.1	- 0.01
$r_b \div 10$	+ 0.7	0	+ 1.0	+ 0.1
$r_f, r_b \times 10$	+ 0.6	+ 5.0	- 0.1	- 0.01
$r_f, r_b \div 10$	+ 0.7	- 0.6	+ 1.0	+ 0.1

For the second example let the modulator be basically of the form discussed in Section 2.3. Since this requires filters at both input and output of the modulator itself, the feedback arrangement shown in Fig. 4(c) can be chosen, it being assumed that the amplifier feeding the modulator has a tuned output circuit peaking at frequency ω_q , so that the circuit of Fig. 2 applies. It has further been assumed that the attenuation of the feedback path is such that its impedance at the input terminals is purely resistive, and that it is the output current (not voltage) which is fed back, since the output impedance is a short-circuit at frequency ω_q .

It is clear from eqn. (27a) that it will be necessary, for satisfactory operation of the feedback modulator, for the ratio i_1/i_0 to be independent of a change in the rectifier resistances, and it can be seen from Fig. 3(c), that this will be the case if $R_R \ll r_f$. It will also be clear from Fig. 3(c), that this particular form of modulator termination leads to considerable variations with change of rectifier resistance, when the scale of the graph is compared with those of Figs. 3(a) and 3(b). Accordingly, in Table 2, where the results obtainable, theoretically, with the feedback modulator are compared with those obtained without feedback, a

Table 2

Change in conversion loss without feedback		Minimum change in conversion loss with feedback				
rectifier forward resistance	optimum terminations	$\frac{1}{10} R_{opt}$	$\frac{1}{20} R_{opt}$	optimum terminations	$\frac{1}{10} R_{opt}$	$\frac{1}{20} R_{opt}$
r_f	0 dB	0 dB	0 dB	0 dB	0 dB	0 dB
$2r_f$	+ 1.5	+ 5.0	+ 5.7	+ 3.1	+ 0.6	+ 0.3
$r_f/2$	+ 0.9	- 4.3	- 5.1	- 2.1	- 0.3	- 0.1

variation in r_f of only 2 : 1 has been considered. Variations of r_b have virtually no effect on this modulator. For convenience R_s has been taken equal to R_R .

The increase of conversion loss when the terminations are changed from R_{opt} to $\frac{1}{10} R_{opt}$ is 9.0 dB ; from R_{opt} to $\frac{1}{20} R_{opt}$ is 14.0 dB . Once again it should be noted that the figures quoted for the feedback modulator are of the *minimum* change in conversion loss: this assumes infinite amplifier gain. In practice, however, it will be possible to approach as closely to these figures as may be desired. Note that just as in the previous example, there is no advantage in using feedback when the modulator terminations are optimum: but the smaller the terminations, the greater the advantage of feedback.

6. Acknowledgment

The author wishes to thank Professor D. G. Tucker for some helpful suggestions made during the course of the work.

7. References

1. D. P. Howson and D. G. Tucker, "Rectifier modulators with frequency-selective terminations etc.", *Proc. Instn Elect. Engrs*, **107 B**, p. 261, May 1960.
2. D. G. Tucker, "The input impedance of rectifier modulators", *Proc. Instn Elect. Engrs*, **107 B**, p. 273, May 1960.
3. E. Peterson and L. W. Hussey, "Equivalent modulator circuits", *Bell Syst. Tech. J.*, **18**, p. 32, 1939.
4. D. G. Tucker, "Elimination of even-order modulation in rectifier modulators", *J. Brit. I.R.E.*, **21**, p. 161, February 1961.
5. G. E. Boggs, "Improvement in gain stability of the superheterodyne mixer through the application of negative feedback", *Proc. Inst. Radio Engrs*, **40**, p. 202, February 1952.
6. D. G. Tucker, "Negative feedback in frequency changers" *Electronic Technology*, **37**, p. 96, March 1960.

Manuscript received by the Institution on 29th June 1960 (Paper No. 622).

REPORT OF THE ANNUAL GENERAL MEETING OF SUBSCRIBERS TO THE Brit.I.R.E. BENEVOLENT FUND

The meeting was held at the London School of Hygiene and Tropical Medicine on Wednesday, 11th January 1961, under the Chairmanship of Professor Emrys Williams (Vice-President).

1. To confirm the Minutes of the Annual General Meeting of Subscribers held on 2nd December, 1959.

Mr. G. D. Clifford, Honorary Secretary of the Fund, read the Notice convening the Annual General Meeting which had been published in the December, 1960 *Journal*. The Minutes of the last Annual General Meeting had been published in the January 1960 *Journal* and were signed as a correct record.

2. To receive the Annual Report of the Trustees for the year ended 31st March, 1960.

The Chairman asked the Honorary Secretary to present the Annual Report of the Trustees, which had been published in the December, 1960 *Journal*.

Mr. Clifford said that particular mention should be made of the co-operation which the Trustees received from other benevolent associations. It had to be remembered that whilst the cost of living, etc., had increased considerably during the last twenty years, the annual income of the Fund had not increased to anywhere near the same extent. Members would therefore be particularly pleased to learn of the co-operation which existed between the Trustees of the Institution's Fund and such bodies as the R.A.F. Benevolent Fund and the London Council for Social Services.

As the Annual Reports showed, the Trustees of the Brit.I.R.E. Benevolent Fund found that the most rewarding help which could be given was by the education of fatherless or orphan children. In this connection the Trustees greatly appreciated the co-operation given by Read's School, the Royal Wolverhampton School, and the Royal Wanstead School.

The Annual Report of the Trustees was approved unanimously.

3. To receive the Income and Expenditure Account and Balance Sheet for the year ended 31st March, 1960.

Mr. Clifford thanked all subscribers for their support during the year and expressed the Trustees' pleasure with the slight increase in donations. He continued: "It should, however, be pointed out that less than 12% of the membership support the Fund.

"I suggest that all members should complete a deed of covenant. By this means the Trustees can recover from the Inland Revenue the tax which the member has paid on the donation, thereby substantially increasing the value of the contribution. The aim of the Trustees is to obtain an income of not less than £2,500 a year which

will enable all reasonable and foreseeable demands on the Fund to be met. Part of this income will come from the interest on the Fund's investments—at present standing at over £10,000."

Mr. Clifford felt that the Accounts and Balance Sheet showed a very satisfactory state of affairs and he had pleasure in moving their adoption. The motion was seconded by Mr. F. G. Diver and passed unanimously.

4. To elect Trustees for the year 1961.

The Agenda named the Trustees who had been responsible for the administration of the Benevolent Fund during the past year. Mr. A. H. Whiteley had been one of the Trustees for nearly 10 years and was in fact the Senior Trustee. As he served on other Institution Committees, however he had asked to be released of his commitments to the Benevolent Fund. Subscribers would wish to express their thanks to Mr. Whiteley for his services.

The Trustees had therefore asked Air-Vice Marshal C. P. Brown (Vice-President) a supporter of the Benevolent Fund for a number of years, to serve as a Trustee. The other Trustees, Professor E. Zepler (President), Mr. G. A. Marriott (Immediate Past President), Rear-Admiral Sir Philip Clarke (Past President), Mr. A. A. Dyson (Member) and Mr. G. A. Taylor (Honorary Treasurer) put themselves forward for re-election. Formal and unanimous approval was then given to their re-election, and to the election of Air Vice-Marshal Brown.

5. To appoint the Honorary Solicitor.

Mr. Clifford said that the Trustees had received particular help from Mr. Charles Hill, Honorary Solicitor to the Fund, and his advice was particularly welcomed by beneficiaries. He moved that Mr. Hill be re-appointed and the proposal was carried unanimously.

6. To appoint the Honorary Accountant.

Mr. R. H. Jenkins had similarly served the Trustees for many years and Mr. Clifford had pleasure in moving his re-appointment. The motion was carried unanimously.

7. Any other business.

Notice of other business had not been received and after thanking all subscribers for their support during the year the Secretary declared the annual general meeting of subscribers to the Benevolent Fund at an end.

Parametric Diodes – Design and Fabrication

Presented at the Symposium on New Components, held in London on 26th–27th October 1960.

By

D. B. DAY, B.Sc.†

Summary : Solid state diffusion into silicon can be used to produce a rectifying junction. The capacitance of a diode made this way varies with the bias applied to it. The device is designed to be a variable capacitance having a low loss. The unbiased capacitance of a diode depends on the starting material and the diffusion parameters but to reduce the value to one that is useful (a few pF) the area has to be limited. A small area of the junction is isolated by ultrasonic cutting, leaving a plinth or “mesa”. Contact to the mesa is made in an encapsulation suitable for use in a waveguide. Amongst other uses, the diodes are suitable for low-noise (parametric) amplifiers, frequency multipliers and high-frequency switches.

1. Introduction

There has been abundant literature¹ on how solid-state voltage variable capacitors can be used as circuit elements at high frequencies. Several articles also have been devoted to the method of fabrication of suitable elements. This paper is intended to give a simple picture of how and why these diodes are designed and fabricated as they are. The first part deals with some diode parameters, which are then related to a design. Finally there are short sections on fabrication and uses of the diodes.

2. Diode Characteristics

2.1. Capacitance

The diffusion in the solid state of group III or group V impurities into silicon introduces either positive or negative charge carriers into the bulk of the material. By the choice of suitable starting material and diffusing impurity a *pn* junction can be produced. This junction separates regions of material in one of which the charge carriers are predominantly positive and, in the other, negative. Rectification and the effect of an inherent capacitance are two of the electrical properties associated with such a junction.

It is known that the junction capacitance can be attributed to a charge depletion layer which is formed in the region of the junction. This layer is formed by the initial diffusion of carriers across the junction neutralizing each other. The charges left on both sides of the junction as a result set up a potential barrier which prevents further diffusing of carriers. The static charges which are not neutralized on one side of the junction repel the carriers on the other. This electrical configuration is represented diagrammatically in Fig. 1.

Such a layer will obviously be affected by voltages impressed across the diode and, as a result, the value of the capacitance has a dependence on the bias applied.² The diode can be thought of as a parallel-plate capacitor, the depletion layer being the dielectric.

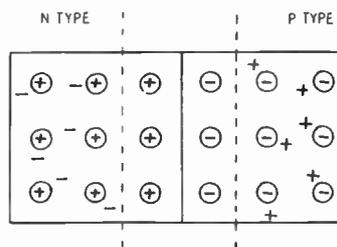


Fig. 1. Junction and depletion layer.

Increasing the reverse bias widens the depletion layer and as a result the value of the capacitance decreases. In the case of abrupt junctions, encountered in alloyed diodes, the capacitance decreases as the square root of the reverse bias:

$$C = \frac{C_0}{\sqrt{1 - V/\phi}} \quad \dots\dots(1)$$

C_0 is the capacitance at zero bias and ϕ a constant.

With solid-state diffusion we get a graded junction and, for the case we are considering, a linearly graded junction, the capacitance will decrease as the cube root of the reverse bias:

$$C = \frac{C_0}{\sqrt[3]{1 - V/\phi}} \quad \dots\dots(2)$$

2.2. Noise

Some mention must also be made of the inherent noise level in the diodes.³ There are three mechanisms producing noise in a *pn* junction and the first one is

† Formerly with Ferranti Ltd., Wythenshawe, Manchester, 22 ; now with the General Electric Co. Ltd., Semi-conductor Division, Hazel Grove, near Stockport.

concerned with minority carriers. (Minority carriers are electrons present in *p*-type material and holes present in *n*-type material.) Thermally generated minority carriers can, if they reach the space charge region (depletion layer), cross it and constitute a saturation current in the reverse direction. The other two mechanisms producing noise are due to majority carriers crossing the junction in the forward direction, becoming minority carriers. Some of these stay and some return, after a period, to become majority carriers again. The returning carriers do not contribute to the net current but do compose the high-frequency component of the noise. The total magnitude of the noise in these diodes is, when compared to other circuit elements, very small.

3. Device Design

The device is designed to produce this swing in capacitance described above, about a value of convenient magnitude. Furthermore, the accompanying losses which occur in the diode must be kept down to a minimum. Figure 2 shows what constitutes a simple equivalent circuit for the diode at microwave frequencies.

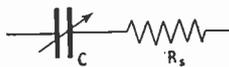


Fig. 2. Simple equivalent circuit of diode.

As has been explained, the manner with which *C* varies with bias is fixed by the method of producing the junction. In designing the device the magnitude of *C* must be suitable for the systems using it whilst that of *R_s* must be minimized.

In the comparison of diodes there has to be some way of expressing the quality of each. In the case of variable capacitance diodes the figure of merit is defined as a cut-off frequency given by eqn. (3):

$$f_c = \frac{1}{2\pi R_s C_{min}} \dots\dots(3)$$

The frequency is defined as that at which the *Q* of the diode equals unity. In the definition *C_{min}* is the minimum value to which the capacitance of the diode can fall with the application of a reverse bias. This value is normally limited by the breakdown of the diode as this latter controls the maximum bias in the reverse direction which can be applied. In order to standardize, and to compare diodes with differing breakdown voltages, *C_{min}* is usually taken as the value of the junction capacitance with 6 V applied in the reverse direction. It is obvious that for a given *C*, *R_s* must be minimized to give the best *f_c*.

The possibilities will now be examined to find the configuration which is likely to give a diode with the best cut-off frequency. After various processes, described below, including the diffusion, the device is as shown in Fig. 3. It is a disc of silicon of 0.060 in. diameter and 0.004 in. thick having a junction at about 8 microns from the top face. Unfortunately the junction capacitance of such a die would be several thousand pF. The value specified for the finished device is of the order of a few pF. One way to reduce the capacitance, and in fact the only way to reduce it sufficiently, is to reduce the junction area. It is found by calculation, and experiment, that the required area of junction is three or four square thousandths of an inch. If the diameter of the dice could be reduced to 0.002 in. to give this cross-sectional area the problem of an extremely high series resistance would then arise. Thus from the capacitance point of view a small cross-sectional area is required, but from the loss point of view a large one is needed.

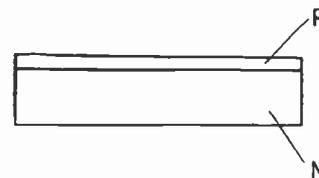


Fig. 3. Die, after diffusion.

One answer to this inconsistency of design requirements is to produce a plinth or "mesa" in the material, making sure that the junction is in the material of small cross-sectional area. This is illustrated in Fig. 4.

How does this configuration lead to more satisfactory device parameters? The manner in which

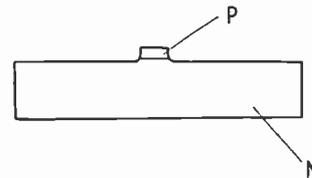


Fig. 4. Mesa diode.

capacitance and resistance are affected by this change in shape will be examined. The value of the capacitance of the device depends directly on the area of the junction. As opposed to this the series resistance depends on the geometry and resistivity of the material on both sides of the junction. The *p*-type material is more conductive than the *n*-type as it has been highly doped during diffusion. For this reason and because the thickness of the *p*-type is less than that of the *n*-type, the mesa is made on the *p* side of

the slice. The part of R_s coming from the n -type material is now not proportionately increased due to reduction of the junction area and will in fact mostly consist of a spreading resistance in going abruptly from a small cross-sectional area (0.002 in. diameter mesa) to a 0.060 in. die.

4. Series Resistance

The series resistance R_s can be considered as two parts, namely R which is bulk resistance of the $\rho L/A$ type and r the spreading resistance. For the purposes of our analysis any part of R occurring in the 0.060 in. diameter die, below the mesa, will be neglected.

$$R_s = R + r \quad \dots\dots(4)$$

Taking d as the diameter of the mesa,

$$C \propto d^2$$

Also $R \propto \frac{1}{d^2}$

and $r \propto \frac{1}{d}$

Thus the product $C \cdot R_s \propto d^2 \left(\frac{A}{d^2} + \frac{B}{d} \right)$

where A and B are constants

$$C \cdot R_s \propto (A + Bd) \quad \dots\dots(5)$$

Taking into account eqn. (3)

$$f_c \propto \frac{1}{A + Bd} \quad \dots\dots(6)$$

From this it will be obvious that if the mesa diameter is small, Bd will be small compared with A and f_c will be independent of d . As the mesa size is increased there will be a decrease in the value of f_c . Simple calculations show that the mesa diameter for which bulk and spreading resistance components become comparable is about 0.0015 in.

5. Relationships between f_c and other Parameters

Diodes fabricated by the author have capacitances going down to 0.5 pF and the corresponding cut-off frequencies range up to 50 kMc/s. Measurements of cut-off frequencies are carried out at 9375 Mc/s on a waveguide bench and capacitances measured on a 1 Mc/s impedance bridge. Within a given batch of dice from the same material the cut-off frequencies of the diodes produced can, to a certain extent, be correlated with the inverses of the capacitances:

$$f_c \propto \frac{1}{C}$$

But if eqn. (3) is taken into account this implies that R_s is fairly constant through a batch of diodes fabricated from the same material.

Another parameter to consider is the impurity concentration gradient at the junction. The relation-

ship between f_c and the gradient is, according to theory, linear with a positive slope.⁴ This indicates that the best diodes will be made from material with a steeply graded junction. In practice this will probably fall off again with very high gradients. Typical values encountered are in the range 10^{22} - 10^{23} atoms/cm⁴.

6. Fabrication and Encapsulation

The starting material used is n -type silicon with a resistivity of about 0.04 ohm-cm. "Paint-on" technique is used to deposit the boron impurity on the surface of the slices. Heating in a furnace diffuses this impurity into the bulk of the material giving a p -type layer at the surface. By this means a junction at a depth of 8 microns is established. The slices of material used are 0.004 in. thick and these are nickel and gold plated, on the junction side, after diffusion to facilitate electrical contact to the mesa in the finished device. Ultrasonic cutting reduces the slices to 0.060 in. diameter dice mentioned earlier in design considerations. Alloying down on to a gold plated brass pin holds the dice for subsequent processing, which includes the formation of a 0.002 in. diameter mesa. The cutting face of the tool is a 0.040 in. diameter flat with a 0.002 in. diameter hole in it. This is placed in contact with the dice and vibrated ultrasonically; the silicon is cut with a fine alumina

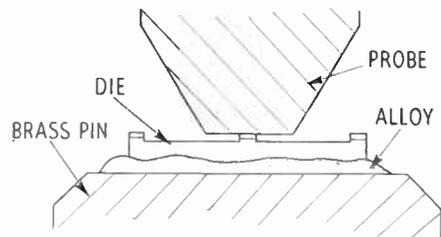


Fig. 5. Diode in the encapsulation.

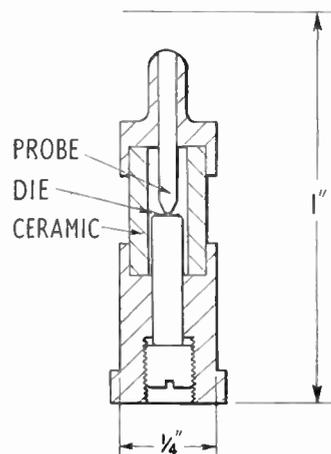


Fig. 6. Cross-section of the encapsulation.

powder as an abrasive and water as the vehicle. The next stages are a wash, chemical etching to clean the die, and drying. The diode is then ready for encapsulation.

Figures 5 and 6 are detail and complete cross-sectional views of the encapsulation containing a diode. Pressure contact is made to the mesa by a probe in the encapsulation. This consists of a ceramic tube to which the two metal ends are joined by the use of metal to ceramic seals. The external configuration is similar to that of a mixer diode. Assembling the diodes is achieved by the use of a screw which pushes the die-carrying pin until contact with the probe is made.

Further forms of encapsulation are at present being developed. One is symmetrical so that diodes can easily be reversed in the same mounting and the second is suitable for strip lines. Both are physically smaller than the existing encapsulation.

7. Uses

Amongst other uses variable capacitance diodes can be used as frequency multipliers and high-frequency switches. Due to their inherent low-noise properties the diodes are also useful for low-noise amplifiers such as the parametric amplifier from which they derive their name.

8. Conclusions

Solid-state devices can be designed to give a circuit element which is a voltage variable capacitor. With other imposed specifications, including a suitable encapsulation, the diode will be useful for work at microwave frequencies, and especially those for which a low-noise unit is advantageous.

9. Acknowledgments

The author would like to acknowledge his thanks to those associated with the parametric diode project, especially Mr. J. D. Pearson. Thanks also are due to the colleagues and friends who gave both encouragement and assistance in the preparation of this paper.

10. References

1. W. W. Mumford, "Some notes on the history of parametric transducers", *Proc. Inst. Radio Engrs*, **48**, pp. 848-53, May 1960.
2. A. Uhlir Jr., "The potential of semi-conductor devices in high frequency communications", *Proc. Inst. Radio Engrs*, **46**, pp. 1099-115, June 1958.
3. A. Uhlir Jr., "High frequency shot noise in p-n junctions", *Proc. Inst. Radio Engrs*, **44**, pp. 557-8, April 1956.
4. A. E. Bakanowski, N. G. Cranna and A. Uhlir Jr., "Diffused silicon non-linear capacitors", *Trans. Inst. Radio Engrs (Electron Devices)*, **ED-1**, pp. 384-90, October 1959.

Manuscript first received by the Institution on 6th August 1960 and in revised form on 30th September 1960 (Paper No. 623).

of current interest . . .

Medical Electronics Meetings

The fourth International Conference on Medical Electronics is to be held at the Waldorf-Astoria Hotel, New York, from 16th to 21st July, 1961. It is being combined with the 14th Annual Conference on Electrical Techniques in Medicine and Biology. As in the case of the Third International Conference held in London last year, the Conference will include a scientific exhibition and the "Plenary" and "Special" sessions will discuss many topics in the area common to engineering, medicine and biology.

The co-ordinator in the United Kingdom is the Biological Engineering Society, and members of the Institution who wish to contribute papers are asked to submit a three-hundred word abstract as soon as possible. These contributions may be offered direct to the Biological Engineering Society or to the Secretary of the Medical and Biological Electronics Group of the Institution.

The Biological Engineering Society itself is continuing its practice of holding all-day scientific meetings, combining visits and lecture demonstrations. The first two meetings were to the National Institute of Medical Research and Guy's Hospital Medical School. The next meeting, which is to be held on 29th April, 1961, will be held at the University of Bristol, and will include visits to the Department of Anaesthetics and the Burden Neurological Institute.

Members in Broadcasting Organizations

The Independent Television Authority has recently announced the appointment of Engineers-in-Charge at three of its new transmitters. Two of these engineers are Associates of the Institution. Mr. Henry N. Salisbury has been appointed Engineer-in-Charge of the Caldbeck Station near Carlisle, and Mr. Kenneth Archer Engineer-in-Charge of the Caradon Hill Transmitter, Cornwall.

An Associate Member with the British Broadcasting Corporation, Mr. J. D. MacEwan, B.Sc., has recently been appointed Engineer-in-Charge, Television, Birmingham. Since 1956 Mr. MacEwan has been Senior Lecturer (Technical Operations) at the Corporation's Engineering Training Department.

Mr. Timothy Joseph Murphy (Associate Member) who is in charge of the Studio Department of the Engineering Division of Radio Eireann recently received the City and Guilds Insignia Award in Technology "for competence in television and sound broadcasting". Mr. Murphy supported his application for the C.G.I.A. with a thesis on "The Design of Modern Sound Broadcasting Studios". Before joining Radio Eireann in 1955 he was for eight years in the Engineering Division of the B.B.C.

I.T.A. Stations in South-West England

Full-power test transmissions began from the Caradon Hill transmitter of the Independent Television Authority on 1st February last. The transmitter radiates a vertically polarized signal in Channel 12, the actual carrier frequencies being vision 209.74325 Mc/s, sound 206.23 Mc/s. The station is equipped with a pair of vision transmitters each having a maximum power output of 5 kW (peak white) and a pair of sound transmitters each having a maximum power output of 1.25 kW (carrier).

The station will have an effective radiated power (vision) of 200 kW to the South-West, 25 kW to the South and South-East and 10 kW to the North-West and North-East. Caradon Hill is some 10 miles North-West of Liskeard, Cornwall and the station is 1,215 feet above sea level.

Education for Management

The setting up of the United Kingdom Advisory Council on Education for Management was referred to in the April 1960 *Journal*. The first meeting of the Advisory Council on 6th February 1961 was addressed by Sir David Eccles, Minister of Education, who said that there was a lot of ground in management education to be made up in Great Britain.

The chief responsibility of the Council is to keep under review the provision for management education in the technical colleges, to maintain contact with other bodies providing management education and to be available to give advice to those other bodies on request.

The Council is broadly based and consists of representatives from management and teaching institutions, from industry and from the professional bodies, including the leading engineering and other scientific institutions. It also has independent members including some from the universities.

The necessity to consider management training in part of the curriculum for some engineers was referred to in his Presidential Address to the Brit.I.R.E. by Mr. G. A. Marriott (published in January 1957).

Diploma in Technology

The National Council of Technological Awards has recently announced its list of awards of Diplomas in Technology for 1960; this brings the total number of Diplomas in Technology awarded to 457. It is announced that 4,969 students are now studying for the Diploma. A further point of interest is that the higher award, Membership of the College of Technologists (M.C.T.), has already attracted twenty applicants who have been registered as candidates.

Radio Engineering Overseas . . .

The following abstracts are taken from Commonwealth, European and Asian journals received by the Institution's Library. Abstracts of papers published in American journals are not included because they are available in many other publications. Members who wish to consult any of the papers quoted should apply to the Librarian, giving full bibliographical details, i.e. title, author, journal and date, of the paper required. All papers are in the language of the country of origin of the journal unless otherwise stated. Translations cannot be supplied. Information on translating services will be found in the Institution publication "Library Services and Technical Information".

AUDIO SPECTRUM ANALYSER

In 1942, H. G. Beljers described an acoustic spectrum analyser for the analysis of rapidly varying sounds such as speech. This analyser is in use at the Institute for Perception Research at Eindhoven and during recent years has been modernized by replacing mechanical rotary switches by electronic switches and also by introducing printed wiring. The analyser contains 79 filters whose pass bands, each a semi-tone in width, consecutively cover a frequency range from 86.5 to 7440 c/s. The voltages at the output of each filter successively produce vertical deflections on an oscilloscope and horizontal deflection is logarithmic.

"An acoustic spectrum analyser with electronic scanning", D. J. H. Admiraal, *Philips Technical Review*, 21, No. 12, pp. 349-56, 1959-60. (In English.)

DISTRIBUTED AMPLIFIER TUBE

A new type of wide band amplifier tube employing distributed input and output circuits has been developed by the Nippon Telegraph and Telephone Corporation. The anode and grid of this tube are helical lines and the velocity of propagation of electromagnetic waves on the anode line is equal to that on the grid line. The signal is amplified during its travel from the input of the grid line to the output of the anode line. The theory of amplification and the measured characteristics of the two experimental tubes are described in the paper. It is stated that the amplification band for one of the tubes extended from zero up to 150 Mc/s.

"Distributed amplifier tube", T. Kojima. *Review of the Electrical Communication Laboratory*, NTT, 8, pp. 343-68, July-August 1960. (In English.)

MEASUREMENTS IN ELECTRONICS

The October 1960 issue of the *Proceedings of the I.R.E. Australia* is devoted entirely to papers on electronic measuring techniques. Subjects dealt with include measurement of receiver noise, screened rooms, measurements on transistors, power measurements, precision capacitors, aerial design measurements, oscilloscopes, field strength measurement, errors in the use of electrical indicating instruments, intermodulation measurements on multi-channel carrier equipment, frequency standards measurements and calibration, transmission line v.s.w.r., studio acoustics determination, piezoelectric measurements, magnetic measurements and an automatic resistance tester.

Proceedings of the Institution of Radio Engineers Australia, 21, No. 10, October 1960.

NOISE ON MAGNETIC TAPE

A theoretical treatment of the modulation noise on magnetic tape has been worked out in a posthumous paper by a German engineer. The active layer of magnetic tape is considered as consisting of elementary magnetic domains with random positions and orientations. Each domain is supposed to be a single cubic crystal capable of carrying a magnetic moment in a direction parallel to one of its axes only. It is assumed that the remanent magnetic moment of each particle is proportional to the maximum magnetic field strength it had been exposed to during the recording process, and to the cosine of the smallest angle between the direction of the field and one of its axes. The voltage that, under these assumptions, appears across the terminals of the reproducing head, and its integral, representing the received signal plus noise, are calculated for a sinusoidal signal and a rectangular pulse. In particular the case of the sinusoidal signal is discussed with the aid of the correlation function. The average noise amplitude shows a time variation at the rate of the signal but, in contrast to a wide-spread opinion, the spectral distribution of the noise power does not depend on the signal frequency; the noise power per unit frequency falls off exponentially with increasing frequency.

"Modulation noise in magnetic tape", P. A. Mann. *Archiv der Elektrischen Übertragung*, 15, pp. 18-24, January 1961.

SUPERDIRECTIVE AND SUPERGAIN AERIALS

The problem of maximum directivity which can be obtained by means of an aerial of given dimensions has been investigated analytically by two French engineers making a simplifying assumption of linear distribution. The conclusions of this calculation have brought out a number of physical concepts which give a simple and exact interpretation to the phenomenon of superdirectivity. It thus appears that the superdirectional aerial is dependent on the possibility of generating in the neighbourhood of its aperture a large reactive field by means of a distribution of independent sources spaced less than half a wavelength apart. But experiment has shown that it is not possible to obtain such distributions unless a unidirectional element is interposed in front of each source, capable of breaking up the standing wave conditions which become established between adjacent sources. In this way it has been possible to design aerials with relatively high superdirectivity whose other features (level of secondary lobes, pass-band, etc.) still show acceptable values. The examples given concern structures of 5 and 11 sources operating in the 9000 Mc/s band.

"Superdirectivity, supergain", G. Broussaud and E. Spitz. *Annales de Radioélectricité*, 62, pp. 289-304, October 1960.