An Ultrasonic Memory Unit for the EDSAC

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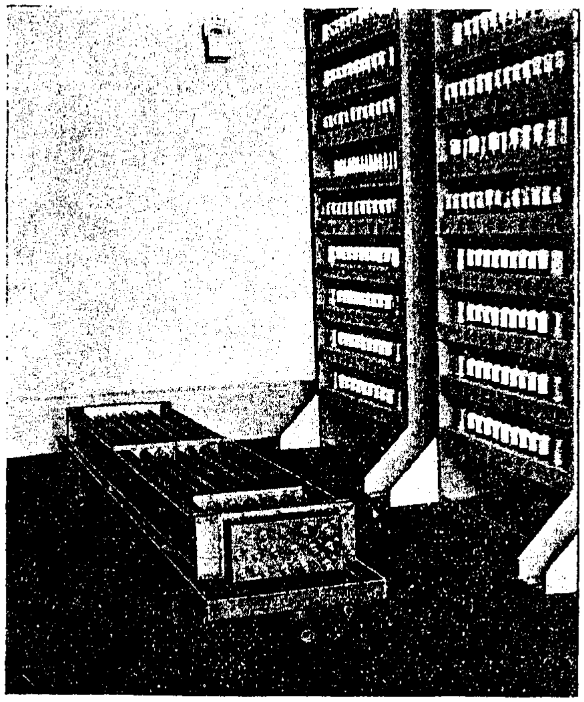

Fig. 5. General view of the computer racks with a completed battery of delay units in the foreground

Introduction

THE successful completion of the ENIAC by the Moore School of Electrical Engineering in Philadelphia marked a new stage in the application of electronic devices to computing.[1,2] This machine suffers, however, from two major drawbacks: its great complexity—it contains in all 18,000 valves—and its very limited memory capacity. The latter defect, although unimportant when solving the ordinary differential equations for which the machine was primarily intended, seriously limits its sphere of application. In order to deal with problems in partial differential equations, for example, one really needs storage capacity for hundreds or even thousands of numbers.

These limitations of the ENIAC were clear to the designers and even before it was finished a second project, for a machine known as the EDVAC (Electronic Discrete Variable Automatic Calculator), was being discussed. One of the authors was privileged to study the plans for this project in August, 1946, when he attended the latter part of a course on electronic computing machines at the Moore School; in this connexion he is especially indebted to Dr. John Mauchly, Dr. J. Presper Eckert, Dr. Herman H. Goldstine and Dr. T. K. Sharpless.

The EDVAC is now in course of construction and a machine on similar lines is being built in the University Mathematical Laboratory at Cambridge. This latter machine is known as the EDSAC (Electronic Delay Storage Automatic Calculator). Although it is not yet complete, two units of the memory have been built. The memory is the central part around which the machine is constructed, and as its design presents many problems of interest to electronic engineers, it is thought that a description of its main features may be of interest in advance of the completion of the whole machine.

The same type of memory is being used in the EDVAC and some information about it has already been published.[3,4]

General Principles

There are many advantages in designing a calculating machine to work in the scale of two. In this scale there are only two digits, 1 and 0, and numbers therefore lend themselves to representation by a train of pulses, the presence of a pulse indicating a "1" and the absence of a pulse a "0." Fig. 1 will make this clear. This system is adopted for the EDSAC and all internal operations in the machine are carried out in the scale of 2. The machine will, however, accept numbers in the scale of 10 and carry out the necessary conversion to the scale of 2 automatically; it will similarly convert output data into the scale of 10 before printing takes place. Users need not therefore take any account of the fact that the machine itself works in an unfamiliar scale.

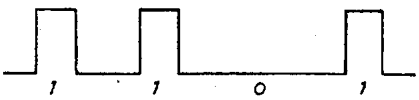

Fig. 1. Representation of binary digits by presence or absence of pulses. The binary number 1101 is equivalent to 2^3+2^2+0+1, i.e., 13 in decimal notation

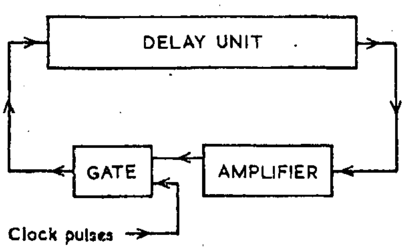

Fig. 2. Regeneration and circulation of pulses in delay unit

The programme of operations to be carried out by the machine is broken down into a series of orders, each of which represents an elementary arithmetical or transfer operation. These orders are expressed in code form as a train of pulses and are stored in the memory until required, in exactly the same way as numbers.

The memory system depends on the use of a device, by means of which a train of pulses may be delayed for a time interval longer than the duration of the train. The pulses are passed into the delay device and when they appear at the output terminals are amplified and routed back to the input. They are thus kept in circulation for an in-

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definite length of time and can be taken out when required. It will be noted, however, that a given group of consecutive pulses is not, in general, available at once, since it is necessary to wait until it emerges from the delay. This disadvantage is fundamental to the present type of memory and cannot be avoided.

The system as described above is open to the objection that the pulses would suffer some deterioration in waveform at each passage through the delay unit, the cumulative effect of which would be fatal to the correct functioning of the device. This difficulty is avoided by modifying the system in the following manner: Instead of being passed direct to the input of the delay unit, the outcoming pulses are applied after amplification to an electronic gate circuit which controls the passage into the delay unit of pulses (known as clock pulses) from a continuously running pulse generator. Each time a pulse appears at the output of the delay unit, a clock pulse is allowed to pass into the input; if no pulse appears, no clock pulse passes into the input. The result is exactly the same as if the pulses were circulating continuously, but they are, in effect, renewed at each passage and successive deterioration of shape is avoided. The arrangement is shown in diagrammatic form in Fig. 2.

Ultrasonic Delay Unit

The delay system used may now be described. It makes use of the fact that ultrasonic waves in liquids travel at speeds which are slow on the time scale on which electronic events can be made to occur, so that it is possible to delay a train of pulses for a comparatively long time by converting them into pulses of ultrasonic sound and passing them down a column of liquid a few feet long. The conversion is conveniently done by means of an X-cut quartz crystal, and an exactly similar crystal can be used at the far end of the tube to convert the ultrasonic pulses back into electrical pulses.

Before being applied to the transmitting crystal, the pulses are modulated on to a carrier wave of frequency 13.5 Mc/s. The crystals are cut to resonate at this frequency when unloaded. Modulation is 100 per cent. in the sense that the amplitude is zero between pulses. The pulses picked up by the receiving crystal are amplified, shaped and used to control the passage of clock pulses in the manner described above. Gating circuits are provided for input and output so that numbers circulating in the delay tube may be cleared when no longer required. The schematic diagram of a unit is shown in Fig. 3.

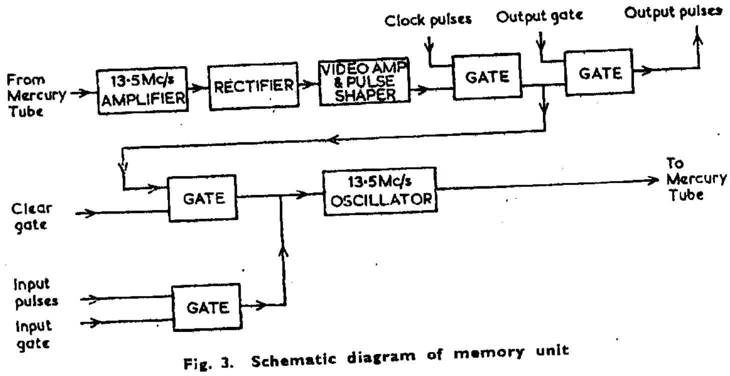


Fig. 3. Schematic diagram of memory unit

The storage capacity of an ultrasonic memory system depends on the length of the liquid column and the time interval between successive pulses. In order to make maximum use of a given length of liquid and therefore of a given overall delay it is clearly desirable to use pulses which are as short as possible. On the other hand the use of pulses appreciably shorter than 1 μS raises very difficult technical problems, and some compromise is necessary. In the EDSAC, the pulses are approximately 0.9 μS long, and the minimum interval between the end of one pulse and the beginning of the next is 1.0 μS. It may be mentioned here that the standard amplitude for pulses throughout the machine is about 18 volts.

For mathematical reasons which are outside the scope of this article, it was decided to make provision for 34 binary digits in each number. In the decimal scale this corresponds to about 10 digits. One additional digit is required to represent the sign, so that 35 consecutive pulses or blank spaces are needed to specify a single number. It is convenient to allow a space equal to one pulse length between consecutive numbers so that the total length of a number is increased to 36 pulses. This interval is sometimes referred to as a minor cycle, a term originally introduced by Dr. von Neumann of the Institute for Advanced Study, Princeton.

Choice of an Ultrasonic Delay Medium

The ultrasonic delay units described in this paper are filled with mercury. There are a number of reasons why this is the most suitable liquid to use, although if necessary satisfactory results could no doubt be obtained with other liquids. In the first place the acoustic impedances of mercury and quartz are similar, so that there is no difficulty in loading the crystal adequately and thereby ensuring good energy transfer with sufficient damping of the crystal to give the required bandwidth. Moreover, the temperature coefficient of variation of velocity of sound in mercury is fairly small over the range of temperatures usually found in a laboratory. It is not therefore necessary to keep the tubes at any particular temperature, but only to ensure that they are all within, say, ½° C. of the same temperature. The frequency of the clock pulses must in this case be controlled electronically by one of the delay tubes so that the time of circulation of pulses is equal to the correct number of clock pulse intervals. An alternative way of proceeding would be to keep the mercury tubes within close temperature limits by means of a thermostat and to use a crystal controlled oscillator. This method is not, however, being used in the EDSAC.

A final advantage of mercury is that it is not corrosive and the tubes can be made of mild steel. It is, of course, necessary to keep the mercury away from all brass parts.

Mechanical Construction

The wavelength in mercury which corresponds to the carrier frequency of 13.5 Mc/s. is about 0.004 in.; this is very small compared with the diameter of the active area of the

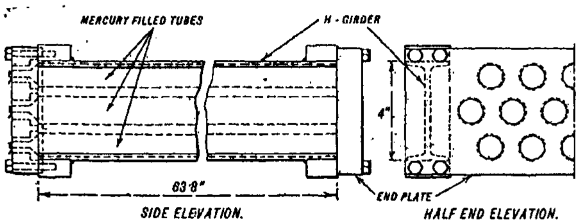


Fig. 4. Construction of battery of mercury tubes

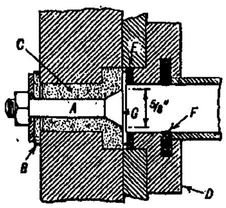


Fig. 6. Assembly of tube and end plate

A = brass electrode
B = Paxolin washer
C = Tufnol insert
D = steel collar
E = rubber washer
F = captive rubber washer
G = quartz crystal (.009 in. thick)

crystals ($\frac{5}{8}$ in.) and it follows from considerations similar to those familiar in geometrical optics that the crystals must be parallel to one another to within about 3 minutes of arc. For this reason a very rigid structure and accurate machining are required.

Fig. 4 is a sketch showing the form of construction adopted for the battery and Fig. 5 is a photograph of an assembled unit. The crystals are located against two plates of steel 1 in. thick, the surfaces of which are ground flat. These plates are held parallel to within an accuracy of better than 0.001 in. and at the correct distance apart by two 4-in. H-girders which have accurately-machined ends. The mercury tubes themselves are held in position between the end plates in the manner shown in Fig. 6.

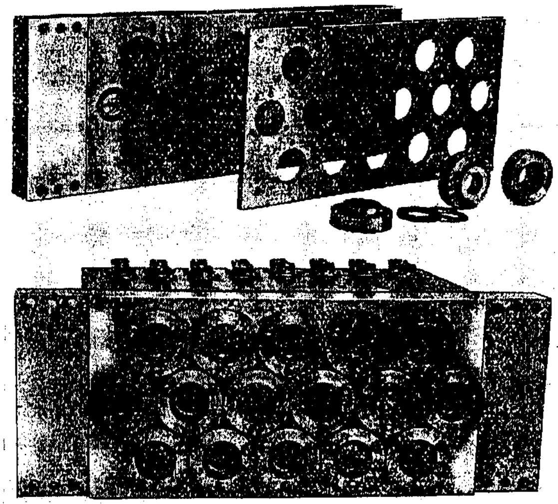


Fig. 7. End-plate assembly of battery. The upper photograph shows the exploded view. The screening cans seen in this photograph have since been replaced by the type shown in Fig. 5

The mercury itself provides electrical connexions to the front surface of each crystal, while connection to the rear is made by means of a brass electrode A which is let into the end plate and insulated from it by a Tufnol insert C and a Paxolin washer B. The final grinding of the end plates is not done until the electrodes have been inserted.

In the memory system being described, each tube is arranged to hold 576 pulses or 16 minor cycles. Since a memory capacity of at least several hundred numbers is required in the complete machine, it will be seen that many separate tubes are required. In the case of the EDSAC these are built in batteries of 16, each battery therefore holding 256 numbers. Two such batteries have been constructed and further batteries will be added as required.

The figure of 16 for the number of minor cycles in a single delay tube was chosen partly because it is a power of 2, and is therefore convenient from the point of view of switching operations, and partly because the resulting length of tube (about 5 ft. 4 in.) lends itself to sound mechanical construction. Also the use of very much longer tubes would have given rise to excessive attenuation. Similar considerations led to the decision to build the tubes in batteries of 16.

It may be mentioned here that the minute air gap which always exists between surfaces in contact, even though they have been ground flat, serves to prevent the passage of ultrasonic energy backwards from the crystal into the brass. This is because of the very large acoustic mis-match between air and brass, and between air and quartz. If this gap becomes filled with some liquid, such as oil, which wets both surfaces, it no longer acts as an acoustic insulator, and a serious loss of performance occurs. Some trouble was experienced at first on account of small quantities of oil trapped in the minute space between the brass electrode and the Tufnol insulator being drawn out by surface tension into the gap between the crystal and the brass electrode. This can be avoided by dipping each brass electrode into shellac varnish before assembly, so that the space between it and the Tufnol insulator is filled. As a further precaution, the use of oil should be avoided when turning the Tufnol insulators.

Each crystal is kept firmly in contact with the corresponding electrode by a steel collar, D (see Fig. 6), and a rubber washer, E, the latter forming a mercury-tight seal. The collar also contains a captive rubber washer, F, against which the end of the steel tube fits, and which forms a second mercury-tight seal. This form of construction gives an extremely rigid structure and makes assembly easy; at the same time the number of parts which have to be machined to a high degree of precision is reduced to a minimum.

Fig. 7 is a photograph of some of the component parts of an end plate assembly, and also shows an assembled end plate.

Assembly and Filling

Before assembly the tubes and crystals are carefully cleaned with carbon tetrachloride, as any dirt or dust tends to find its way to the surfaces of the crystals and impair operation. In the ordinary way mercury does not wet quartz, and in consequence there is a tendency for a thin film of air to be trapped between the mercury and the crystal. As in the case of the air gap behind the crystal, this has the effect of reducing transmission to a very low level. One way of getting over this difficulty would be to use chemically pure mercury and to pay careful attention to cleaning the surface of the quartz crystals; if this is done, mercury can be made to wet quartz. A better method, however, is to fill the tube first with some other liquid such as alcohol which wets both quartz and mercury. When the mercury is poured in, the alcohol is displaced and a thin film left on the surface of the crystals. This film is too thin to have any appreciable effect on the performance except that it acts as a bridge for the passage of acoustic energy. An experimental tube filled in this way has been in use for over a year and shows no sign of falling off in performance.

It was at first thought that the use of commercial mercury from which the bulk of the oxidisable impurities had been removed by a chemical method would give satisfactory results. Experience has shown, however, that the velocity of ultrasonic waves in different samples of mercury prepared in this way can differ by as much as 0.1 per cent. The effect is presumably due to remaining impurities, and for this reason it is best to fill the battery with double-distilled mercury.

The battery of tubes is placed in a welded steel tray which collects the alcohol displaced during the filling operation and any mercury which may overflow.

The crystals are connected to the electronic equipment by means of coaxial cables of 70 ohms impedance, and screening boxes attached to the ends of the battery contain the necessary matching circuits. These are very simple, each consisting of a 68-ohm resistance in series with a coil which tunes out the crystal capacity. Good screening at the end of the tubes at which the signal level is low is essential in order to avoid pickup of stray pulses radiated by electric motors and other laboratory equipment.

Circuits

An important aspect in which an electronic calculating machine differs from most other applications of pulse technique is that many of the waveforms are not repetitive. For example, at one moment a memory tube may be storing a number which consists of a continuous train of pulses and at the next moment this number may be replaced by one which contains a few pulses only, or even no pulses at all. As a result it is necessary to provide D.C. restoring diodes at every point in the circuit where there is a capacity resistance coupling, in order to prevent changes occurring in the D.C. level. The result is that D.C. restoring diodes make up an appreciable fraction of the total number of valves in the machine.

A typical gating circuit, or electronic switch, is shown in Fig. 8. The two inputs are applied through cathode followers V_1 and V_2 to the cathodes of diodes V_3 and V_4, the anodes of which are connected together and taken up to H.T. positive through a resistance R. Since the output impedances of the cathode followers are low compared with R, the anodes of V_3 and V_4, and hence the grid of the output cathode follower, can only rise in potential if the grids of both V_1 and V_2 rise; the output potential then follows that of the grid of V_1 or V_2 whichever is the lower.

Thus if a train of pulses is applied to the grid of V_1 and a positive going square wave to the grid of V_2, the pulses will appear at the output for as long as the square wave lasts, but will cease to pass as soon as the grid of V_2 returns to zero. Alternatively, two trains of pulses may be applied to each grid; a pulse will appear at the output when there is a pulse in each input, but not otherwise.

In practice there is a slight " break-through " when a pulse is applied to one grid only, the other being held at zero potential. This arises because the output resistances of the cathode followers V_1 and V_2 are not zero, and because the resistance of a diode in a conducting condition is also not zero. In the memory system being described, EB34's (double diodes) are used for the diodes, and EF54's (RL7's), connected as triodes, for the cathode followers. In this case the break-through amounts to about 13 per cent. for an applied pulse of 20 V peak amplitude, and the overall loss suffered by a pulse passing through the circuit is about 2 db. In certain cases, when break-through from one particular input is especially undesirable, it may be possible to arrange that the zero level for this input is slightly above that of the other. Break-through of pulses appearing on this input will not then occur, although break-through of pulses on the other input will be somewhat increased.

The performance figures given above are quite adequate for the circuits associated with the mercury units. In certain other parts of the machine, however, diode gates using EA50's are being used. If the resistance R is increased to 100 KΩ and the cathode resistors reduced to 1 KΩ the break-through is then only 8 per cent.; the transmission loss is still about 2 db.

The circuits used in association with the mercury tubes will now be described.

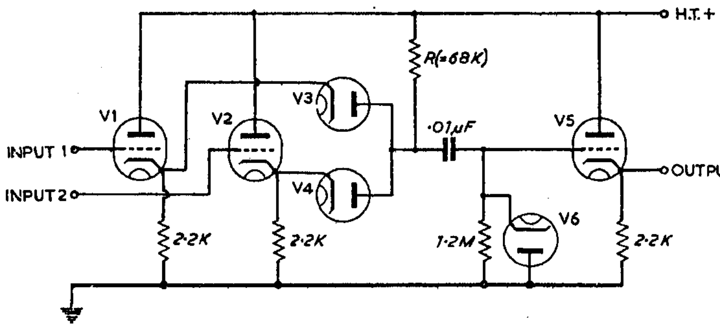


Fig. 8. Typical gate circuit

Fig. 9 shows the way in which pulses are modulated on to a 13.5-Mc/s. carrier before they are passed to the transmitting crystal in the delay tube. V_3 is an electron-coupled oscillator which is normally prevented from oscillating by V_2 which acts as a damping valve, its cathode impedance $(1/g)$ being connected across the tuned circuit. The incoming pulses of amplitude 18-20 volts are applied to the grid of an amplifier (V_1) which is biased back by about 10-12 volts in order to provide protection against spurious pulses entering the system from outside. When V_1 conducts, its anode potential falls and V_2 is cut off. The damping impedance is therefore removed from the tuned circuit, and V_3 begins to oscillate. In order that it should cease to oscillate promptly when the applied pulse ceased, it was found necessary to include an extra damping resistance (2.2 KΩ) in the cathode circuit of V_2.

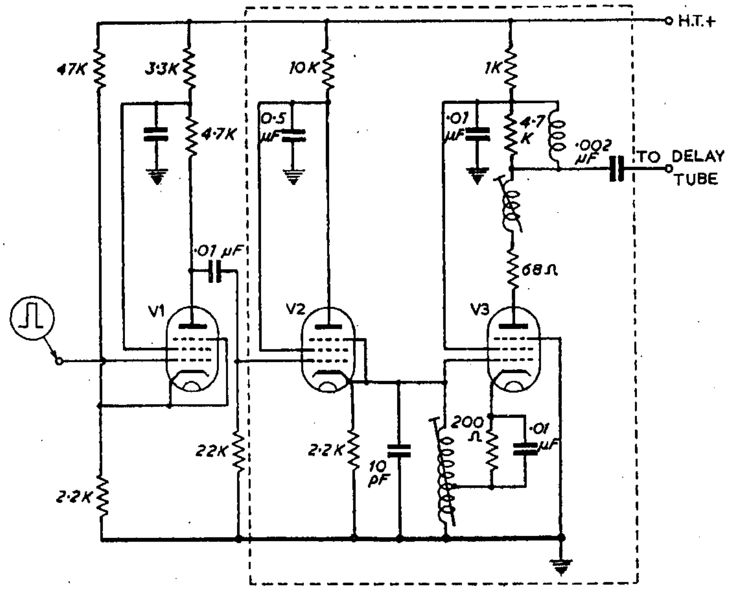


Fig. 9. 13.5 Mc/s oscillator circuit

R.F. pulses from the anode of V_3 are fed to the delay tube through a length of 70-ohm coaxial cable. Correct matching is achieved by the circuit shown which presents a parallel tuned circuit to the valve, and a series tuned circuit to the cable.

Details of the circuit used to amplify and regenerate pulses which have passed through a delay tube are given in Fig. 10. The R.F. pulse input to the transmitting crystal at 70 ohms is about 25 volts peak, and the loss resulting from transmission down the column of mercury together with the conversion loss at the crystal is about 68 db. The output from the receiving crystal at 70 ohms is therefore only about 10 mV, and two stages of R.F. amplification are provided before rectification.

It was decided after some consideration to design the system to have a bandwidth of 1 Mc/s. at 3 db. down (1.5 Mc/s. at 6 db. down). This is not sufficient to preserve the shape of the pulses, and they are lengthened to slightly less than 1.9 μS, *i.e.*, each pulse just fails to overlap the following pulse. In order to avoid difficulties with D.C. restoration, it is necessary to ensure that after rectification there is always a clear interval between pulses: this is done by applying a steady bias to the rectifier, so that only the tops of the pulses are able to pass through. This bias is arranged to be adjustable by means

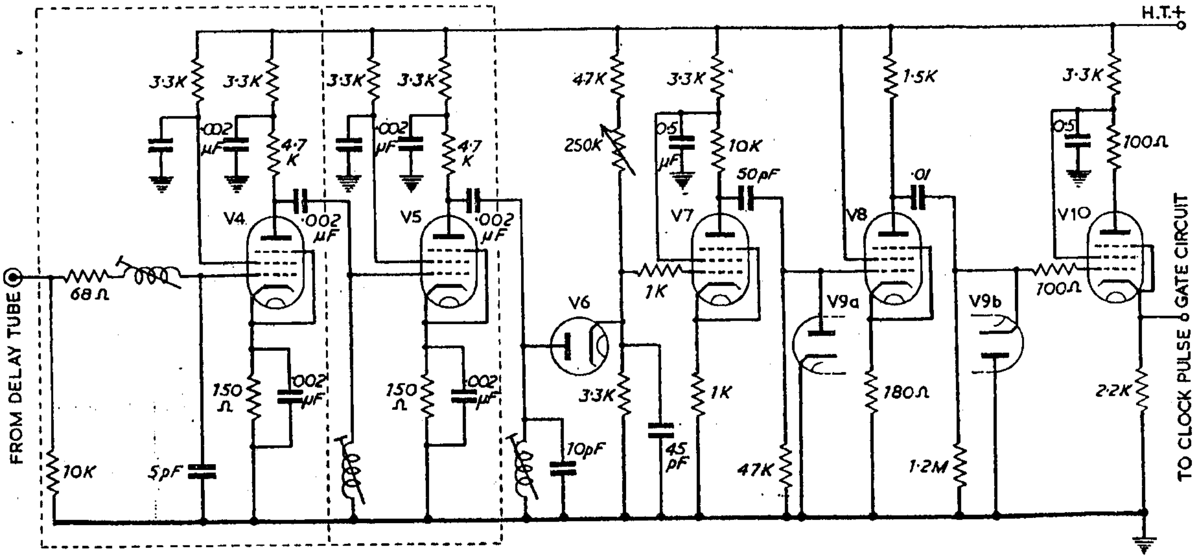


Fig. 10. R.F. amplifier, rectifier and pulse-shaping circuits

of a variable resistance, and this control takes the place of a gain control. The bias acts as an additional safeguard against the entry into the system of interfering signals from outside.

As an alternative, the system might have been designed to pass pulses without appreciable lengthening; a bandwidth of something like 4 Mc/s. would have been required for this purpose. While this would have been entirely practicable, the signal level at the input of the amplifier would have been lower, and an additional stage of amplification would have been necessary.

After rectification the pulses are passed into two shaping stages, one having a short time constant C-R coupling. The output pulse, which is between 1.6 and 1.8 μS long and about 28 volts in amplitude, is used to gate clock pulses. Since the clock pulses are only 0.9 μS long, there is an overlap of between 0.7 and 0.9 μS. This provides sufficient tolerance to allow for slight differences between units, variation of clock pulse frequency, etc.

Short Tubes

In addition to the long tubes comprising the main memory batteries, there will be a requirement in the control and computer units of the EDSAC for short tubes giving delays of length 1 minor cycle and ½ minor cycle. A sketch showing the mode of construction of one of these tubes is given in Fig. 11, together with a photograph of an assembled unit.

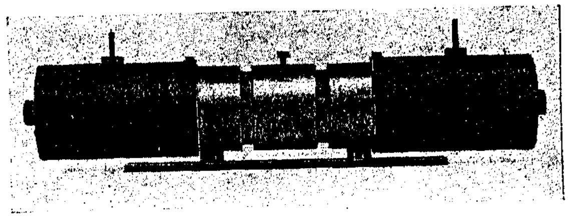
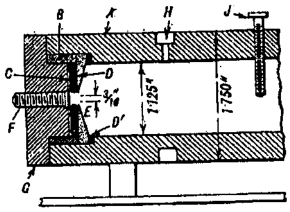


Fig. 11. Short tube, with sketch of its construction
A = steel tube
B = Tufnol sleeve
C = quartz crystal
D & D' = rubber washers
E = bevelled, sandblasted, mild steel washer
F = brass electrode
G = Tufnol plug
H = filling and expansion hole
J = steel plunger



It will be seen that the diameter of the active area of the crystal is only 3/16 in. compared with ⅝ in. in the case of the long tubes, and that it is surrounded by a bevelled and sandblasted washer. This is in order to reduce the amplitude of pulses which are reflected at the surfaces of the crystals and which makes several passages of the tube before entering the amplifier. As a further measure to this end, a 4 B.A. screw is inserted in the middle of the tube (along a diameter); this acts as a baffle, and causes a certain loss of energy at each passage of the pulses. Similar devices are unnecessary in the case of the long tubes, since the attenuation in the mercury is sufficient to reduce to a negligible amplitude pulses which pass more than once along the tube.

Acknowledgments

The authors would like to acknowledge gratefully much advice on the design and handling of mercury delay tubes which they have received from Mr. T. Gold. They are also greatly indebted to Mr. P. J. Farmer and other members of the laboratory staff for their enthusiastic assistance.

References

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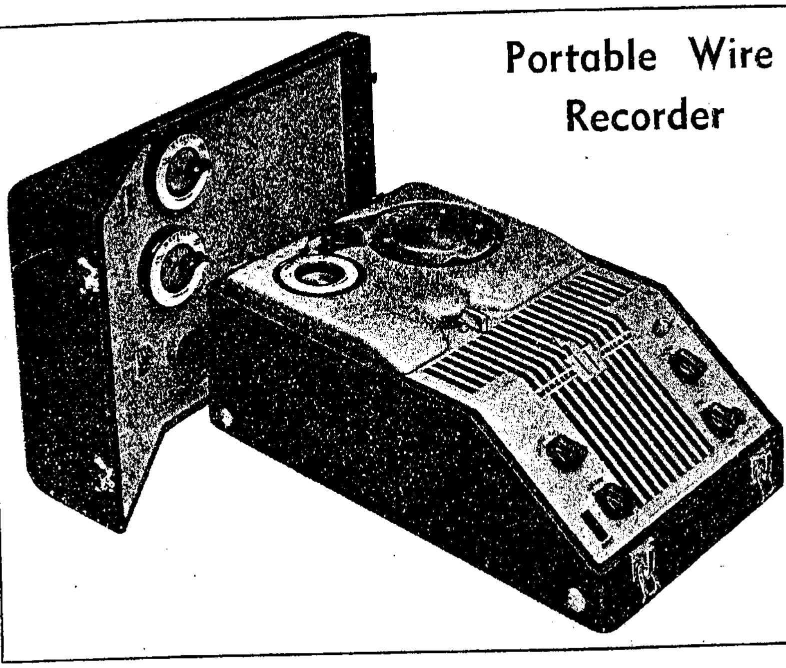
Portable Wire Recorder



THE Webster-Chicago Model 80 is a self-contained, portable magnetic wire recorder and player. It is sold complete with microphone and three spools of wire, two ½-hour and one ½-hour.

The wire is 0.004 in. diameter and runs at a speed of 2 ft./sec. for recording and 14 ft./sec. for rewinding, the driving motor being of the 4-pole, shaded-pole induction type. A single recording head is used for recording, playing and erasing. Four valves are used in the apparatus, three as amplifiers and one as a rectifier. Tone and volume controls are fitted and there is a built-in 5¼-in. loudspeaker, also an output socket.

The price in America is about £38. Makers: The Webster-Chicago Corp., 5610 Bloomingdale Avenue, Chicago 39, Illinois, U.S.A.