RESEARCH IN RADIO ASTRONOMY

FURTHER research in the field of radio astronomy has become possible by the opening of the Mullard Radio Astronomy Observatory which will augment the progress already achieved in Manchester and Sydney.*

To obtain the greatest amount of information from radio waves from outer space two requirements must be satisfied. First, the radiations must be received with the greatest possible strength. Second, the aerial must be of a kind which will provide an accurate measure of the angle of arrival of the waves. The power to make this measurement is called the "resolving power" and a great resolving power requires a large aerial. The obvious way to make observations in Radio Astronomy is thus to construct the largest possible aerial. Comparatively small aerials of this kind are in existence in Holland, Germany, and the U.S.A., and a large one with a diameter of 250 ft. is being constructed at Manchester University.

Resulting from earlier work in the Cavendish Laboratory at Cambridge, Mr. Martin Ryle, F.R.S., has shown† the possibility of making aerial systems for use as "interferometers"; the first large interferometric aerial was built in 1952 and has provided important results relating to the astronomical sources of radio waves. It is thought that some of the sources detected and measured with the equipment are at such a great distance that the waves from them take 3,000 million years to reach the earth—a distance greater than that at which stars and nebulae are visible even with the largest telescopes.

The success of the first large interferometer has shown that a still larger one will yield even more information. With the very generous help of Mullard Ltd., and the benefit of a D.S.I.R. grant, the Mullard Radio Astronomy Observatory has been built near Cambridge.

Figure 1 shows the positioning of the aerials used at the new Observatory. The "resolving power" of an aerial depends on the interaction or "interference" of the radio waves received at its edges, and the further apart these edges are, the greater is the resolving power. If the aerial is split into two parts, which are then moved apart for some considerable distance, the total area of the aerial is unaltered and the total power received is the same as before; but if the waves received in the two parts are properly combined they will, by their "interference" effect, provide a resolving power which is increased proportionally to the distance between them. In this way it is possible to increase the resolving power far beyond what is practicable with a single large aerial, and at the same time to keep the collecting power the same.

Furthermore, the technique of "aperture synthesis" has enabled the collecting area of the aerials to be made effectively even larger, since one of the parts of the aerial is made moveable, as shown in Fig. 1. The radio star interferometer works on a wavelength of 1·7 m, whilst the galactic background noise aerial is a pencil beam instrument working on a wavelength of 8 m and having a sensitivity patern of about $1° \times 1°$ to the half power point. The latter does not employ interferometric techniques. There are also other aerials as shown on the plan, e.g., for solar observations during the International Geophysical Year.

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Some Cambridge workers consider that their observations favour the theory that the Universe is expanding from an initial highly condensed state; this conflicts with the view which supposes a continuous creation of matter. Workers in Australia have stated that, with a different type of radio telescope, they have not been able to confirm the Cambridge view. The matter is so important for cosmological theories that every effort is being made to extend and improve the observations so that it can be decided without doubt which view is correct.

The new Observatory was opened by Sir Edward Appleton, F.R.S., on the 25th July last. In his speech at the Inaugural Dinner Sir Edward stated that the Mullard Company had assisted Cambridge University ". . . to maintain an old tradition—a radio tradition. We must remember that its first Professor, J. Clerk Maxwell, was the father of radio. Following him, Lord Rayleigh illuminated many radio developments in a manner which still keeps yielding modern benefits. J. J. Thomson's early researches were on the scattering of electro-magnetic waves; while, as every radio student knows, Rutherford's first love was the subject of wireless in which, at one time, his work rivalled that of Marconi himself. Nor should the radio work of Professor Mott himself be forgotten. For, during the war, he was responsible for both practical and theoretical progress in the field of radar. He made an outstanding improvement to the operational accuracy of anti-aircraft radar and also made the first mathematical investigation of the strength of the radar reflections to be expected from various shapes of targets."

The Cambridge project, which will cost probably more than a quarter of a million pounds, is an excellent example of the collaboration which can exist between Industry, the Government and the research work of Universities. Apart from its main purpose, the work involved may bring new information to the radio engineer, especially in the field of communications. Indeed, one of the first problems of the Observatory will be overcoming the interference from man-made transmissions, a point which was also commented upon by Sir Edward Appleton.

There are now various techniques in this comparatively new field, as for example a steerable paraboloid, 600 feet in diameter, which is to be used by the National Radio Observatory in America. Whatever method is employed, the technique used at Cambridge is of great international interest, involving the use of many new electronic aids.
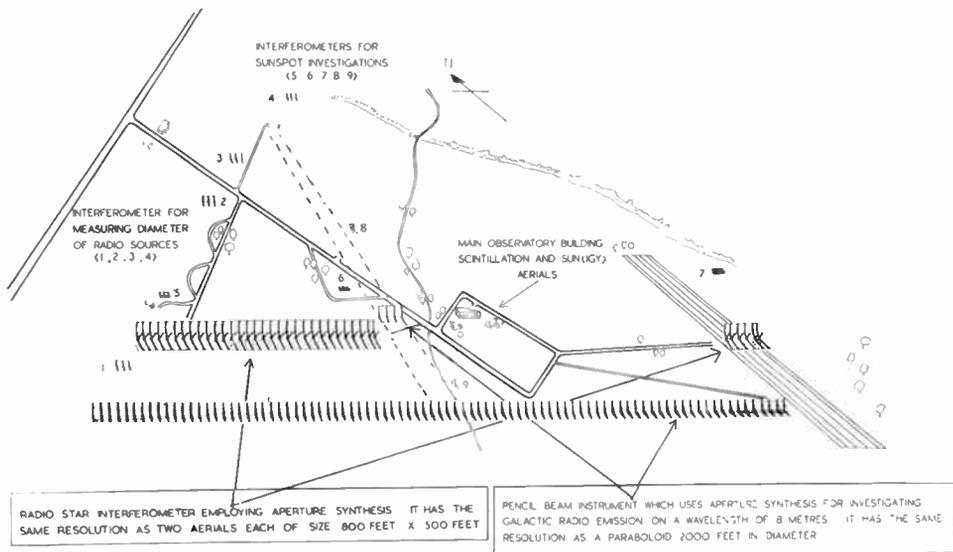

Fig. 1. Plan showing the positions of the aerials at the Mullard Radio Astronomy Observatory.

HIGH SPEED ANALOGUE-TO-DIGITAL CONVERTERS*

by

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A paper presented at the Convention on "Electronics in Automation" in Cambridge on 29th June 1957. In the Chair: Professor D. G. Tucker.

SUMMARY

Some control and computing problems are discussed in which advantage may be gained by encoding analogue quantities into digital form for subsequent processing. A voltage-to-digital converter has been designed for use with an electronic analogue computer in order to combine analogue and digital computation techniques. The system is basically a servo with a digital-to-voltage converter as a non-linear feedback element. A binary register, driven from a 100 kc/s clock pulse, is operated by gates arranged to allow an increasing or decreasing count, dependent on the sign of the error between the voltage input to the converter and the voltage analogue of the number in the register. Functional descriptions of the main parts of the equipment are given, with reference to some of the factors that have been found to be critical. The apparatus is now working, but experience has shown that considerable increase in both speed and accuracy is possible, and modifications which would provide this improvement are described.

1. Introduction

Increasing accuracy requirements in automatic information recording and processing are leading to a wider use of digital computers in control systems, data reduction and analysis. In a considerable number of applications, however, the information itself is continuous in nature, e.g. angular or linear displacement, voltage (representing such variables as speed, temperature, viscosity) etc., and this gives rise to hybrid continuous-digital systems.

One example of this occurs in the control of machine tools, where the programme of work may be detailed in digital fashion on punched cards or tape, whereas the mechanical process itself is continuous. It is necessary to provide a digital representation of the movements of the tool so that they may be compared with the instructions. Another type of hybrid system occurs in the field of high-speed computing, particularly in the study of physical systems. Here it is frequently the case that some parts of the computation require to be performed with a higher accuracy than others. Further, it appears to be fundamental that this higher

accuracy is normally required for parts of the computation concerned with mathematical manipulation; representation of the transfer functions of components does not usually have to be so precise. Thus it may be advantageous to combine the speed and simulation properties of the analogue computer with the accuracy of the digital machine.

The usefulness of hybrid control systems and computers is very much dependent on the performance of the equipment used to change the information from continuous to digital form and vice versa. This converter must have an accuracy, range of input, and bandwidth (i.e. maximum and minimum rates of change of input which can be converted) which are sufficiently high to cause negligible distortion of the accuracy, range and bandwidth of the input information.

2. Analogue-to-Digital Conversion Principles

Comprehensive and detailed reviews of analogue-to-digital conversion, and accounts of particular converters may be found in the references,[1-6] but a brief summary of the principles employed is given below, so that the method of conversion described in this paper may be considered in relationship to the entire field.

Analogue-to-digital converters may be divided into two major groups according to

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the encoding process. In one group are those which depend upon a two dimensional geometrical pattern for quantitization, while in the other group are those which depend only upon a suitable arrangement of logical electronic circuitry for encoding. The former group will be referred to as geometrical converters, while the latter will be referred to as all electronic converters. For most, but not all, geometric converters, the continuous input quantity is a linear or angular displacement, while for the all electronic converters, the input quantity is normally a continuous voltage, or occasionally a continuous frequency band.

2.1. Geometric Converters

In geometric converters, two-dimensional patterns, which are variations of the simple forms illustrated in Fig. 1, are used as converting elements. The rectangular patterns in (a) and (b) are used where the input quantity is a linear displacement, while the disc patterns in (c) are used where the input quantity is an angular displacement. Various methods of reading the code are available. One method is to photograph the pattern on a glass disc such that the pattern is composed of opaque and transparent areas. A light source is placed on one side of the disc, and depending upon whether a transparent or an opaque area is between this light source and a photocell detector, the light beam is transmitted or absorbed, giving a pulse or no pulse from the detector. Another convenient method of readout is to make the pattern of electrically conducting and non-conducting areas, which are detected by brush contacts. A further variation is to record the pattern on a magnetic drum, the readout being effected by a row of magnetic heads.

As the resolution of these geometric encoders increases, the size of the area available for one of the least significant digits decreases for a given overall size of pattern, and so the precision engineering problems are increased. Consequently the factor limiting the resolution obtainable with geometric encoders is mechanical engineering practice. In order to overcome the problem of producing a large number of small areas on one disc, two discs are attached to two shafts which are connected by gears. At present geometric shaft encoders are capable of resolutions up to 1 part in 2^{19}, by using two
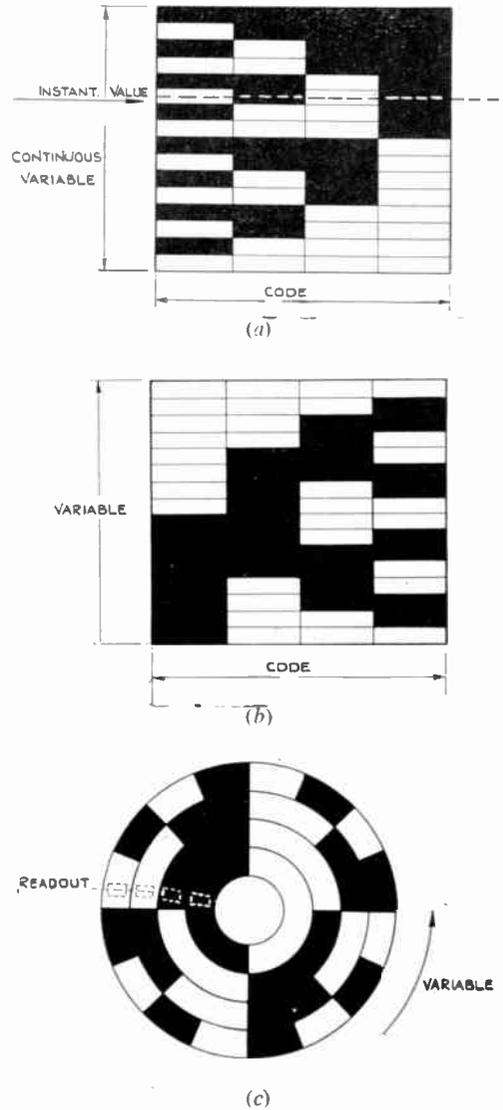

Fig. 1. Forms of binary code.
(a) Normal binary code.
(b) Gray code.
(c) Binary disc.

geared shafts.[7] Patterns on one disc[8] may be made to a resolution of 1 part in 2^{19}. Sampling rates of about 500 per second are achievable with these encoders.

The fastest type of converter in this class accepts a voltage input, which becomes displacement of an electron beam in a cathode ray tube. A rectangular binary coded mask is placed on the face of the tube so that a train of light pulses is generated when the beam is

deflected at right angles to the signal deflection. Alternatively, the pattern may be permanently photographed on to the target of the tube to generate an electron pulse train. Sweep rates of a few million per second are achievable, allowing independent conversions to be made at this rate with suitably fast readout mechanism. However, to achieve 10-digit accuracy, severe limitations are placed on the geometry of the tube, and on the linearity of the wide-band input amplifiers. For a light-obstructing mask on the face of the tube, conversion speed is limited by the response time of photocells to about 20,000 conversions per second.

The digital code may be read from the pattern either serially or in parallel, depending upon specific requirements. The variety of codes available for such applications include the normal binary code, binary decimal code, and cyclic progressive (e.g. Gray) code. A cyclic progressive code is used to advantage in geometric converters. It may be seen with reference to the normal binary code pattern in Fig. 1 (a) that a readout along the transition between codes 7 and 8 may lead to an ambiguity in any of the digit places. This is the worst case for the given scale, but there can be an ambiguity in the least significant two digits at every second transition. Transitions between adjacent numbers in the Gray code however involve a change in only one digit place, and for any digit place an ambiguity results in an uncertainty of only 1 unit in the number.

2.2. All Electronic Converters

Some of the principles on which converters using only electronic circuits have been based are summarized below : —

(a) A voltage is generated internally at a common summing point by varying the combination of parallel summing resistors, across which standard voltages are applied. The correct combination is chosen by a succession of delayed comparisons of this internally generated voltage with the applied voltage by one comparator. The binary decisions are serially controlled by a clock timing arrangement.

(b) A voltage is generated internally on a potentiometer principle, the number of pickoff points being finite, and adjacent pickoff points being separated by the minimum resolvable voltage. Comparison with the continuous input voltage indicates equality between the two voltages, and the searching process is halted.

(c) In a method similar to that described in (a) a separate comparator is used for each comparison of standards with the continuous input, and so successive differences are obtained at the output of each comparator. No clock pulse is used, each comparator being activated on completion of the more significant decisions. The result of this is that the minimum of logical circuits is required.

(d) A voltage sweep linear with time is initiated at the same instant as a gate passing clock pulses to a counter is opened. The voltage sweep is compared with the input voltage, and at the instant at which equality is attained, a pulse closes the gate to the counter. The number of clock pulses registered by the counter in the interval defined above, is then a measure of the unknown voltage.

(e) A second method of time encoding is to employ a variable frequency oscillator in which the frequency is a linear function of the control voltage. If the unknown is used as control voltage, and pulses from the oscillator counted for a fixed interval of time, the number registered in the counter is a measure of the input voltage.

Some practical considerations of the relative merits of representative converters employing the methods described above may now be discussed.

Referring to the method described in (a), there are different ways of programming the voltage switches, between the standard voltages and the summing resistor, for optimum performance for the particular application. The summing resistor values are weighted according to a geometric series of base 2, so that each summing resistor effectively adds standard voltages in a geometric series for comparison with the input voltage. By suitable combinations of these standard voltages

$$\left(\frac{V}{2^n}, \frac{V}{2^{n-1}}, \ldots \ldots \frac{V}{2} \right)$$

it is possible to derive $(2^n - 1)$ equally spaced voltage levels. One method of programming the switches, for high speed conversion, is to

cause the standard voltages to be switched for comparison one after the other in order of decreasing magnitude. The block schematic of the circuit arrangement is shown in Fig. 2. A ring counter is driven by a clock pulse, and the pulses from the ring control the bi-stable circuits of the digital register, which in state 1 connect the resistors to the standard voltage, and in state 0 connect the resistors to ground.
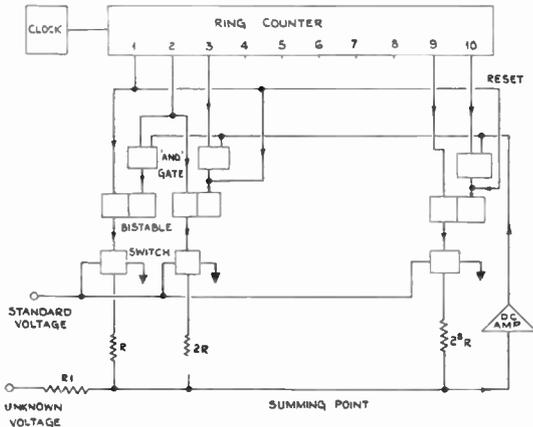

Fig. 2. "Bit-by-bit" converter.

At pulse 1, all bi-stable circuits except the most significant are reset to 0, and the most significant is set to 1. The unknown voltage is compared with the input, and the sign of the output from the d.c. amplifier determines which is the greater. If the unknown voltage is greater than the standard, the gate does not pass pulse 2 to reset the most significant bi-stable circuit, but if the unknown is less than the standard, the gate passes pulse 2 to reset the bi-stable to 0. Pulse 2 also changes the state of the next bi-stable circuit controlling 0·5 of the standard voltage from 0 to 1. The sign of the output from the d.c. amplifier determines whether the state of this digit place should be 0 or 1, and the decision is put into effect at pulse 3. In this process, the difference between the contributions of the input voltage and the sum of the standard voltages which have been accepted is less than twice the contribution from the next standard to be tested. The final difference is less than the effective least significant standard voltage, and the final result is determined in a period equal to the clock period multiplied by the number of digits in

the code. The switches may be relays or electronic switches depending upon the desired operational speed.

Converters have been constructed on this principle which are capable of providing in one case a scale of $\pm 2^{12}$ at a sampling rate of 8000/sec, and in another a scale of 2^{10} with 100,000 independent conversions per second.[9] Such converters may be used for processing continuous inputs in the audio frequency range in the course of vibration and transient analyses.

Alternatively, the switches for the standard voltages may be programmed by a reversible counter so that the internally generated voltage rises or falls in a series of equal discrete steps. When equality between the internally generated voltage and the input voltage has been reached the counter remains stationary. Then, any change in the input voltage is followed by the number in the counter either increasing or decreasing one unit at a time until equality is again reached. Although the method is inherently slow for rapidly changing inputs in that the state of the counter may increase or decrease by only one unit per clock pulse, the method allows a readout to be made during each clock period for slowly varying inputs. In this system there is an overall feedback loop. It is on this principle that the converter described in this paper operates, and advantages of the method are given in sections 3.2 and 5.3. One converter[10] operating on this principle has a scale of 2^{11} and a sampling rate of 200,000 per sec, so that full-scale inputs of up to about 15 c/s can be followed with full accuracy.

The field of application of the method described in (b) is restricted to slowly varying or stationary input voltages, because the potentiometer slider is moved by an electro-mechanical device such as a uniselector switch, and pulse rates used are about 20 per second.[11] Scales of $\pm 2^{13}$ are available in this type of converter. Since the application is often for a stationary input a visual readout in decimal notation is often provided.

The method indicated in (c) has been used for a quantizer which provides a readout in cyclic progressive code.[12] Although the method avoids the logical circuits and ring counter of method (a), there are as many amplifiers and discriminators as there are digit places in the

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code. This number of amplifiers would be undesirable particularly for an a.c. signal input as a result of the limited bandwidth.

The method of time encoding described in (d), and illustrated by Fig. 3, has the advantage of requiring little logical circuitry. The limiting factor in accuracy is linearity of the voltage sweep, for which a figure of 0·05 per cent. is achievable.[13] The sampling rate is limited by the speed of operation of the pulse counter and the number of digit places desired. For example, the time required for a 10-digit converter at 5 Mc/s pulse rate, is 200 microseconds for a full scale encoding. The sampling rate is about 1000/sec.
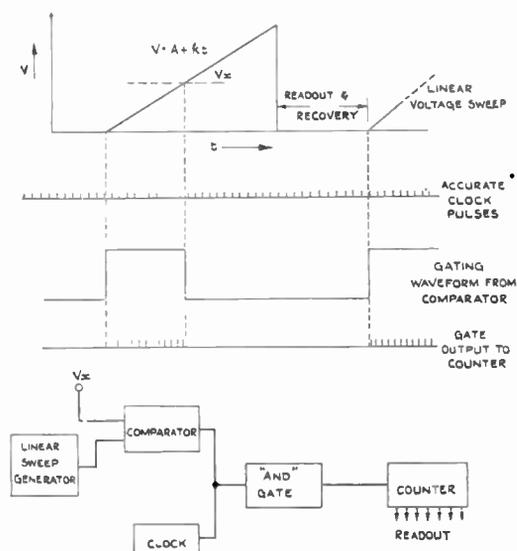

Fig. 3.   Time encoder.

The codes produced by the converting elements of the digitizers described above may be normal binary, cyclic progressive binary code, or binary coded decimal. However, the coding arrangement is flexible, and in certain cases one code may be transformed into an alternative code by a suitable conversion matrix.

3. Design of a Converter for use with an Analogue Computer

The particular converter described in this paper was required for use with an electronic analogue computer in order to digitize voltages representing the machine variables, so that analogue and digital computation could be combined. Nearly all of the techniques mentioned in section 2 could be used in this application, but it was considered that an all electronic device would be preferable to one of the geometric type, mainly because of the difficulties of changing the information from a voltage to a displacement.

3.1. Speed and Accuracy Requirements

The performance of the existing analogue equipment fixed the accuracy required of the converter at $\pm 0·1$ per cent. of the maximum of ± 100 V. The problems on which the computer was engaged concerned non-linear servos with statistical inputs, which were being studied either on a true or a slowed-down time-scale. The frequencies of interest were between zero and about 15 c/s. In order to give a conversion with an accuracy of $\pm 0·1$ per cent. of a sinusoid of this maximum frequency with an amplitude equal to the peak input voltage, the counting rate on a binary scale must be not lower than about 100,000 least significant digits per second. It is also necessary that the binary representation be within $\pm 0·1$ per cent. of the true value when the information is being read. It was intended that the converter should be capable of working into several different types of digital equipment, and if this is to be achieved readily, the binary values must be within the stipulated limits of error for the majority of the time.

3.2. Design of the Converter

These considerations led to the choice of an electronic servo arrangement with a binary digital-to-analogue converter as the feedback element. The binary number is increased or decreased so as to remain a representation of the input voltage. This type of system allows the fastest possible following of a single slowly varying input, with the facility for accurate read-out at any multiple of the digit repetition rate.

The general principle on which the converter operates may be seen from Fig. 4. Here the number in the register is converted to the voltage analogue and compared with the input voltage by the error detector. If a difference exists, then clock pulses are passed by the gate in such a fashion that the count in the register is either increased or decreased so as to offset the error.

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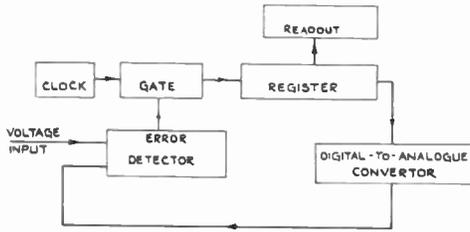
Fig. 4. Block diagram of the experimental converter.

Circuits have been designed by W. G. Hughes[14] to meet the above speed and accuracy requirements with the chosen form of converter, as follows:

The range of variation of the input voltage was ± 100 V, and the convention used to represent this in binary form was that -100 V should be zero, and $+100$ V should correspond to the full register. This is equivalent to adding a constant to the input voltage so that it varies from zero to $+200$ V.
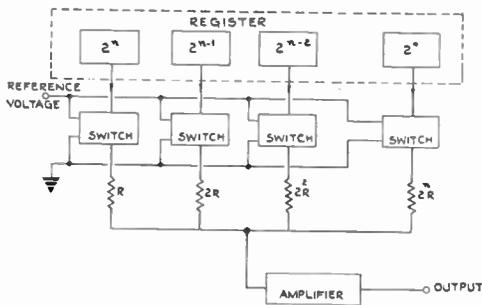

Fig. 5. Digital-to-analogue converter.

The digital-to-analogue conversion is arranged by connecting a precision electronic switch to each stage in the register (Fig. 5). With the switches are associated resistors whose values are in inverse proportion to the significance of the particular digit. When a stage of the register is set to "1" the switch connects a reference potential to its resistor, and for a "0" the resistor is earthed. The ends of the resistors remote from the switches are commoned and connected to an amplifier, so that the voltage at its output is the analogue of the digital number.

This amplifier is used to amplify any error that may exist between the digital representation and the input voltage, by adding further summing resistors (Fig. 6). A steady bias

voltage is added via resistor R_B, this being the constant required to change the effective range of the input voltage from ± 100 V to $0 - +200$ V, and the unknown is added via R1. With sufficient gain in the amplifier (in this case about 200) a usefully large output will be given by an error equivalent to the least significant digit. The performance requirements for this amplifier are rather stringent. It must maintain its gain from d.c. up to several times the pulse repetition rate in order that inputs from d.c. up to the required 15 c/s can be converted accurately. (It should be noted that a lag in the error detection which is long compared with the pulse period could cause the servo to become unstable. A number of writers have considered the question of stability of servos containing continuous and discontinuous elements in the loop.[15,16]) A further requirement is that, in the interests of accuracy, any drift or noise introduced by the amplifier must be small compared to the voltage representing the least significant digit.
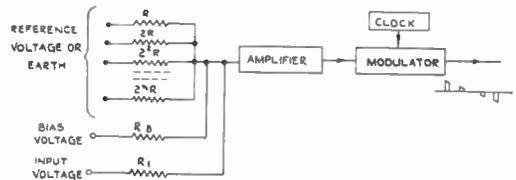

Fig. 6. Error detector.

The error appearing at the output of this amplifier is sampled once every pulse period by a modulator driven by the clock, giving an output of the form shown in Fig. 6. This output passes to a sign selector (Fig. 7) which connects positive-going pulses to one line when the sampled error signal is positive, and positive-going pulses to a second line when the sampled error is negative. A threshold has been set into
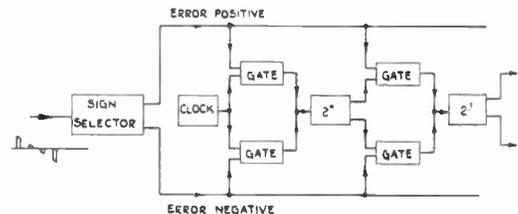

Fig. 7. Counter control.

this sign selector, so that neither line is activated if the error is less than about half that corresponding to the least significant digit. This prevents the last stage of the register from oscillating at balance. The two lines are used to control a pair of gates between each stage of the binary register in such a manner that with one line activated, corresponding to, say, a positive error, pulses from the clock are added, while if the error is negative, so that the other line carries the control pulses, the count is decreased. The direction of counting is arranged to decrease the error between the voltage input to the converter and the voltage analogue of the binary number.

4. Realization of Design

The circuits comprising the converter divide themselves into two main blocks, the error detector and the register. Since there is an internal digital to analogue converter· many of the circuits are required to operate on continuous voltages without disturbing the voltage levels, and to maintain long term d.c. stability. The remainder of the circuits are digital in nature, and are concerned only with sequences of events. Consequently the blocks of the converter are grouped into two sections for further consideration.

4.1. *Functional Circuits*

Included in this section are the reversible counter and its associated gates, the modulator and sign selecting channels.

4.1.1. Reversible counter

The most important feature of the logical circuitry is the reversible counter. The binary circuits of the counter or register have been designed to operate at a pulse repetition frequency of 100,000/sec, as required by the specification. The switching of the standard resistors depends on the transitions of the binaries, which in turn depend on the carry pulse from previous stages. At a pulse repetition frequency of 100,000/sec, transition time has presented no problem, the transition time of the binary circuits in use being 1 microsec for a voltage swing of 100 V. The time taken for the trigger pulse to carry through 4 binary stages is less than 1 microsec. However, it is obvious that the p.r.f. cannot be increased by an order (to 1 Mc/s) unless a big improvement is effected in the binary transition time. One reason why this transition is so long is that the anode voltage swing is 100 V in order to give effective switching of the 50 V reference being used. Further, a twin triode (CV.455) is being used in the Eccles-Jordan circuit. However, the
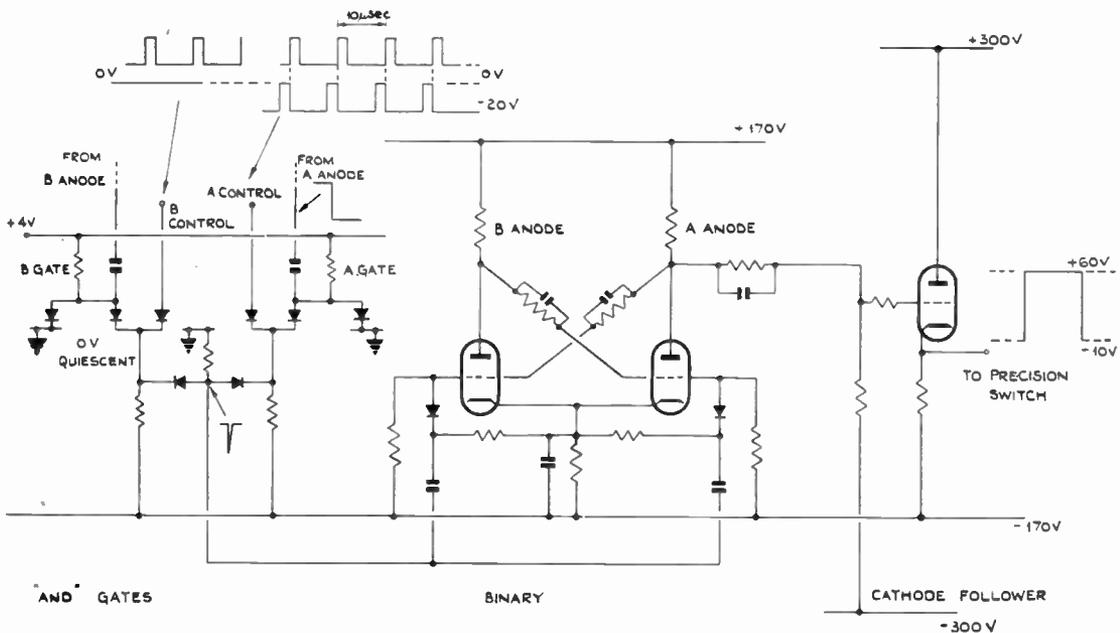

Fig. 8. Gate and binary stage.

circuit is quite adequate for the present requirement. Factors involved in increasing the p.r.f. are considered further in section 5.2. The circuit of the binary stage is shown in Fig. 8.

Since any switch may be required to remain open or closed indefinitely· the voltage levels of one binary anode have to be transferred to the switches on a d.c. basis by a potential divider. This results in attenuation of the difference between the anode voltage levels, but for other reasons it was undesirable to use any other than a +170 V supply for the binary anode loads. To prevent loading of the potential divider, the divided point is followed by a d.c. cathode follower.

In order to use the passive differentiators and gates between the binary stages for deriving and controlling the carry pulses, the binaries have been designed to trigger from a pulse of about 4 V in amplitude. In this way a sharp low amplitude pulse is derived without overloading the binary circuits.

4.1.2. Gates

The binary counter is rendered reversible by changing the source of carry pulses, for a particular stage, from one anode of the preceding binary stage to the other anode. All carry pulses from anodes (A anodes) controlling the voltage switches are either passed or inhibited at any transition time through gates (Fig. 8) according to the signal on one control line (A control line). The same operation is performed on carry pulses from the remaining binary anodes (B anodes) by the second control line with the reservation that only one control line is active at any given transition time. If the convention, that an "A anode" non-conducting indicates state 1 of the binary, is adopted, then the "A gates" should be open for an increasing count in the register.

An illustration of the reversal of direction of count of a four stage counter, such as described above, in response to a change of control waveforms· is shown in Fig. 9. The upper trace is an error signal which causes the control line, appropriate to the sign of the error signal, to be activated. The lower trace is the voltage at the common point of the summing resistors and shows the direction of counting in synchronism with the sign of the error signal.

4.1.3. Modulator and sign selecting channels

The error signal modulator or interrogator initiates the control circuitry for direction of counting in the register. The modulator consists of a double diode bridge (Fig. 10) such that one bridge conducts while the other is non-conducting, and vice versa, the outputs of the bridges being commoned at point A. The input to one bridge, which conducts during the sampling period, is the error signal, while the input to the other bridge is zero. Power is supplied to the modulator by antiphase waveforms at points B and D, which are derived from the clock pulse generator by a push-pull twin-triode amplifier. Large transients cannot arise through mismatch of the waveforms because the output is clamped either slightly above or slightly below earth by diode bridge X until it is non-conducting, by which time the other bridge is conducting. The transients which do arise are of about ±1 V amplitude, as a result of diode contact potential.
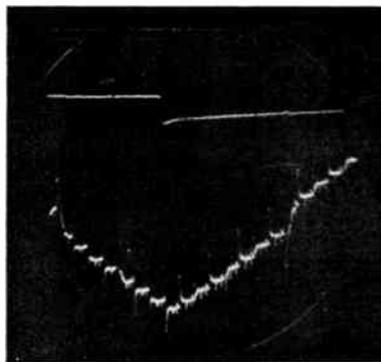

Fig. 9. Bidirectional counting. Sweep duration 200 microseconds.

The modulated error signal is fed to a push-pull amplifier, to each anode of which is attached a C–R network for the purpose of d.c. restoration and sign selection of the error signal, as illustrated in Fig. 10. During the interval in which the modulator output is clamped to ground, the C–R junction is also clamped to ground and the capacitor is charged to the voltage between the amplifier anode and earth so that it can serve as a store. During the sampling period, the clamp is removed, the anode of the amplifier changes potential in accordance with the error signal, and so does the C–R junction, which has a long time

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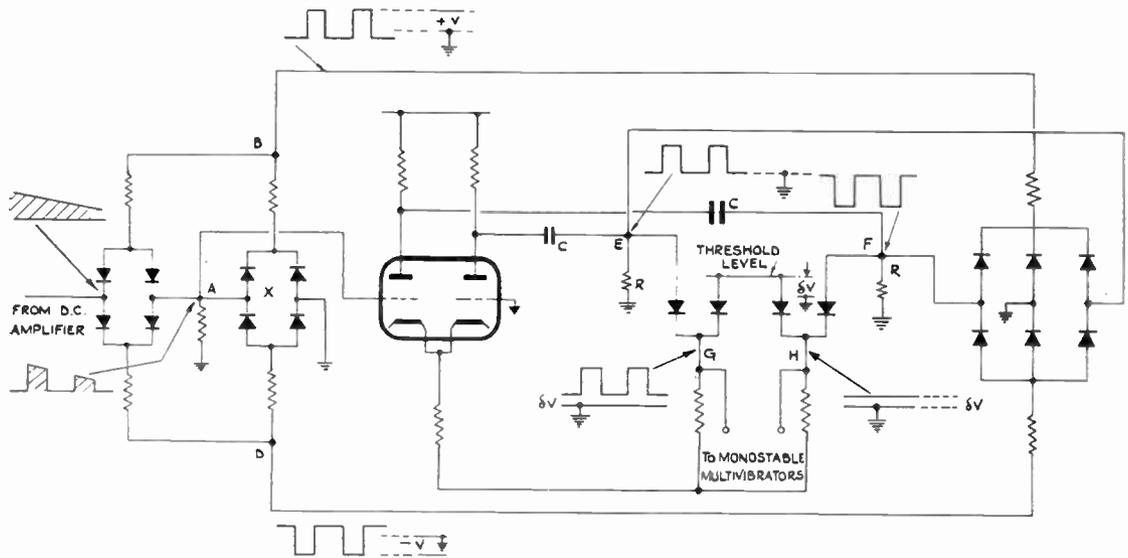
Fig. 10. Error detector.

constant. In this way, the potential at either E or F goes positive during the sampling period depending on the sign of the error voltage. It is at this point that a threshold level is set, such that if the error signal is not sufficiently large, no voltage change appears at points G and H. In this way the limit of discrimination of the feedback loop can be set, and the counter prevented from oscillating about the value of the input voltage. Any voltage which rises above the threshold is amplified and differentiated to provide trigger pulses for the monostable multivibrators which control the interstage gates in the register.

4.2. The Error Detector

The circuits included for description under this heading are the precision voltage switches, the d.c. amplifier, summing resistors, and the reference voltage supplies. The important considerations for these circuits are accuracy of function with regard to voltage, and long term voltage stability. Speed of response to step function inputs is important also, for the specification requires that the error voltage at the output of the d.c. amplifier be available for inspection in less than 10 microsec after a change of count in the register.

4.2.1. Precision voltage switches

The function of the precision voltage switches

is to close one end of the summing resistors to the reference voltage or ground through a low impedance, the transition time being as small as possible. The circuit for the precision voltage switch is shown in Fig. 11, for which the controlling voltage levels are supplied from the output cathode follower in Fig. 8. For a reference voltage of 50 V and an accuracy of 0·1 per cent., the difference between V and V_1 should be less than 0·05 V when the bridge is conducting. If the current flowing through each of the four diodes was the same, then by choosing four diodes in two matched pairs, it could be arranged that $V_1 - V = 0$. However, the current for the load resistor R1 flows through diode 2 only, which would lead to unbalance of the bridge for the above choice. A procedure for overcoming the unbalance of the bridge when a load current is flowing in R1 has been adopted. When R1, R2 and R3 have been chosen, the relative currents in the respective diodes may be calculated assuming the voltage drop across each diode to be the same. Then from a large number of diodes for which the characteristics around the known operating point have been measured, diodes having the required characteristics for the bridge are chosen. The characteristic around one point only need be known since the bridge is a constant current device when conducting, by
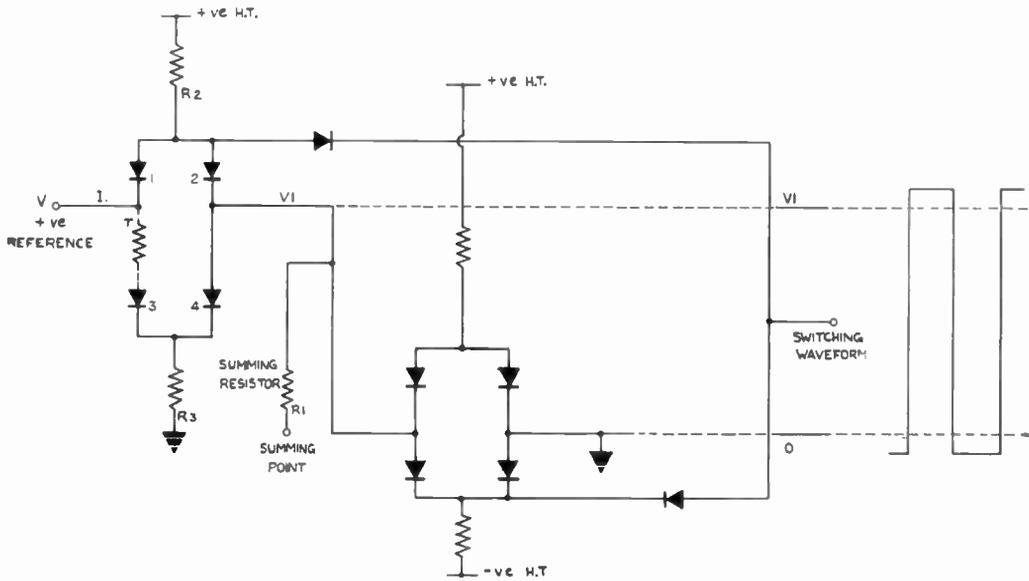
Fig. 11. Precision voltage switch schematic.
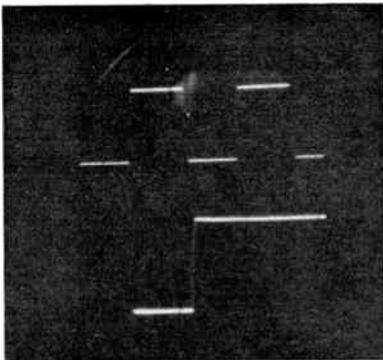
Fig. 12. Precision switch waveforms. Sweep duration 40 microseconds.

virtue of a fixed value of V. It has been found in practice that $|V_1 - V_0|$ is consistently less than 0·05 V when the procedure indicated above is adopted. An alternative method of restoring the balance is to insert resistors (r in Fig. 11) in series with the diodes.

The voltage rise and fall times at the output of the switch during transition are the same as those of the switching waveform as illustrated in Fig. 12, the lower trace being transitions at the output of the switch.

4.2.2. D.c. amplifier

The requirement for the d.c. amplifier is that it should have a gain of about 200 and a pass-band sufficient to permit operation of the converter at a pulse repetition frequency of 100,000/sec. Consequently, the desired pass-band is about 500 kc/s. Further, since the quantized voltage levels are separated by intervals of 12 mV at the summing point, for a reference voltage of 50 V and a 10-digit resolution, the drift should be small compared with 12 mV. For high sampling frequencies, drift stabilization by means of an a.c. feedback loop would introduce a phase lag, so the effect of drift has had to be minimized by other means. The circuit diagram of the d.c. amplifier used is shown in Fig. 13. Two differential amplifier stages are used for the purpose of reducing the effect of heater and h.t. fluctuations. An attempt has been made to eliminate the common mode variation as far as possible in the second stage by the use of a high impedance circuit as cathode load. The long term drift measured with reference to the input grid has been limited to ± 2 mV over a test period of a few days. The frequency response of the amplifier is demonstrated in the oscillogram of Fig. 14, in which the upper trace exhibits the input test pulse which was attenuated in order not to limit the amplifier, and the lower trace shows the response of the amplifier to the pulse.

4.2.3. Reference voltages

The positive and negative reference voltages

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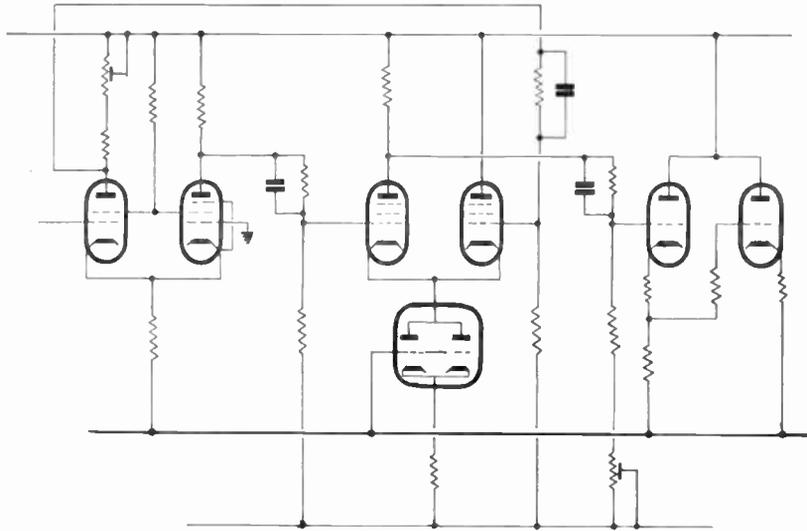
Fig. 13.   D.c. amplifier.
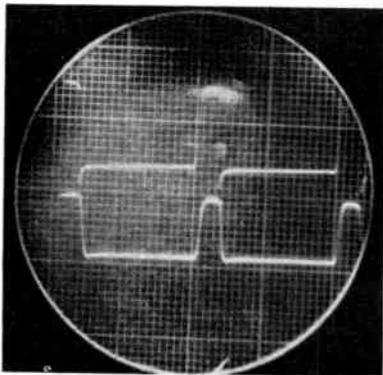
Fig. 14.   D.c. amplifier pulse response.   Sweep
duration 20 microseconds.
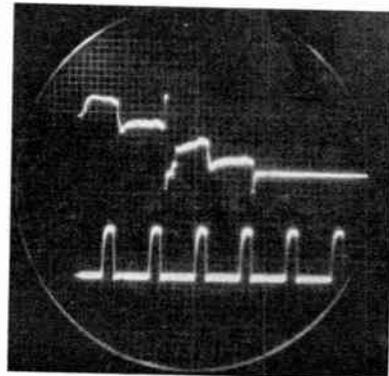
Fig. 15.   Amplified summing point voltage.   Sweep
duration 60 microseconds.

are supplied by standard drift-corrected computing amplifiers using high stability input and feedback resistors. The input to the amplifier supplying the positive reference voltage is supplied by a reference battery, and the amplifier supplying the negative reference voltage is fed from the positive reference voltage. In this way, the effect at the summing point of any variation in the reference cell is reduced as compared with using two separate reference cells.

4.2.4. Summing resistors

For an accuracy of conversion of 0·1 per cent. of full scale, the requirement for accuracy of the switched summing resistors in order of decreasing significance is 0·1%, 0·2%, 0·4%,

and so on. The remaining two summing resistors which are not switched, the input voltage resistor, and the negative reference voltage resistor, are required accurate to 0·1 per cent. From considerations of operating speed, the time constant at the summing point should be small compared with 10 microsec, so that following a step voltage input via one of the summing resistors, the summing point responds to the pulse before the output of the amplifier is sampled. The value of the most significant summing resistor has been chosen to be 50 kilohms, so that for a reference voltage rail of 50 V the current load on the switch is 1 mA. It is desirable to operate the switches with not more than such a load in the interests of power
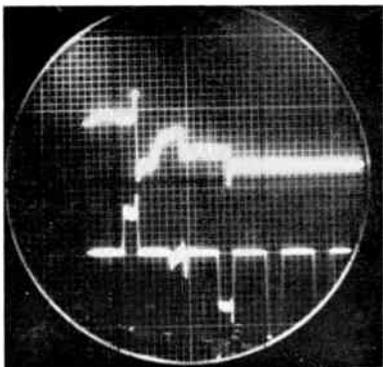
**Fig. 16 (a).** Error voltages. Sweep duration 50 microseconds.
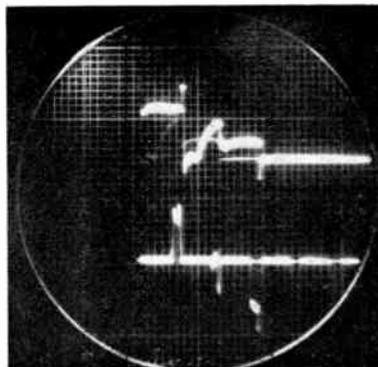
Fig. 16 (b) Error voltages. Sweep duration 50 microseconds.

economy, even though lower value summing resistors would reduce time constants at the summing point. A reduction in the value of the reference voltage by an order is not possible using the d.c. amplifier as a voltage discriminator. From the point of view of accuracy and long term stability, wirewound resistors would be chosen for the more significant summing resistors, but the remanent inductance for impedance of the order of 100 kilohms renders their use intolerable. Consequently, for the more significant summing resistors, cracked carbon high-stability resistors have been used because of their low inductance. It may be thought that the relatively high thermal coefficient of these resistors would prohibit their use, but since the resistors have been kept in close proximity, their temperatures are not very different, so that the differential change of resistance with temperature is small. The combined frequency response of the summing point and d.c. amplifier to a stepped input is shown in Fig. 15. The step changes in the voltage level are the result of changes in the count of the register by the least significant digit.

4.3. Readout

As yet a system of readout has not been tested, firstly because of its secondary importance with respect to the study of the conversion itself, and secondly, because the requirements for the readout are dependent upon the digital computer into which the converter will write the code.

4.4. Converter Stability Test

The procedure adopted for testing the stability and resolution of the converter is as follows. With a voltage input of 0 V, the register is continually cycled in one direction and the voltage levels of the d.c. amplifier inspected for an interval in the middle of the cycle. At this time, the voltage at the summing point passes through 0 V and so does the output of the d.c. amplifier. Consequently any change in this level is readily observed at the output of the modulator. The oscillograms of Fig. 16 exhibit the output of the d.c. amplifier on the upper traces, and the output of the modulator on the lower traces. The voltage level on the left of the oscillograms corresponds to the count (0 1 1 1 1 1 1 1 1 1) for which all resistors except the most significant are conducting. The adjacent level corresponds to the count (1 0 0 0 0 0 0 0 0 0) for which only the most significant resistor is conducting. Consequently, any differential change in resistance of the summing resistors is readily observed. The oscillogram of Fig. 16 (b) was photographed 3 days after that of 16 (a). During this time there were no significant changes either in the absolute voltage levels or the relative voltage levels.

5. Future Work

It is felt that the accuracy and speed of this type of converter can be increased considerably over the values achieved with this experimental model, and that the equipment can be used for other purposes as well as straightforward digitizing. Some of the projected investigations into improvement of speed and accuracy of conversion, and the application of the general

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principle to function generation are outlined below.

5.1. *Increase in Accuracy*

Any major improvement in accuracy of conversion requires an increase in the sensitivity and stability of the voltage comparator. One method of approach is to modulate the error signal before amplification (which could then be done in an a.c. amplifier), thus eliminating the problem of amplifier drift. It is considered that a modulator, probably using silicon transistors, can be designed to introduce less noise and drift than the d.c. amplifier.

Resistors of higher stability than 0·1 per cent. would be required for higher accuracy. Metal film resistors have not yet been tested in this application, but may give the required stability. If the reference voltage level could be reduced it may be possible to use wire-wound resistors, if necessary in an oven.

5.2. *Increase in Speed*

Before an improvement of an order in the clock pulse rate can be achieved, transition times of the binary circuits and the time constant at the resistor summing point will have to be reduced. A reduction in the reference voltage level from 50 V to 10 V, with a corresponding reduction in the impedances of the summing resistors, would be a way of
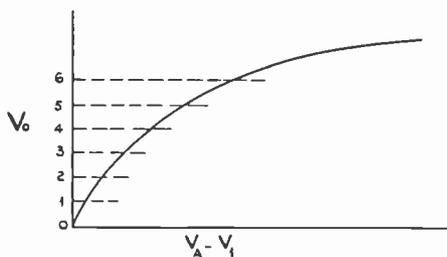
Fig. 17. Form of response of non-linear error detector.

achieving this and would also make a completely transistorized unit possible. However, this can be done only with a more sensitive voltage comparator so that the problems of

speed and accuracy are interrelated to some extent.

A somewhat different method of tackling the problem is being considered for inputs which change more rapidly than can be followed by the present form of converter. The servo principle would be retained, but the error detector would be modified to have an approximately logarithmic characteristic. In Fig. 17, $V_A - V_1$ is the error voltage between the input and the analogue of the number in the register; V_0 is the voltage output of the modulator. This output would be used to drive gates in such a manner that if the error were such as to cause an output between 0 and 1, then clock pulses would be connected to the least significant digit; for an output between 1 and 2 the clock would be connected to the next least significant digit and so on. By this means the logic, and hence the speed of response, can be optimized with respect to rate of change of input. It should be noted that it is not necessary to quantize this output and provide gates for every digit in order to achieve a significant increase in speed. This technique will provide conversion of inputs ranging from the originally specified slowly varying voltage up to step inputs, due, for instance, to multiplexed input voltages, in the minimum time.

5.3. *Other Possible Applications*

Due to the dependence of the digital-to-analogue conversion on the reference voltage, it is inherently possible to use the equipment for dividing one variable by another as well as providing a digital representation of the quotient, if the reference is replaced by one variable.

The servo technique causes the error detector to produce an output only when the input quantity is changing. Thus the converter can be used as a form of differentiator as well as digitizer, and with the addition of conventional analogue computing elements it can be arranged to provide differentiation with respect to variables other than time.

The accuracy and speed with which operations of this sort can be effected has not yet been studied, but it is hoped to devote some attention to this when the primary task of developing a satisfactory converter is completed.

6. Acknowledgment

7. References

1. M. L. Klein, F. K. Williams and H. C. Morgan, "Analogue to digital conversion," *Instruments and Automation*, **29**, pp. 911-917, May 1956.

2. M. L. Klein, F. K. Williams and H. C. Morgan, "Practical analogue-digital converters," *Instruments and Automation*, **29**, pp. 1109-1117, June 1956.

3. M. L. Klein, F. K. Williams and H. C. Morgan, "High speed digital conversion," *Instruments and Automation*, **29**, pp. 1297-1302, July 1956.

4. P. Partos, "Industrial data-reduction and analogue-digital conversion equipment," *J.Brit.I.R.E.*, **16**, pp. 651-678, December 1956.

5. C. W. Bower, "Survey of Analogue to digital Converters," National Bureau of Standards Report 2755, Washington, July 1953.

6. H. E. Burke, "A survey of analogue to digital converters," *Proc. Inst. Radio Engrs.*, **43**, pp. 1455-1462, October 1953.

7. Librascope, Inc.

8. Baldwin Piano Co., Cincinnati, Ohio.

9. J. B. Rea Co., Inc., Santa Monica, California.

10. Epsco Inc., Boston, Massachusetts.

11. Non-linear Systems Inc., Del Mar, California.

12. F. Raasch, "A progressive code digital quantizer," *Trans. Amer. Inst. Elect. Engrs*, **72**, Part I, pp. 567-571, November 1953.

13. F. Beckett, "A rapid digital to analogue converter for numbers having eleven binary digits," *Proc. Instn Elect. Engrs*, **103**, Part B Supplement, pp. 427-436, April 1956.

14. W. G. Hughes, "Proposals for a Fast, Accurate, Voltage Analogue to Digital Converter." Ministry of Supply Report (unpublished).

15. W. K. Linvill and J. M. Salzer, "Analysis of control systems involving digital computers," *Proc. Inst. Radio Engrs*, **41**, p. 901, 1953.

16. R. H. Barker, "A servo system for digital data transmission," *Proc. Instn Elect. Engrs*, **103**, Part B, No. 7, January 1957.

COMPUTING APPLICATIONS WHERE ANALOGUE METHODS APPEAR TO BE SUPERIOR TO DIGITAL*

by

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A paper presented at the Convention on "Electronics in Automation" in Cambridge on 29th June 1957. In the Chair: Professor D. G. Tucker.

SUMMARY

In solving scientific engineering problems and design studies the first step consists of formulating the mathematical analogue of the problem which is to be studied. It is then a matter of convenience which means are employed to realize this mathematical model—analogue or digital. There are therefore no *a priori* reasons why either method is to be preferred and the choice will be dictated by the exigencies of the problem and the equipment in existence.

Some advantages of analogue machines are quoted and three particular problems are studied for which analogue methods appear to be superior, namely the computation of non-linear heat flow, noise analysis, and the Monte Carlo method for solving neutron collision problems.

1. Introduction

The first step to be made in trying to solve a physical problem theoretically is formulating a description of the events which describe the problem.

This in general, when accomplished, consists of a mathematical statement which describes a system which is a considerable idealization of the original problem. It may even be said that the physical system represented by the mathematical equation does not exist. In fact this idealized system is the *mathematical model,* or *mathematical analogue* of the problem to be studied. "Automation" is brought in when a physical system is set up which in its idealized form will obey the same mathematical relationships. This new physical system simulates the problem to be solved and this process can be done by electronic means. In the electronic digital machines the physical system consists of sets of pulses which represent the variables of the problem. One then establishes the same relationships between these sets of pulses as exists between the variables in the mathematical analogue of the problem. Even if the digital representation of the mathematical statement is exact it will only represent the

mathematical analogue and the machine acts as a digital simulator of the mathematical problem. Continuous operations can only be approximated, but they can be approximated very well. The price one has to pay is the time taken for solution.

The approach is different in the electronic analogue machines. Here the variables of the mathematical problems are represented by currents and voltages and the relationships established between them must represent the ones expressed by the mathematical model. The accuracy of this method is determined by the accuracy with which this mathematical model is realized over the relevant range of parameters and time intervals.

A priori then, there is no self-evident reason why one method of simulation, analogue or digital, is more general than the other and this is in fact confirmed by experience. In the U.S.A., where automatic computing is applied to a much greater extent than in this country, general purpose analogue computers and general purpose digital machines are treated on an equal basis and the choice of their use is largely dictated by their suitability for the problem in hand.

The obvious limitation on the general purpose analogue machines is accuracy, but a reasonably up to date analogue machine

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performs its linear operations with an accuracy of 0·1 per cent. or better. Using electromechanical techniques the same accuracy can be achieved for non-linear operations at the expense of frequency response. Using completely electronic means fairly simple wide-band multipliers (1000 c/s) can be made with a reasonable accuracy (0·25 per cent.) while non-linear functions can be generated with an overall accuracy of 1 per cent.

These accuracies are acceptable for most types of engineering problems and are often better than the primary data.

2. Advantages of General Purpose Analogue Machines

It is therefore not surprising that for many engineering problems general purpose analogue machines may prove to be more suitable than their digital counterpart and the author has listed below what he believes to be some of the advantages of analogue machines: —

(i) Programming of the problem takes less time and modifications can be very easily introduced.

(ii) The analogue machine is faster and can be used on a one-to-one time scale with actual hardware.

(iii) It can more readily deal with complicated systems.

(iv) The machine can be readily monitored at all times during the running of the problem.

(v) The operator has physical access to the important parameters and can see at once the effect of a parameter change.

(vi) The analogue machines are in general easier to service and fault diagnosis is simplified.

(vii) They possess a growth factor. By this is meant that general purpose analogue machines can be built up in relatively small self-contained units. If the problem is too large for one such unit it is generally an easy matter to run a number together.

In the following sections some problems will be discussed which will illustrate some of the points listed.

3. Transient and Frequency Response

A well known application is to set up the transfer function of a given system using a repetitive square wave forcing function. The transient response is then displayed on a cathode-ray oscilloscope.

By adjustment of the parameters the desired response can be approximated. Another version of this application is to obtain the frequency response of the transfer function. To do this one replaces the square wave forcing function by a sine wave and measures amplitude and phase of the output. Each point on the response curve can be obtained in a matter of minutes.

If this is to be done digitally one has to treat the problem either as the integration of a set of differential equations, or work out the impedance of the system. Obviously a considerable amount of programming and preparatory mathematical work has to be done and the whole job would take considerably longer.

4. A Non-Linear Heat Flow Problem

4.1. *Statement of the Problem*

A problem which arose was the transient temperature distribution in a slab of width $2l$ which was heated equally on both sides. Newton radiation condition was assumed at the boundaries $\pm l$ (see Fig. 1).
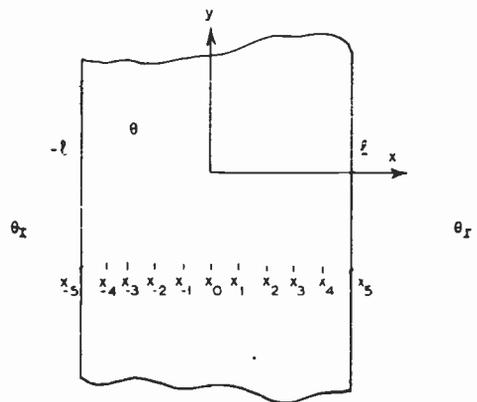

Fig. 1. Semi-infinite slab, showing finite difference stations.

$2l$ = thickness of slab.
θ_i = outside temperature.
θ = temperature inside slab.
$x_{-5}\, x_0\, x_5$ = finite different stations.

The non-linearity arose in that, due to the very wide variation of temperature of the heat input function, the material constants had to be considered to be temperature dependent. Also the heat transfer coefficient h was time dependent, as well as the temperature θ_I of the outside medium (see Fig. 4).

To be more precise, the equations to be solved was

$$\rho c \frac{\delta\theta}{\delta t} = \frac{\delta}{\delta x}\left(k \frac{\delta\theta}{\delta x}\right) \qquad -l \leqslant x \leqslant l \qquad \ldots\ldots(1)$$

with the boundary conditions

$$\theta = \theta_0 \qquad -l \leqslant x \leqslant l \qquad t=0$$

$$\left.\begin{array}{ll} -k \dfrac{\delta\theta}{\delta x} = h(\theta_s - \theta_I) & x = l \\[2mm] k \dfrac{\delta\theta}{\delta x} = h(\theta_s - \theta_I) & x = -l \end{array}\right\} t>0 \qquad \ldots\ldots(2)$$

where $2l =$ thickness of slab

    $k =$ thermal conductivity ⎫

    $\rho =$ density   Temperature

    $c =$ specific heat   ⎭ dependent

    $h =$ heat transfer coefficient ⎫

    $\theta_I =$ temperature of media ⎬ Time

            outside slab ⎭ dependent

    $\theta_s =$ surface temperature of slab.

A similar problem has been reported by Albasiny and was solved on a digital computer (Pilot ACE).[1] In our case the problem would have required re-programming and it was decided to solve it by analogue methods using a general purpose analogue computer known as Lace (Luton Analogue Computing Engine).

A mathematically simpler expression is obtained by introducing new variables φ and H defined by

$$\varphi = \int_{\alpha}^{\theta} k(z)\,dz \qquad \ldots\ldots(3)$$

$$H = \int_{\beta}^{\theta} \rho c(z)\,dz \qquad \ldots\ldots(4)$$

where α, β are arbitrary.[1,2]

With the aid of these variables eq. (1) becomes

$$\frac{\partial H(\theta)}{\partial t} = \frac{\partial^2 \varphi(\theta)}{\partial x^2} \qquad \ldots\ldots(5)$$

with boundary conditions

$$H = \text{constant} = \int_{\beta}^{\theta(0)} \rho c(z)\,dz$$
$$-l < x < l \quad t=0 \qquad \ldots\ldots(6)$$

$$\left.\begin{array}{ll} -\dfrac{\partial\varphi}{\partial x} = h(\theta_s - \theta_I) & x = l \qquad t>0 \\[2mm] \dfrac{\partial\varphi}{\partial x} = h(\theta_s - \theta_I) & x = -l \quad t>0 \end{array}\right\} \ldots\ldots(7)$$

In this form it can be integrated numerically giving an integral $H(x, t)$. Since H is a known function of θ, one obtains after inverting, θ as a function of x and t.

Also in the boundary conditions θ_I can be expressed as a function of φ, since here again the functional relationship is known.

Finally, as a matter of convenience, H is put equal to 0 at $t=0$ by taking β, which is arbitrary, equal to θ_0.

4.2. *Analogue Method of Solution*

The method of solution is standard (one of finite differences). The differential operator in the x direction is replaced by a finite difference operator. Dividing the thickness l into n equal intervals and if φ_i and H_i are values of φ and H at $x = x_i$ and $x = il/n$ $(i=0, 1, \ldots n)$ then

$$\frac{\partial H_i}{\partial t} = \left[\frac{\partial^2\varphi}{\partial x^2}\right] x = x_i$$

and ignoring fourth order differences this equation becomes

$$\frac{dH_i}{dt} = \frac{n^2}{l^2}(\varphi_{i+1} + \varphi_{i-1} - 2\varphi_i) \qquad \ldots\ldots(8)$$

and the boundary conditions at $x = l$

$$\frac{dH_n}{dt} = \frac{2n^2}{l^2}(\varphi_{n-1} - \varphi_n) + \frac{2hl}{n}(\theta_I - \theta_s) \ldots\ldots(9)$$

$$H_i = 0 \qquad i=0, 1, \ldots n \qquad t=0$$

φ_n is, of course, the value of φ at the outer face and θ_s the surface temperature corresponding to station n.

Since the problem is symmetrical with respect to the plane $x=0$ one takes $\varphi_{-1} = \varphi_1$.

The block diagram represents eq. (8) and (9) in Fig. 2 and is self explanatory. In this problem eight stations have been used. The combination of the φ_i gives $(dH_i)/dt$, which when integrated gives H_i. One now has to obtain φ_i, this is obtained by the function generators which give $\varphi(H)$.
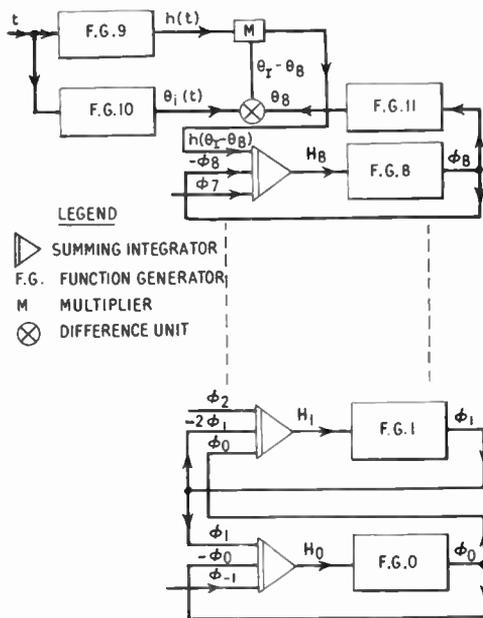
Fig. 2. Block diagram of non-linear heat flow computation.

Note.—The function generators have double ended outputs. The appropriate −ve sign is used where necessary.

The setting up of the function generator and the realization of $\varphi(H)$ needs separate mention. Graphs were supplied giving c and k as functions of temperature θ. These graphs were set up on function generators using a repetitive saw-tooth sweep for θ. The output of these generators were integrated thus obtaining H and φ simultaneously as a function of θ. By connecting φ to the y plates of a c.r.o. and
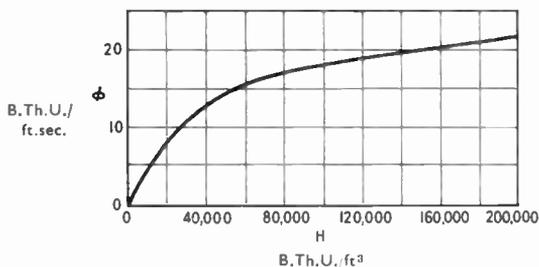

Fig. 3. φ versus H.

using H as a time-base a visual picture of $\varphi(H)$ is obtained (see Fig. 3). Using the same H now as a sweep for a further function generator the

output of this one can be nulled against the original trace. In this way each function generator can be set up in approximately ten minutes.

The functions $h(t)$ and $\theta_I(t)$ for the boundary conditions were approximated by sections of straight lines (see Fig. 4). The effect of the approximations is seen on the curve labelled H_8 which refers to the slab surface (see Fig. 5). This shows typical transient responses for all the stations considered plotting H, which is a function of θ against time.
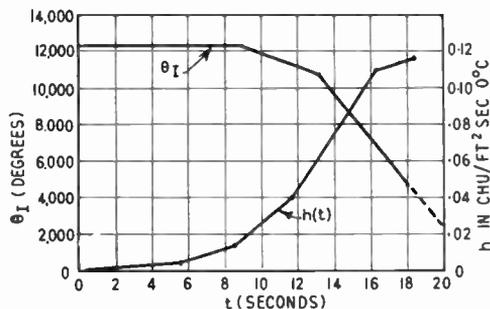
Fig. 4. $\theta_I(t)$ and $h(t)$.
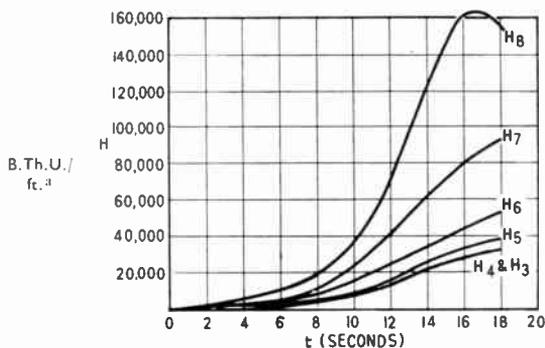
Fig. 5. Typical solutions H versus t.

A point of particular interest was the temperature distribution in the slab when the outside skin reached its maximum temperature, known as the critical temperature distribution. This is shown in Fig. 6 where the temperature distribution in the slab is plotted versus x, with the slab thickness as parameter. The crosses are points obtained by hand computations for two thicknesses.

The accuracy obtained is gratifying.

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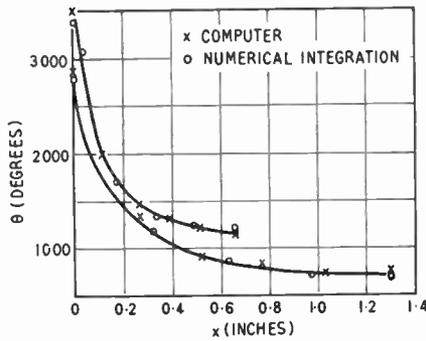
Fig. 6. Critical temperature distribution.
× computer   ⊙ numerical integration

4.3. *Comparison with Digital Machine Solution*

If this problem had been solved on a digital machine then one would have probably followed the method explained in Ref. 1. In any case this method can serve as a basis for comparison.

The principal difference between the two methods is that on the digital machine the integration with respect to time is perforce a step by step method. This means that the integration interval has to be kept small. This is indicated in the paper by Albasiny.[1]

If one uses the Runge Kutta method for integration with respect to time then an integration interval of about 1/25 sec is required for the problem considered.

Since we are interested in about 20 sec problem time this means that about 500 steps have to be used. A reasonable estimate of the time taken to compute one step of integration is about 2·5 sec. (This may not be optimum programming). The whole run will therefore take about 20 minutes machine time and this does not include punching out time. In the analogue problem a one-to-one time scale was used giving a factor of 60 on time scale. Furthermore Albasiny shows that if the number of stations is doubled to increase the accuracy for small *t* the digital machine time goes up by a factor of eight. The analogue machine time remains unaltered.

In running time alone therefore, the analogue machine has a considerable advantage: if programming time is included as well the analogue machine scores overwhelmingly.

5. Resistance Analogues

Passive resistance analogues are used for the solution of a large class of problems, in particular all those associated with Laplace's equation. An extensive literature exists on this subject (see Ref. 3).

General purpose analogue machines can be used on the same type of problems with the advantage that instead of summing passively this will be done actively. Thus the nulling is automatic. They will certainly not be slower than their digital counterpart and again the operator has the advantage of being able to see at once what the effect is of changing a parameter.

6. Noise Analysis

In many servo and communication applications it is important to know the spectrum of random varying signals which are either superimposed on the input signals or constitute the input signals themselves.

The simplest way to obtain a noise spectrum is to measure the noise power in a number of narrow frequency bands (preferably rectangular). The output is then squared and integrated so that the mean noise power can be obtained for this frequency band (see Fig. 7).
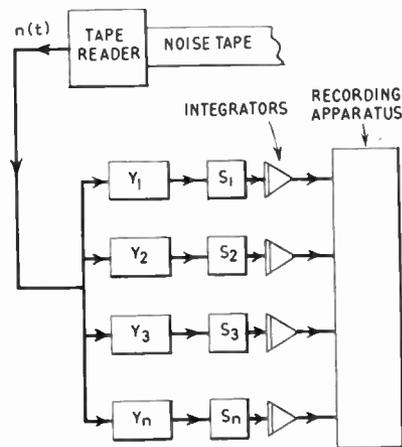
$n(t)$ - NOISE SIGNAL
$Y_1 ... Y_n$ - FILTERS WITH APPROX RECTANGULAR CUT-OFF
$S_1 ... S_n$ - SQUARERS

Fig. 7. Arrangement for noise analysis.

On completion of the run a new set of filters is switched in and the record replayed.

It has been found convenient to make the noise tape into a closed loop containing a blank portion. During the blank portion of the tape the filters are switched to their new values so the whole process is automatic.

This method has proven to be extremely fast and flexible. On the other hand noise analysis on a digital machine would be very laborious. It would, in fact, have to be done in stages— first of all the auto-correlation function would have to be computed and then its Fourier transform derived. Apart from the large amount of data to be stored—runs have been done with as many as 5000 points—both computations involve a very large number of multiplications which are amongst the slowest of the digital processes.

7. Monte Carlo Problems

One of the greatest advantages claimed for digital machines is that it allows one to carry out what are known as Monte Carlo processes.

In many problems under consideration either the input signals or a parameter in the system or both are only known statistically (i.e., Brownian motion, noise etc.). The output of such a system can then only be known statistically and in most cases the solution cannot be achieved analytically. One now starts to play the following game. A representative set of samples of the randomly varying input is therefore collected or fabricated and the system is tested for each input sample. The corresponding output set is collected. From this set the relevant data such as standard deviation, spectrum, probability distribution can be obtained. The longer the "game" is played the larger the output sample and the better the statistics of the output samples will be known for this type of input.

In such a way one may establish the overall accuracy of a radar directed gunnery system, or the lethality of a missile system, or details of atomic scattering processes. A typical example of the latter and its simulation will be described below.

In an atomic pile fast neutrons are released. These neutrons have an eventful life. They can collide with the graphite nuclei, with a given probability they can be lost from the pile, they can go up the air channel, they can be recaptured by other uranium cores or their own or finally they can become thermal after a number of collisions. A schematic representation of such a pile is shown in Fig. 8. One wants to know what happens to the neutrons and where they land on the cores once they become thermal.*

In other words a fast neutron is launched from a core at height z, angle θ, φ (see Fig. 8). The question is what happens to it until it is recaptured as a thermal neutron by one of the uranium cores thus producing fission.
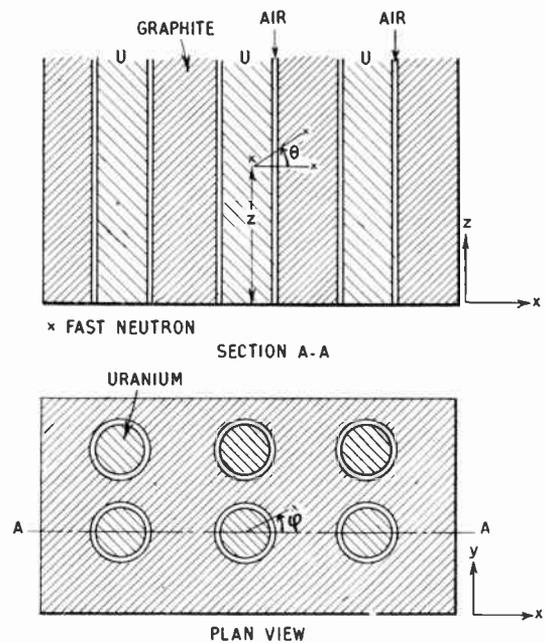
Fig. 8. Section and plan view of "atomic pile" used in collision problem.

An analogue machine would solve this problem as follows: Two random processes are to be considered. The interval between collisions and the angle over which the neutron is scattered and its corresponding velocity change after collision.

* The atomic pile and the neutron collision mechanisms considered do not represent any actual pile, but have been constructed to illustrate this kind of problem.

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A magnetic tape is prepared on which one channel (A) represents the time intervals at which scattering takes place; this depends on the cross-section of the material. A second channel (B) represents the random distribution of scattering angles.* The set-up is shown in Fig. 9. When a pulse is registered in the (A) channel—this corresponds to a collision—then the gate is closed in the output of the (B) tape channel, giving a scattering angle and a corresponding change of energy. This will give the new velocity components of the particle, which after integration determine the position vector of the neutron at any time. Gate and computing circuits are included in the block labelled computer.

The velocity and position co-ordinates of the particle are continuously monitored to establish whether the particle has strayed in a special region. For example, if the centre of uranium rod 2 has co-ordinates x_2, y_2 and radius r_2 and x, y, z are the co-ordinates of the particle then when

$$(x - x_2)^2 + (y - y_2)^2 < r_2^2$$

the neutron is in the uranium core and will have a different capture cross section. This condition operates relay 1 thereby switching the input to Channel A_1. This represents the collision intervals of a fast neutron in uranium. When

$$(x - x_2)^2 + (y - y_2)^2 > r_2^2$$

tape A is used again.

If r_{2a} is the outer diameter of the air channel, then if

$$r_2^2 < (x - x_2)^2 + (y - y_2)^2 < r_{2a}^2$$
$$\text{and} \quad v_x^2 + v_y^2 = 0$$

then the neutron will be lost. This condition is catered for by relays 2 and 4 which become operative when the neutron is in the air channel and if also $v_x^2 + v_y^2$ becomes sufficiently small. These will operate the stop compute relay and this operation is recorded on counter 2.

Similarly if a, b, c are the dimensions of the pile the neutron is lost whenever $x > a$, $y > b$, $z > c$.

This operates sets of relays which again operate the stop relay and counter 3—only one such relay is shown (relay 5). If the

* To simplify the diagram the random scattering process is only represented by one channel. In practice this will consist of two channels or more.
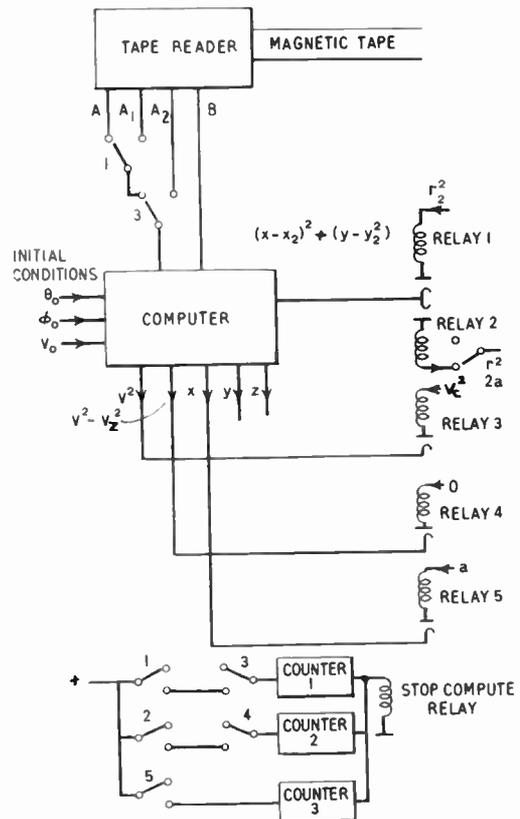
Fig. 9. Computing arrangement for neutron-collision problem.

A : fast neutrons in graphite
A_1: fast neutrons in uranium
A_2: slow neutrons in graphite

All relays are shown in the unenergized conditions. Only the circuitry for $x \geq a$ has been shown.

neutron velocity

$$v^2 = v_x^2 + v_y^2 + v_z^2 = v_c^2$$

where v_c is the thermal velocity, the cross section of the neutron in graphite is changed again and a further collision tape A_2 has to be used. This is done by relay 3. Now when the neutron reaches a uranium core it will be captured, fission will take place, and the exercise is over. This is recorded on counter 1. The z co-ordinate is measured as well and by doing a number of runs the life statistics of the neutron and its last resting place for a given launch angle for this particular reactor configuration can be established.

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Estimate of running time.—It is expected that the average number of collisions of a neutron during its lifetime is of the order of 400 to a thousand. The read out speed of the magnetic tape can easily be such that the average pulse rate is 100 per sec. Therefore one run would take 10 seconds at the most. Assuming that 100 runs is a large enough sample for one set of initial conditions this amounts to 15 to 20 minutes for one initial condition. Allowing ten initial values in φ and ten in θ then the total programme will take 25 to 35 hours machine time. Allowing for changing tapes and setting of controls one could double this time but two working weeks would be a considerable overestimate.

In the writer's opinion this compares favourably with the machine time required for a similar problem on a digital machine.

8. Conclusions

The examples used representing physical problems of a very different nature have illustrated the point that general purpose analogue machines are in many cases more suitable for solving these problems than the general purpose digital computer; providing the accuracy limitations are accepted.

It must be realized that the examples quoted are not isolated cases but are only samples of the whole set of engineering problems excluding the set of measure zero where very high accuracy is required.

Before concluding it should be pointed out that the superiority of one kind of machine over the other does not reside in the fact that one is analogue and the other digital. This is only the economic expression of a fundamental aspect which is best expressed by the difference in their flow diagrams.

Digital machines are essentially serial machines operating in a discrete manner, that is—they only produce the individual frames of a television picture. If a number of parallel events have to be presented this is done by scanning and interlacing the events since in the present state of the art it is too expensive to provide a parallel accumulator, multipliers, parallel access to the memory, etc.

The analogue machine presents a continuous recording of the whole system. It tries to represent the block diagram of the system and its units are cheap enough to be able to represent simultaneous events simultaneously. The position is thus as follows. If one wishes to represent physical systems as they are, i.e. continuously and events as they occur, then one is forced for economical reasons to choose an analogue system, thereby accepting its accuracy. If one wishes for a higher accuracy then one is driven to digital methods and costs then dictate the choice of a machine operating in a serial manner. One can well conceive a machine combining the attractive features of both, i.e., a machine that has the organizational advantage of what is now called an analogue computer with the accuracy of digital machines. This would be a machine very similar in its mode of operation to the analogue machine but with its operational amplifiers and nonlinear units. wherever necessary, replaced by digital units performing the same rôle but with increased accuracy.

Finally it seems that nomenclature has to be rationalized. One speaks of digital and analogue machines as if this described their differences. This is not true. The opposite to digital working is continuous operation and to serial working is parallel.

Machines like DEUCE or PEGASUS are digital serial machines, while an analogue computer is in general a continuous parallel machine. This clearly shows the distinction between the techniques and the *modus operandi* of the machines.

9. Acknowledgments

10. References

1. E. L. Albasiny, "The solution of non-linear heat-conduction problems on the pilot ACE," *Proc. Instn Elect. Engrs,* **103**, Part B, Supplement, pp. 158-162, 1956.

2. G. O'Brien, M. Hyman and S. Kaplan, "A study in the numerical solution of partial differential equations," *J. Maths and Phys.,* **29**, pp. 223-251, 1951.

3. C. Liebmann, *Journées Internationales du Calcul Analogiques. Actes,* September 1955, p. 346; and other articles in the same publication, pp. 370, 377, 385, 396, 401, 406, 410.

A COMMENT ON THE PAPER

"COMPUTING APPLICATIONS WHERE ANALOGUE METHODS APPEAR TO BE SUPERIOR TO DIGITAL" *

by

A. Gilmour†

The use of large scale digital computing machines for solving Monte Carlo problems concerning the tracking of neutrons is now quite common in the United States and in this country. Many authorities consider that to study the movement of neutrons in a reactor by Monte Carlo methods the largest and fastest digital machines available are required.‡ It is therefore surprising that Mr. Gomperts should advocate the use of an analogue machine for this purpose. The author has chosen a very special type of problem to be solved by Monte Carlo methods and extrapolated from this to give the impression that an analogue machine is the right tool for Monte Carlo work. The problem described in Section 7 refers to the tracking of neutrons through an atomic pile and is based on what is known as the two-group theory. This assumes that neutrons can be divided into two groups, fast and thermal, and that to each of these groups there corresponds a mean free path, scatter, fission and absorption cross-sections. Now this is a considerable simplification as the cross-section of a neutron depends upon energy in a rather complicated manner and the two-group theory assumes that only two energy groups (fast and thermal) exist. One of the main reasons for using Monte Carlo methods to study nuclear systems is that this is probably the only way in which account can be taken of all the variations of cross-section with energy. When the two-group theory is used some analytical method for calculating the constants of the system is often more efficient than Monte Carlo methods.

The problem described in the paper is a very special case of Monte Carlo work, therefore, because variations of cross-section with energy are not considered in detail and also because no account is taken of neutrons created in fission. In general, as for example, in reactor criticality studies, it is essential to study the history of neutrons after fission has occurred and this part of the problem has been specifically omitted from the example given in the paper.

The author has said that two working weeks would be a generous overestimate for solving the problem he describes on an analogue machine. However, much more complicated Monte Carlo problems than this have been solved on digital machines in a fraction of the time. To obtain some idea of the facility with which a digital machine can solve Monte Carlo problems, it is sufficient to quote the example of the DEUCE which has been used for solving neutron tracking problems containing all the complications of variation of cross-section with energy and storage and tracking of fission neutrons, and has solved them in 15–20 hours. About a quarter of this time has been spent on the statistical analysis of the results, another feature which is not included in the problem described in the paper.

Mr. Gomperts has certainly demonstrated that an analogue machine can be used for very simple Monte Carlo problems but it cannot be inferred from this that it could be used for the type of Monte Carlo work which is being carried out on digital machines in this country and in the U.S.A. today.

‡ M. H. Kalos and H. S. Wilf, "Monte Carlo solves reactor problems," *Nucleonics*, 15, May 1957.

NOTICES

Council Dinner

The customary dinner of the Council and Committees of the Institution will be held at the Savoy Hotel, London, on Friday, October 11. The Immediate Past President, Rear-Admiral Sir Philip Clarke, and Lady Clarke, will be Guests of Honour and the occasion will provide an opportunity to express appreciation of Sir Philip's term of office.

It is hoped that members who are attending will be accompanied by their ladies. Tickets, obtainable from the Institution, cost three guineas each and include dinner and cocktails.

West Midlands Section

At the Annual General Meeting in Wolverhampton, on June 3rd last, Mr. J. P. Hannifan was elected Chairman in succession to Mr. J. Cunningham-Sands. Other members elected to the Committee were Messrs. D. C. Mason (Membership Secretary), P. Huggins (Programme Secretary), A. D. Lewis, R. E. Head, H. Fellows, J. T. Rowe. Mr. R. A. Lampitt was re-elected Honorary Secretary.

Programmes of Meetings 1957/8

A booklet containing details of *all* meetings of the Institution in London and of the seven Local Sections in Great Britain for the forthcoming session will be published during September. Copies will be sent to all members in the British Isles.

Particulars of any additional meetings and of alterations to the published programme will be given in the *Journal* under the heading of "Forthcoming Institution Meetings".

Higher National Diploma in Production Engineering

A scheme, the first of its kind, for full-time courses leading to the award of a Higher National Diploma in Production Engineering has been arranged by the Ministry of Education in conjunction with the Institution of Mechanical Engineers and the Institution of Production Engineers. Arrangements for part-time courses leading to the award of Higher National Certificates in Production Engineering have existed since 1941.

A full-time Diploma course must extend over at least three years and must, as a rule, be taken at one college. It must also be suitable for students who have had full-time education normally up to the age of 18 and who, before starting the third year of the course, have had at least one year's regular employment in the engineering industry.

Diplomas in Technology

The National Council for Technological Awards has recently announced the names of further courses which have been recognized as leading to the Diploma in Technology. One of these is a sandwich course in Physics and Technology of Electronics which is being conducted by the Northern Polytechnic's Physics Department. Another is the Electrical Engineering course now being proposed by the Borough Polytechnic in which there is opportunity for specialization in radio and electronics.

The remaining courses are outside the Institution's field but it is interesting to note that, of the four colleges included in this list, only one is a College of Advanced Technology.

Electronic Computer Exhibition in 1958

An Electronic Computer Exhibition, to include data handling equipment of all kinds, is to be held at Olympia, London, from November 28 to December 4, 1958. The Exhibition, which will be the first of its kind to be held in Great Britain, is being sponsored, at the suggestion of the National Research Development Corporation, by a joint committee of the Radio Communication and Electronic Engineering Association and the Office Appliance and Business Equipment Trades Association. Concurrently with the Exhibition there will be two symposiums at which papers dealing with the application of computers to problems in business, industry and science will be read and discussed. One will be an international technical symposium organized by the National Physical Laboratory, while the other will be on business computers and will be organized by the two Associations.

The Exhibition will show complete systems of automatic electronic data processing equipment, including digital and analogue computers, all the new forms of magnetic input and output equipments, high-speed printers and telemtering systems.

INTEGRATION OF COMPUTERS WITH FACTORY PROCESSES*

by

A. H. Cooper, B.Sc.†

SUMMARY

Manufacturing processes in which each unit of the product may need individual treatment can be integrated with, and controlled by, computers. At each decision point in the flow of the product through the factory, the computer takes account of the overall production plan, the conditions in the neighbourhood of the decision point, and the past history of the product-unit involved. This application of computers involves more transfers of information than in a mathematical or business computer, but the speed at which the information must flow is much slower. Hence, the preferred basis and form of the computer are unusual. The paper describes typical computers for this class of application and the manner in which they fit into the requirements.

1. Introduction

Computers have become an integral part of modern commercial practice, extending and speeding up the work which has been started with punched cards. In fact, when we think of punched cards, we automatically think of their use in business machines for the handling of facts and figures in commercial offices. On this occasion when we are discussing the automatic control of machinery, it is a good thing to remember that the first use of punched cards dates from many years before Hollerith applied them to the problems of the American census, and in doing so laid the foundation for their use in accounting. The first use of punched cards as a storehouse for tabulated information was in the Jacquard loom which revolutionized the weaving of arbitrary patterns.

The Jacquard loom dates from early in the industrial revolution, but the technique hardly spread outside weaving until very recently. There is probably a straightforward mechanical reason for this: in the loom it is possible to group the control of all the heddles in a small space and to operate the heddles with quite small mechanical forces. Most other machines require larger forces, and the pressure which can be exerted directly by a piece of cardboard

is insufficient, just as most other machines have far fewer controls to operate than has the Jacquard loom with its hundreds of heddles. As long as the controls of machinery were simple and could be encompassed by a human operator, and as long as these controls needed considerable effort, then the punched card was an inappropriate method of control and made no headway. Lately, circuits have been devised which will enable us to use switches requiring but little pressure which can be operated directly by punched card or perforated tape, and which can produce not only on/off commands, but quantitative instructions to a machine calling for exact positioning of the elements of the machine. (See Appendix 1). Within recent years, therefore, punched cards and punched tapes have become a standard method of machine control.

Insofar as we are concerned with a single machine or a single group of machines doing a standardized series of operations, the machine or machines and the controller can be a simple straightforward combined unit. The automatic factory exists in most people's minds as an extension on these lines. In actual fact, it is rarely possible to organize a factory which is merely a combination of automatically controlled machines; it becomes necessary in addition to provide for a flow of information as well as, but separate from, the flow of products.

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2. Continuous Processes

When the product is continuous (as in chemical engineering) or quasi-continuous (as in most mass-production) the problems of control are fundamentally those of feedback theory. Fig. 1 shows the block schematic of an elementary continuous factory, and the similarity to an amplifier with multiple feedback paths is obvious.
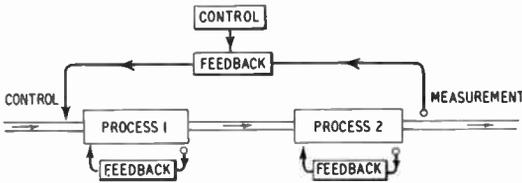

Fig. 1. Control of continuous factory process.

In general, this type of process does not call for, nor lend itself to, integration with a computer. Conventional amplifier theory and feedback techniques, including the powerful effect of control in the feedback path, lead to the required result, even though the time-delays are completely different from those of conventional amplifiers.

Analogue computers are useful in handling such problems, firstly as analytical simulators for exploring the operation of the installation in the design stage; then for the analysis of operation during the commissioning and early operation phase, in the operation called "parameter learning"; and finally as a forecasting tool to work through in fast time the effects of a change, to guide the operators in changing conditions. None of these functions, however, comes within the title of "integration with factory processes": the computer is an aid, not an integral part.

3. Discontinuous Processes

Although the schematic diagram of Fig. 1 has been often used as typifying "automation," it describes only one class of factory and does not help with the factory where the products are "personalized."

The manufacturing trends of the last century or more have been towards the production of greater quantities of fewer varieties of each product; factories have tended more and more towards quasi-continuous processes. There is now a tendency away from this, a tendency for sociological or for purely commercial reasons to offer the customer a complete freedom of choice: this leads to an attempt to manufacture individual products to order, but by quantity production methods and at low prices.

When each item of the product has an identity, the analogue computer is useless except in an overall statistical way, and our computation must be digital. Since the control of the process must take account of events which happen (perhaps without warning) during the course of production, the computations must take place at the same pace as production; in other words the computer must be integrated with the production process.

4. Digital Computation

In a digital computer we have, in general, a series of elements which in general terms can be grouped as shown in Fig. 2:
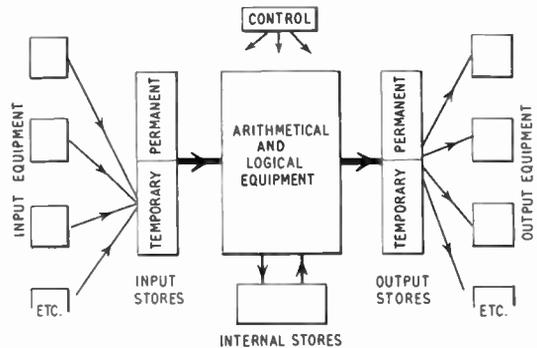
Fig. 2. Block schematic of basic digital computer.

(1) Input equipment collecting the information which has to be handled by the computer.

(2) Input stores which contain permanent or semi-permanent information necessary for the operation of the computer, and semi-permanent or transient information collected by the input equipment.

(3) Arithmetical and logical elements which process the information from this store.

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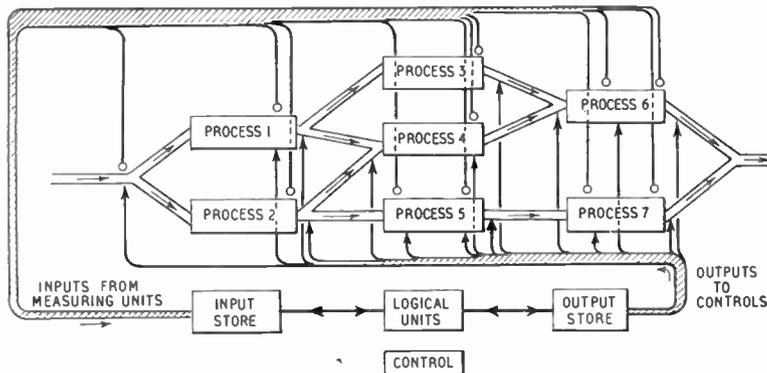
Fig. 3. Block schematic of factory with interconnected choices of production processes.

(4) Output stores which receive the processed information and which may also contain permanent or semi-permanent information necessary at the output of the computer.

(5) Output devices for producing, in a tangible form, those items in the output stores which are called for.

(6) A control system which (generally as the result of a pre-arranged programme) originates and co-ordinates the work of the other units.

The first digital computers were organized by mathematicians for mathematicians, and these six elements took certain sizes and shapes. More recent computers for business purposes have had to have different inter-relations between their functional parts, and our experience in the use of digital computers for the control of factory processes indicates the need for yet another apportionment of the constituent parts.

The characteristic of a factory control computer which qualitatively leaps to the eye is the way in which the input and output of the computer calls for equipment disseminated around the factory. Fig. 3 indicates a simplified schematic of a factory making a product which calls for a number of alternative processes at various stages in the passage of products; the computer must take note of information gathered at a number of points, and it must issue information and commands at another large number of points.

Figure 3 should be compared with Fig. 1; and in comparing them it must be remembered that whereas Fig. 1 shows a system where control is continuously variable, Fig. 3 shows one in which control must be available step-wise to cope with each individual product as it passes through.

5. Quantitative Considerations

To form an idea of the parameters, let us take as an example a factory producing motor cars. Let us assume that the factory is making about 100 vehicles an hour, and that there are about 2,000 vehicles at various stages of work in progress. Let us also assume that at 50 points at various places in the factory it is necessary to take decisions.

We have found that the variable features of a typical motor vehicle can be defined in 200 binary digits, and the stores of the computer must therefore hold about half a million bits. Each car on arriving at a decision point will originate an entry into the computer and require a decision from the computer. Accordingly, the computer will have to handle an average of about one enquiry per second.

These parameters are in considerable contrast to those of a business computer where many millions of bits may need to be held in store, and where the rate of entry may, depending on the organization of the computer, be between hundreds and hundreds-of-thousands per second. In general, we have found that the arithmetic and logic of the factory computer is

much less voluminous than that of a business computer, and each entry involves only one or two arithmetical operations and not dozens which may be involved in a single pay-roll or invoicing item.

Another, and operationally more significant, difference, is that the factory computer does not lend itself, as does the business computer, to the marshalling of its inputs and outputs into tidy coherent blocks of work. It is possible for a digital computer in an office to be used for a period of hours on one job, such as pay-roll calculations, and then to be changed to work for another period of hours on invoicing operations; the necessary inputs are stored until they can be released into the computer for processing. (Note that we have said this is possible though in many offices the organization and autonomy of different departments would not allow this to take place). In a factory this is not possible because the entries arising on the average once per second from the factory cannot be stored but must be processed as they arise. Economics will lead to some risk of delay; if the mean rate is about once per second, then there will be several cases each day when more than ten enquiries arrive within a second. It is probably uneconomical to provide arithmetical units to cope with this high rate, and we have rarely found a case where a delay of less than five seconds between an enquiry and a decision was essential.

6. Information Storage

If a computer, such as is used for accounting, is adapted to control a factory, it would be found, as we have already seen, to have too large a storage capacity and a wastefully high entry-rate capacity. In general, too, it will be found to be dearer than some of the alternatives we shall consider later. To obtain the maximum benefit from past experience and present manufacturing resources in the high-speed digital computer field, it is desirable to find ways of reducing the cost of such a machine, but most of the attempts have so far resulted in small savings of costs which are not nearly enough to bridge the gap between these expensive machines and the cheap alternatives which can be designed.

The storage of a business computer is, for instance, generally provided in a series of units, which increase in capacity and in access time. What is needed in the factory computer is a unit with a slower access time and capacity rather lower than that of the magnetic drums and tapes of business and mathematical machines, but at a considerably reduced cost. Factory control computers have been made with other types of store, and work is going on to devise and develop stores which are optimized for the particular problems; some of the factors involved are given in Appendix 2.

Up till now, the greatest economies have been obtained by using individual stores rather than by concentrating all the storage in one centralized element. One additional reason for splitting up the store into a number of small units is that if all the storage is in one combined unit, one single fault in that unit can bring the whole factory to a stop and in the limit can remove all the factory records.

7. A Practicable Solution

Fortunately, a storage medium exists commercially in the form of punched paper tape, and the combination of a perforator, a run of tape and a reader form an elemental store which fits well into the needs of this type of computer.

At this point it is well to consider the way in which goods are handled in the factory. In general, one can consider that they will be passed to and between the manufacturing processes on conveyors, and that upon the conveyors the order in which the goods proceed will remain unchanged. Let us take the unit of conveyor as that length of conveyor in which this criterion is satisfied; it may be only a few feet long, or it may be a considerable fraction of a mile. Insofar as we are concerned with the order in which the goods are presented for the manufacturing processes, it is the conveyor rather than a processing plant which is the philosophically important unit.

It follows, therefore, that the unit of computer storage, in which is housed the information about a group of items in one of these "no overtaking" conveyor-units is a significant quantity. The elementary store therefore becomes a kind of conveyor simulator in that inputs are fed into it at a time when goods

enter the conveyor unit, outputs are read out of it whenever the goods have to undergo a process during the run of this conveyor, and information is read out and transferred elsewhere when the goods finally leave this unit of conveyor. This elementary store, therefore, has a dual personality. From the computer designer's point of view, it is a store and is treated logically as a store is treated in computer organization; whereas the production engineer will see it as a conveyor simulator. In this latter role it can be built into a mimic diagram or similar graphical representation of the factory processes, and during the present intermediate stage, while automatic control of processes is being assimilated and accepted by production engineers, this additional facility of simulation is valuable.
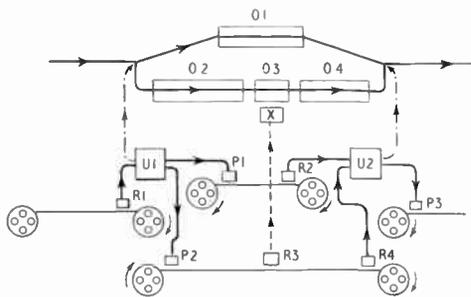

Fig. 4. Detail of digital control of one section of a factory.

The logical and arithmetical processes which have to be provided can be instanced by considering Fig. 4, which shows a small system of conveyors and the associated conveyor simulators and logical units. Goods arrive from the left; some of them have to go through operation O1 and others have to go through operations O2, O3 and O4. They merge and depart on the right. The tape of the conveyor simulator on the left has in store all the information about the goods arriving on the conveyor on the left. This information is in the form of a block of perforations which in a complicated series of processes may be up to 30 characters of 5 holes each. When one unit arrives at the divergent junction of the conveyors, a signal is sent to the store and the next word is read. One character in this word

will describe the choice to be made, whether the goods go to O1 or O2. The unit U1 selects this word and in normal operation will control the points on the conveyor so as to send the goods along the right path, and at the same time operate its own switching to transcribe the output of reader R1 either into perforator P1 or perforator P2. (Note that as the character may not be at the beginning of the word, it may be necessary to incorporate with unit U1 a buffer store to hold the characters before the relevant one.)

The choice made in unit U1 may be one of any of the following, depending on instructions given from the central controller:

(1) The choice in normal operation in which a character is read and unconditionally interpreted as O1 or O2.

(2) The extreme fault case where one or other of the conveyors is out of operation and all the goods have to take the other path.

(3) The conditional interpretation which would apply when, for instance, O2 path has to have its load reduced, and the treatment of this path was reserved for goods which at a later point in the factory would be receiving preferential treatment. In this case the code for this later treatment would be combined with the normal code for the "O2" path in an "and" gate so that only those calling for O2 and the later treatment would take the O2 path.

(4) The converse of this where even if both the O1 and O2 paths were completely available, one of them might be conditionally inhibited if one half of a later pair must be lightly loaded.

It is assumed that the operations which go on during the run of the conveyors are partly automatic or inevitably and partly conditional. Operations O1, O2 and O4 are assumed to be applied to all the goods, but O3 is an operation which is specific to each item. As an item arrives at this station, the corresponding word in the store is called up and read by R3 and transmitted to X. At this point it can be displayed on an illuminated sign, or it can be used to release appropriate components from a supply conveyor, or it can initiate a machine

operation. Typical of such instructions is the choice of a paint colour, where one 5-hole character will give the choice of 15 colours which, in general, is sufficient.

When the goods have reached the right hand end of the conveyors, they have to merge; this merging must be done with a minimum of delay to the goods on the conveyors, and with the minimum departure from a logical sequence. A wide variety of criteria have had to be employed. One of the easiest to apply is the preservation of a serial number. Readers R2 and R4 read the words on their respective tapes and U2 subtracts one from the other, and releases the unit with the higher serial number. As with most criteria, this one has to be overridden during and immediately after fault conditions when units will be merging from the delayed conveyor with serial numbers far lower than the other; these would be given preference and would soon lead to a jam on the other conveyor unless this serial number criterion could be automatically overridden.

If the path through O1 is shorter than that through O2, O3 and O4, then the order in which the goods leave is not the same as the order in which they enter. The serial number has therefore changed and can no longer be used by itself. We can either compute the serial numbers which will be effective at each of the convergent junctions, and include them all in the data which is stored on the input tape and passed through the factory. (At each converging junction the locally effective serial number is read and acted upon but, having served its usefulness, is not transcribed into the next store.) The other alternative is to include in U2 a more advanced arithmetical unit which adds to each serial number the appropriate handicap before carrying out the subtraction. This latter alternative involves more equipment at each U2 unit and is only desirable if there are so many junctions that the transient serial numbers (which may run into four characters each) push up the word length beyond the capacity of convenient buffer stores.

If the goods are not personalized, and carry no individual serial numbers, then other criteria are necessary. The most commonly useful criterion is the occupancy of later branches of conveyors. If later conveyors can accept goods

in a certain ratio, it is desirable to offer them a mixture of goods from the output of this present conveyor in the required proportion. In general, only the needs of the immediately succeeding conveyor can be coped with in this way, particularly if these two have different transit times so that goods leave them in a different order from their entry order. In any case, it is necessary to override this criterion, not only under fault conditions, but also if the attempt to maintain the correct proportion offered to the next conveyors results in the output of one or other of the present conveyors being held back, thus causing congestion.
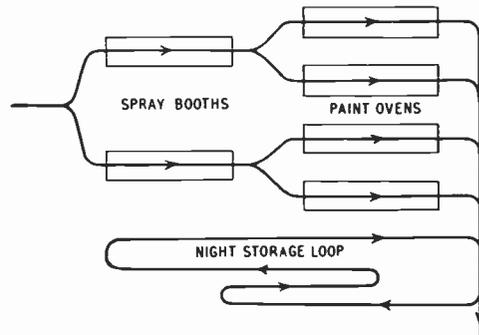

Fig. 5. Section of a factory which has been digitally controlled.

The example we have considered is a very simple one. Fig. 5 gives one section of the paint shop of a car factory where the inputs divide between two spray booths; each spray booth divides into two drying ovens; the outputs of them all combine on to a single line which normally feeds out through the bottom of the diagram, though at the end of a shift the ovens feed out into the storage loop from which it emerges at the beginning of the next shift, blended with the new output of the paint ovens. (This artifice is necessary to provide a stock for the immediate start of the next operation in the morning while avoiding the need for leaving any cars in the paint ovens over night.) All the branches of the conveyors are of different lengths, and can run at different speeds. Intermediate processing information on masking, paint colour, etc., has to be issued at a large number of points, and a mixture of serial number and conveyor occupancy criteria

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has to be applied at the merging points of the 5 lines which feed the output. The economical solution of this computer problem is based exactly on the lines given in Fig. 4, but it represents a very considerable technical effort.

8. Preparation of Work Programme

We have considered the position of a set of conveyors or of production units in the middle of a factory. We have assumed that the work has been reaching these conveyors in accordance with a programme which has been determined in order to ensure the maximum use of the manufacturing facilities available. This necessitates a calculation of a sequence which when deranged as a result of the handicaps due to the different path lengths pursued by the different units of work still presents as uniform a load as possible to the different branches of the conveyor system.

We can proceed in two ways to produce this sequence. Though we have preferred to use a special computer for control of the factory because it is impossible to compress its requirements into a short period of time and to use a general-purpose digital computer for part of its working week, when we come to the preparation of the sequence, it is possible to compress these calculations which do not have to be done in the real time of the factory; we can carry out these calculations quickly on the general purpose digital computer if this is available in the factory and has some available time. The operations of preparing for the sequence are a straightforward exercise for a programmer of any reasonable competence.

In some cases there will be special reasons for using a special separate computer for the preparation of the sequence. A typical reason arises when it is necessary to match very exactly the items which are manufactured against the individual orders arriving from customers. A preferred way in which to do this is to prepare first of all a basic sequence which meets the requirements of factory loading; if, for instance, the factory can give 10 per cent. of its products a superior style of paint work, then the basic sequence will call for superior paint work on a suitably distributed 10 per cent. of the total. Each day we have to match the basic sequence against the individual orders of customers and

it is only at this point that the exact apportionment of the various colours of paint among the 10 per cent. of high quality painted products becomes important.

The preparation of this type of sequence calls for elementary computing facilities and a machine can be made which will perform these functions, using the same units and parts as the conveyor simulators. This eases the problems of maintenance and simplifies the problem of introducing computer techniques to factory operators.

In an extreme case, it is possible to work without any pre-arranged programme, orders being fed into the computer and materials being fed to the conveyor system as the orders arrive, though unless one is prepared to face the possibility of serious under-loading of some sections of the plant and over-loading of others, some previous programme is highly desirable and if the borders are fed in at a rate which approaches the manufacturing capacity such a programme is virtually essential. At a lower production rate, it is possible to provide some elementary computing facilities which, by adding the relevant handicaps to the serial numbers of the work fed in, will be able to predict the existence of later overloads and congestions in the production units and on the conveyors, and inhibit ill-chosen demands.

9. Automatic Reporting

The pre-arranged programme serves not only as an input to the computer, but also as a forecast to sections of the factory coming after the part which is automatically controlled. There will, however, arise troubles in production which will result in serious departures from this predicted order, and then it becomes necessary to read out from the stores and pass the information to these later departments which will be affected. For instance, referring back to Fig. 4, if there were a breakdown in operation O1, all the work in that section would be delayed. If now we run the tape on the simulator associated with O1, we extract from reader R2 all the information about the work which is in that section, and this information can be transmitted in any desired form to the parts of the factory where it is needed. If at the same time we connect reader R2 back to

perforator P1, we can regenerate the information in this store.

10. Future Trends and Possibilities

The integration of computers with factory processes is a relatively new development, but it is not too early to talk about future trends.

The generation of the programme to which the factory has to work has already been mentioned as something which can be done by another computer of more conventional business design. We can expect to see some development in the direction of establishing a common machine language between two computers (one a "business" computer and the other a factory control computer) so that the output of the first can be produced in a form which is most conveniently read by the second. It must be admitted that most of the difficulties of interconnection of the two computers, particularly if they are of different manufacture, may be commercial and political, but there is no need to complicate these difficulties by the presence of language differences which necessitate the addition of the expensive translating device.

Although up to the moment punched paper tape has formed a very convenient storage medium, it seems likely that something more convenient, and possibly cheaper, can be made in the future. It must be remembered, however, that in the next few years at any rate, such a store is likely to need the addition of some display devices if it is to compete with the visual presentation which a punched paper tape store provides to the user.

Any alternative store which has a higher reading and writing speed would offer the possibility of centralizing the arithmetical and logical units, though it must be remembered that there are serious arguments against as well as for this.

In a few years' time, the use of computers to control factory processes may be commonplace, and the need for a mimic diagram or similar display may vanish, but at the moment it is a real psychological attraction for the factory management.

The techniques which have been discussed as applicable to production will undoubtedly extend into the control of warehouses and similar complicated stores. Some progress has

been made in this direction already but, in general, it has merely touched the fringe of the problem and does not seem to have been accompanied with much finesse. There is room for considerable processing of the information which has to be handled since by doing so one can effect considerable economies in the amount of mechanism necessary for handling the associated goods. Although the control of warehouses is a study in its own right, any progress which is made will undoubtedly have its effect on the control of manufacturing processes.

From the point of view of those of us who are designing and installing factory control computers, perhaps the most hoped for future trend is a wide extension of their use. This is not an entirely selfish hope since it seems that with modern production costs, the introduction of the computer into the control of the factory is the most likely way by which we shall be able to undo the most unpleasant aspects of the industrial revolution and, after a century of mass production, restore to the customer the freedom which mechanized production took away from him.

11. Acknowledgments

12. Appendix 1: Some notes on the use of punched tape or cards for machine control

When punched tape or cards are used for machine control, it is essential that the system should be inherently free from errors. If one of the holes of a Jacquard loom card is faulty it leads to a blemish in the fabric which is woven but it would not lead to disaster. If a punched card or punched tape is used for controlling a machine a single mistake can be serious. The most commonly used expedient for guarding against this is the introduction of redundant digits in the characters. In Fig. 6 are shown two forms of the punched tape code for the numbers 0 to 15. The left hand row of holes has the value 1, the next, value 2, the next, value 4 and the next, value 8, while the right hand row is a redundant digit which is added in accordance with an anti-parity or parity convention. In the example (a) there is
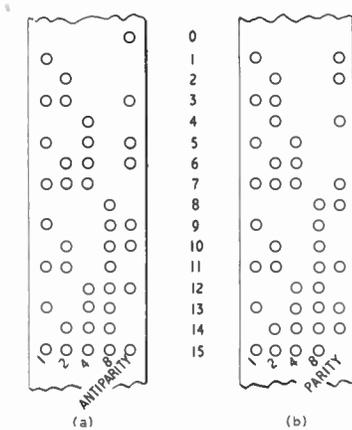
Fig. 6. Typical 5-hole numerical codes using (a) parity and (b) anti-parity redundancy.

always an odd number of holes for any character and in example (b) there is always an even number. In Fig. 7 are the switch contacts associated with the reading of this type of tape. In the contacts at the top of the diagram a continuous path is provided when none of the contacts are operated or when any even number are operated. When these contacts are operated by a tape perforated according to the convention of Fig. 6 (a), the existence of a continuous path means an even number of holes and therefore must give an alarm signal. Conversely if this reader were being used for tape perforated according to Fig. 6 (b) a continuous path would be the "operate" signal.

In fact, it is not possible to use all the codes which are shown in the diagram. For instance, the anti-parity code for 15 would equally be
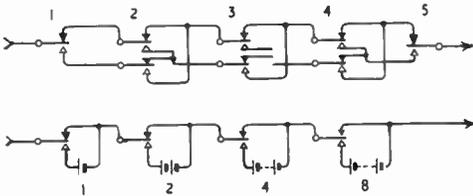

Fig. 7. Circuit for sensing parity or anti-parity information, and for synthesizing analogue voltage from tape information.

given by a break in the tape and this code is usually reserved to indicate that accident. Similarly, in a parity code, it is usually difficult to use the character zero because this corresponds with no perforations and though

acceptable in the middle of a long word, its presence at the beginning of a word would be ambiguous.

The lower row of contacts in Fig. 7 indicate in a very elementary way how the binary values corresponding to each of the holes can be combined so as to give increments of one unit of voltage up to a total of 15. Another typical circuit arrangement is shown in Fig. 8. In this we have a tree of contacts so that the combinations of holes will provide a path from the left hand side to one of the numbered outlets on the right hand side. By this means the punched tape can be made to select one of the 16 circuits and call up any one of 16 operations. This example is particularly interesting as showing the complexity which arises in the relays associated with quite simple operations such as this.
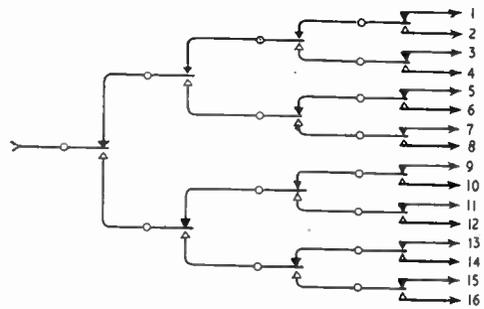
Fig. 8. Relay tree for selecting any of 16 circuits under the control of a 4 (or 5) hole punched tape.

13. Appendix 2: Storage Systems for Factory Control Purposes

Two aspects of significance in stores used for factory control computer design are:—

(a) Coverage of Store. It may contain all the information about all products, or it may be limited to those products in one section of the factory.

(b) Reading and Writing Speed. This may be high, as in business or mathematical digital computers, or low, only tens of digits per second. If the former, the mathematical units may be shared; if the latter, individual (probably simpler) mathematical units are needed.

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13.1. *Advantages and Disadvantages of Various Types of Stores*

(i) Punched Paper Tape

Local storage only; slow read and write; information visible and legible; little risk of mutilation; cheap if few local stores are needed.

(ii) Mechanical Stores (pin drums etc.)

As punched paper tape, but mechanism may be costly due to very large number of accurate parts required.

(iii) Magnetic Tape used in same manner as punched tape

As punched paper tape, but can be more compact. Probably needs "d.c. sensitive" heads with difficult amplification problems.

(iv) Magnetic Drum

General storage, fast read and write; expensive unless fast access allows many arithmetical units to be shared. Probably needs separate visual display.

(v) Magnetic Tape used conventionally

Access time generally too long and storage capacity needlessly high. Wide endless tapes used as drums may be economical.

(vi) Magnetic Core Matrices

Storage capacity far too small, and potential access time needlessly fast for present factory applications.

13.2. *Need for Additional Temporary Stores*

Problems of compatibility between the store and the peripheral devices may lead to introduction of temporary stores. If the writing rate of the store is very high, the information from sensing units in the factory may need to be generated at a high pulse frequency, and transmitted at this frequency; each of these may be difficult. The output of the computer, whose form is largely interconnected with the design of the storage system, has in general to be interpreted into the operation of switches, relays and contactors, whose timing will be similar to that of the slow stores. Thus the use of stores with high writing and reading speeds may lead to further temporary stores, and probably codes and decoders, to match these speeds to the operation speeds of electro-mechanical input and output devices.

GRADUATESHIP EXAMINATION—MAY 1957—PASS LISTS

These lists contain results for *all* successful candidates in the May Examination. A total of 509 candidates entered for the examination which was held at 61 centres. This number includes 157 candidates attempting parts of the examination in order to complete qualification for election to Graduateship or Associate Membership of the Institution.

LIST 1

The following candidates having completed the requirements of the Graduateship Examination, are eligible for transfer or election to Graduateship or higher grade of membership.

Candidates in Great Britain

BARNARD, Clifford Albert. (S) *London.*
BECKLEY, Herbert Reginald. (S) *London.*
BLEZARD, Kenneth Brian. (S) *Littlehampton.*
BOWEN, Kenneth. (S) *London.*
CARREYETT, Trevor Walter. *Bristol.*
DIVECHA, Gautamrai Amritlal. (S) *London.*
DOUGLAS, Walter Harry Brookes. (S) *London.*
FOTHERINGHAM, Peter Ernest Albert. *London.*
HEWITT, Patrick John. (S) *Birmingham.*
HOLDEN, Dennis George. (S) *London.*
JAROSZ, Jerzy Jan. (S) *London.*
KACZMARSKI, Wieslaw. (S) *London.*
KYI, Maung Aung. (S) *London.*
LUTHRA, Suraj Parkash. (S) *London.*
McKENZIE, John George. (S) *London.*
MULDOWNEY, Gerald Charles. *London.*
MYCROFT, George Herbert. (S) *Bristol.*
POTTS, Kenneth Harry. (S) *Manchester.*
RAYBONE, Norman Edward. (S) *Birmingham.*
REED, Christopher. (S) *Bristol.*
REID, William Lawrence. (S) *London.*
ROBSON, Alan. (S) *Newcastle-upon-Tyne.*
SAHNI, Pritam Singh. (S) *Birmingham.*
TATNALL, Dennis Sidney. *London.*
TOMLINSON, Edward Rex. (S) *Manchester.*
WALES, Sidney Alfred. (S) *H.M.S. Armada.*
WARIN, John William. (S) *London.*
WHITE, Nigel John. (S) *Bristol.*
WOOLFORD, Alan John. (S) *London.*

Overseas Candidates

AZAR, Yoram. (S) *Tel-Aviv.*
BHACKA, S. J. (S) *Bangalore.*
BHAGAT, Shiv Raj Huria. (S) *Agra.*
BHATIA, Rajendra Nath. (S) *Bombay.*
BUTA. Singh. (S) *Delhi.*
CHOPRA, Janak Kumar. (S) *Delhi.*
CORDEIRO, Joseph Rufino. (S) *Nairobi.*
DWIVEDI, Munesh Bal. *Lucknow.*
FIRLOTTE, Joseph Leander. (S) *Toronto*
GABOR, Reuben Peter. (S) *Tel-Aviv.*
GANDOTRA, Indar Mohan. (S) *Delhi.*
GARAI, Profulla Kumar. (S) *Delhi.*
GODSI, Mayer. (S) *Tel-Aviv.*
HATTANGADI, Vasant Annaji. (S) *Bombay.*
JATHAR, Nilakanath Balakrishna. (S) *Bombay.*
KHAN, Mohamad Idris. *Karachi.*
MADAN LAL. (S) *Delhi.*
MATHEWS, Abraham. (S) *Agra.*
MEHTA, Gunvant Jagjivandas. (S) *Bombay.*
NALBENTIAN, Benjamin. (S) *Sao Paulo.*
RAHEJA, Udhavlal Topandas. (S) *Bombay.*
RAJENDRA NATH. (S) *Shillang.*
SAPRU, Kanhaiya Lal. (S) *Bombay.*
SARMA, D. Parameswara. *Bombay.*
SAWNEY, Mohan Singh. (S) *Delhi.*
SEKHRI, Guatam Dev. (S) *Delhi.*
SUBRAMANIAN, L. (S) *Bangalore.*
TSAMOUSSIS, Ffstratios. (S) *Athens.*
WILKINSON, David. (S) *Lagos.*

LIST 2

The following candidates were successful in the parts indicated

Candidates in Great Britain

ANWAR, Salahuddin Nurul. (2) (S) *London.*
ASQUITH, Stanley Francis William. (4) *London.*
BASSETT, Edward James. (1, 2, 3) (S) *Bristol.*
BENTLEY, Edward Leslie. (5) (S) *London.*
BIRD, Gordon Joseph Alexander. (3) (S) *London.*
BOWN, Kenneth Albert. (2) (S) *London.*
CHESTER, Michael William. (3) *Lowestoft.*
COOK, David William. (3) (S) *Lowestoft.*
CORBEN, Clifford Bernard. (1) *London.*
CRIDLAND, William Wyndham. (1) (S) *Manchester.*
DAVIS, Eric Cambridge. (1) (S) *London.*
FRAZER, Charles Henry. (3) (S) *Newcastle-upon-Tyne.*
FRENCH, William Robert. (1) (S) *Birmingham.*
GEORGE, Julian. (3) (S) *London.*
GRICE, William Henry. (2) (S) *London.*
HAIGH, Fred Ellison. (2) (S) *Edinburgh.*
HALTON, Dennis Lewin. (4) (S) *London.*
HOPKINS, Roland Michael Terrence. (2) (S) *London.*
HORN, Peter Jack. (1) *London.*
JACKSON, Michael. (3) (S) *Bristol.*
JONES, William Byron. (1, 3) (S) *O.W.S. "Weather Explorer"*
KENTLEY, Eric William. (1) (S) *London.*
LAM, Yat Wah. (1) (S) *London.*
LARGE, Douglas Blake. (3) (S) *London.*
LUFF, William. (1) (S) *London.*
McDONNELL, William George. (1) (S) *Manchester.*
MOYDEN, Frederick John. (2, 3) (S) *Manchester.*
NEWMAN, Henry John. (1) *London.*
O'CONNOR, Joseph Francis. (1) *Manchester.*
PANTHAKY, Jal-Khurshed. (2) (S) *London.*
PARSONS, Ronald. (1) (S) *London.*
RICE, Matthew Joseph. (2, 3) (S) *Dublin.*
SPENCER, Godfrey Stanley Gibson. (4) (S) *London.*
SMITH, Harold Albert. (1) (S) *Manchester.*
STRIDE, Regent. (1, 3) (S) *London.*
TOWNSEND, Brian Joseph. (3) (S) *Bristol.*
WALLACE, David John. (1) (S) *London.*
WHITEHILL, William Kenneth. (1) (S) *Cardiff.*
WILKINSON, George Arthur. (3) (S) *Hull.*

Overseas Candidates

ALTARATZ, Jacob. (1) (S) *Tel_Aviv.*
ANANTHANARAYANNAN, Subramanya. (2) (S) *Madras.*
BEN-DOR, Baruch. (3) (S) *Tel-Aviv.*

BRUNNER, Amos. (1) (S) *Tel-Aviv.*
D'CUNHA, James Aloysius. (2) (S) *Bombay.*
de BRUYNE, Pieter. (2, 5) (S) *Delft, Holland.*
DOGRA, Yash Pal. (2) (S) *Delhi.*
DUGGAL, Didar Singh (3) (S) *Agra.*
EDIRISINGHE, Don Francis. (2, 4) (S) *Bombay.*
GIRI RAO, Pabbisetty Venkata S. (2) (S) *Bombay.*
GOPICHAND, Kalluri. (2) (S) *Bangalore.*
GOSWAMI, Joginder Pal. (3) (S) *Agra.*
HANDA, Jagdish Rai. (3) (S) *Agra.*
HARBANS SINGH SARNA. (3) (S) *Lucknow.*
HERLEKAR, Balvant Vishnu. (4) (S) *Bangalore.*
HOLTZHAUSEN, Petrus Johannes. (4) (S) *Johannesburg.*
JAGJIT, Rai. (3) (S) *I.N.S. Valsura, Jamnagar.*
KAPOOR, Gopal Krishan. (1, 3) (S) *Kanpur.*
KAPOR, Onkar Nath. (1, 2) (S) *Lucknow.*
KUDDYADY, Chandrashekhar Raghunath. (2) (S) *Bombay.*
LAKSHMINARAYANAN, Thirunillai Mahadevan (2, 4) (S) *Hyderabad.*
LEVI-MINZI, Gad. (2) (S) *Tel-Aviv.*
LIPSCHITZ, Gerhard Gad. (1) *Tel-Aviv.*
MANDAL, Sukumar. (3) (S) *Dehradun.*
MARATHE, Yashvant. (3) (S) *Bangalore.*
MARTENS, Alexander Eugen. (1, 2, 3) (S) *Toronto.*
MENON, Venugopala V. (1, 2, 3) (S) *Bombay.*
MUKHERJEE, Samir Kumar. (2) (S) *Delhi.*
NARASIMHAN, Villiambakkam Venkatachari. (1) (S) *Madras*
NARULA, Bhagwan Dass. (3) (S) *Bangalore.*
NEWMAN, Martin Myer. (1) (S) *Tel-Aviv.*
PANCHAPAKESAN, Ramachandra. (2) (S) *Madras.*
RAMACHANDRA IYER, Ramaiyer. (2) (S) *Hyderabad.*
RUPRAI, Balwant Singh. (3) (S) *Bombay.*
SADASIVA DASS. (1) (S) *Delhi.*
SATHYANARAYANAN, N. (3) (S) *Madras.*
SHAH, Rajendra Kantilal. (2, 4) (S) *Bombay.*
SHAHI, Brij Lal. (2) (S) *Delhi.*
SHUKLA, Ratan Prakash. (1) (S) *Agra.*
SIVASANKARA PILLAI, A. (2) (S) *Tiruchirapalli.*
SMIT, Cornelis. (4) (S) *Delft, Holland.*
STEYN, Marthinus Jacobus Dewald. (3) (S) *Cape Town.*
SUBRAMANIAN, N. (3) (S) *Tiruchirapalli.*
SWAMINATHAM, Gopala Krishna. (3) (S) *Bangalore.*
TOEG, Haim. (1) (S) *Tel-Aviv.*
UPENDRA, Dattatreya Bhardvaj. (4) (S) *Bangalore.*
USMAN, Miraz Mohd. (3) (S) *Dhahran.*
VISWANATHAN, G. S. (4) (S) *Bombay.*
YOGINDER SINGH HASWAL. (4) (S) *Delhi.*

(S) denotes a Registered Student.

LIMITS FOR OSCILLATOR RADIATION FROM TELEVISION AND V.H.F. RECEIVERS

IN 1954, the British Radio Equipment Manufacturers' Association announced limits which had been adopted by the Association for oscillator radiation from television and v.h.f. receivers, and details were given of the method of measurement. The limits were set out under three headings, (i) direct radiation measured at a distance of 10 m, (ii) aerial terminal voltage, and (iii) oscillator voltage appearing at the mains terminals.

Since then, considerable work has been carried out, both in this country and internationally, on the standardization of a method of measurement having special regard to (a) simple site and apparatus requirements, (b) simplicity of measurement, and (c) repeatability of results, within reasonable limits, at different sites. As a result of this work, a method of measurement of the total free space radiation at 3 metres has been evolved by the International Electrotechnical Commission and it is anticipated that, with minor amendments, this will be universally adopted.

The receiver is arranged so that the oscillator valve is 1 m above a metal ground screen (9 m × 6 m) on which is also set up the field strength meter. A horizontal, and rotatable dipole (2·25 m long for television, 1·5 m for v.h.f. f.m.) is fitted 4 m above ground, connected to the receiver by a feeder 3·9 m in length. The aerial of the field strength meter is 3 m distant and is set either vertically or horizontally, and the procedure lays down the precise heights at which measurements are to be made as well as the correct sequence.

The method is thus sufficiently compact in its requirements to permit the apparatus to be set up on, for example, a flat roof. Its features have been extensively considered by the appropriate technical committees of B.R.E.M.A. with the result that recommendations were submitted that this method should now supersede the previous method of measurement at 10 metres; although the former aerial terminal voltage measurement is no longer laid down as part of the measurement, it should be noted as an additional measurement which is useful to designers.

At the same time, limits of radiation were reviewed and recommendations were made as under:

30 Mc/s– 41 Mc/s, not exceeding			200 μV/m
41 Mc/s– 68 Mc/s,	,,	,,	70 μV/m
68 Mc/s–100 Mc/s,	,,	,,	200 μV/m
100 Mc/s–174 Mc/s,	,,	,,	500 μV/m
174 Mc/s–216 Mc/s,	,,	,,	200 μV/m*
216 Mc/s–250 Mc/s,	,,	,,	1,000 μV/m

After making allowances for the differences in methods, the amount of "in-band" radiation in Band I is unchanged from the former limit, but the "out-of-band" limit up to 100 Mc/s has been slightly relaxed and new limits have been established for the range 100–250 Mc/s. The upper frequency limit for mains terminal voltage measurement has been fixed at 100 Mc/s and the limit remains 500 μV into the specified network, or 1·5 mμW.

The Association hopes that both these recommendations will be widely accepted. With the development of the v.h.f. bands for television and f.m. sound broadcasting, the whole question of mutual interference between receivers is attaining an increasing sagnificance, and it is considered essential that these limits should be met.

This method of measurement and the same limits are also applicable to radiation at i.f. harmonics, which have been found to be troublesome in particular with some v.h.f./f.m. receivers.

It is anticipated that both the method and limits will be incorporated virtually unchanged in the revised British Standard 905 which is to be published later this year. Details of the procedure for measurement at 3 metres have been prepared for convenience, prior to the publication of the British Standard, and may be obtained from the Association at 59 Russell Square, London, W.C.1.

* A television receiver tuned to Channel 6 and using the standard i.f. with oscillator high is not required to meet the "in-band" limit, but must not exceed 1 mV/m.

ELECTRONIC HEATING AND AUTOMATION*

by

M. T. Elvy (Associate Member)†

A paper presented at the Convention on "Electronics in Automation" in Cambridge on 29th June 1957. In the Chair: Mr. L. H. Bedford, C.B.E.

SUMMARY

The principal methods of applying r.f. induction and dielectric heating are recalled, with particular reference to the employment of the electronic heater in conjunction with special purpose mechanical handling equipment. Work coil, electrode and associated handling equipment design are discussed. Aspects of the design of suitable electronic generators are outlined. Some of the commercial applications of electronic heating in the electronic valve, metalworking, woodworking, plastics and food industries are described. Applications considered include the outgassing and getter firing of electronic valves; petrol tank soldering; the hardening of starter ring gears, ball race tracks, rocker pads, cam followers, tappet screw heads and crankshafts; the manufacture of moulded wood products from wood waste; the welding of plastics sachets; the dielectric embossing of upholstery; and the removal of moisture from foodstuffs.

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1. Introduction

Electronic heating is now well established as an industrial heating process. It has been shown to be a tool with a range of existing and potential applications complementary to and, in some cases, rivalling those of the purely thermal process of conduction.

The development of this form of heating, which involves a radio frequency technique, began with converted radio transmitters being employed for outgassing and getter firing applications in the radio valve industry. Applications have increased steadily, with the present time witnessing electronic heating in general use throughout the electronic valve, metalworking, woodworking, plastics and many other industries.

Electronic heating is not suitable for all industrial heating applications, but, where it is applied intelligently, it will usually offer considerable advantages over some of the older and more conventional forms of heating. In particular, it lends itself through mechanization to semi- and fully automatic heating processes which employ a minimum of work handling. In order to obtain full utilization of such processes, it has become increasingly important for the equipment manufacturer to provide not only the electronic heater but the associated mechanical handling equipment as well. To this end, an overall design philosophy has to be accepted at the outset of the development which will ensure that electronic and machine design principles are integrated for the purpose of establishing optimum work flow.

Other important advantages which electronic heating offers to industry are:

(a) The equipment is ready for immediate use;

(b) The rate of heating of the work can be many times faster than when heat is transferred by conduction, convection or radiation;

(c) Working conditions are improved as a result of not heating up the surrounding atmosphere;

(d) The use of skilled labour is minimized;

(e) The equipment can usually be incorporated in the production line, thus reducing internal handling costs;

(f) Many heating applications previously regarded as impracticable may become possible;

(g) The selective heating of metals involving very high rates of energy transfer may be achieved without the necessity for electrical or mechanical contacts;

(h) Distortion of metal as a result of heating may be reduced to a minimum. Far less scaling occurs than with other methods of heating and without the need for a protective atmosphere;

(j) Precise quantitive control of the heating process can be maintained, thus minimizing scrap;

(k) An electrically homogeneous non-conducting body may be raised in temperature uniformly throughout its mass;

(l) The rate at which non-conducting materials may be heated is many times faster than by conventional heat transfer methods;

(m) Overheating or burning the surface of temperature-sensitive non-conducting materials is reduced, if not eliminated, due to the absence of an external source of heat.

2. Nature of the Work

The manner in which an alternating current flows and heat is generated within a material or the work depends mainly on the frequency of the current and the conductivity of the material. If the frequency is high and the conductivity is high, the current will tend to concentrate at the outer surfaces of the work due to the effect of lower inductive reactance exhibited by the outer layer paths of the material. This will give rise to surface or near-surface heating. On the other hand, if the conductivity is low, the current distribution tends to be more uniform, and heat is generated throughout the mass of the work.

It is convenient when considering the broad applications in which materials of any kind are heated by radio frequency currents to separate the materials into the categories of good conductors and dielectric materials of low power factors.

2.1. *Good conductors*

The depth of alternating current penetration* within a conductor is given by

$$\delta = 1\cdot98\sqrt{\frac{\rho}{\mu f}} \qquad \ldots\ldots\ldots(1)$$

where δ = depth of current penetration in inches
ρ = resistivity of the material in microhm-centimetres
μ = permeability of the material
f = frequency in c/s.

It will be seen, therefore, that the depth of current penetration will be less or the skin effect more pronounced at high frequencies and with conductors having high values of permeability and low specific resistance.

For a given frequency and physical dimensions of the work, materials such as copper, brass and steel exhibit quite different values of current penetration (Table 1; Appendix) and therefore different heating effects. In the case of the ferromagnetic materials, the permeability will increase with rise in temperature until the Curie point is reached, when the permeability will, within the range of a few degrees centigrade, fall to unity. Resistivity will also increase with rise in temperature.

2.2. *Dielectric materials of low power factors*

The power density developed within a dielectric load is directly proportional to frequency and the square of the potential gradient through the dielectric. It is these two factors which govern the rate of heating of a given dielectric of loss factor $e'' = k\cos\theta$.

$$P_v = 1\cdot41\, FE_1^2 e'' \qquad \ldots\ldots\ldots(2)$$

where P_v = power density in watts per cubic inch
F = frequency in Mc/s.
E_1 = dielectric voltage gradient in kilo-volts (r.m.s.) per inch
e'' = loss factor of the work.

For a given applied voltage and frequency, the displacement current (Fig. 1) which flows in a dielectric material is proportional to the dielectric constant (k) of the material. The component of the current that is in phase with the applied voltage and represents a loss is proportional to the power factor (cos θ) of the dielectric. It is usually convenient when considering such a dielectric loss to express it

in terms of a series resistance R_s. Provided that R_s is small compared with ωC, it is sufficiently accurate for most dielectric heating applications to express the power factor in the form $\cos\theta = \omega C R_s$. (The error is less than 1 per cent. for values of cos θ below $0\cdot1$.)
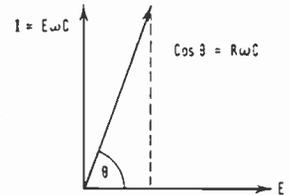

Fig. 1. Vector diagram for displacement current and applied voltage in a dielectric.

By combining equation (2) with the expression which is given in the Appendix for the thermal power requirements of the work, a useful expression[1] (equation (3)) may be derived. This equation relates rate of heating in terms of the applied voltage and frequency for properties concerned exclusively with the material forming the work.

$$\frac{\Delta T}{t} = \frac{F(V')^2\sigma}{48\cdot7} \qquad \ldots\ldots\ldots(3)$$

where ΔT = temperature rise of the work in °C
t = time in seconds
F = frequency in Mc/s
V' = applied voltage per thousandth of an inch
σ = heat factor of the work $= \left(\dfrac{k\cos\theta}{cS}\right)$
k = dielectric constant of the work
cos θ = power factor of the work
c = specific heat of the work
S = specific gravity of the work.

Table 2 (Appendix) provides values for the heat factor of various dielectric materials.

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* The penetration depth δ is defined as the depth at which the current density has fallen to $36\cdot8\%$ of the density at the surface. The limited depth of penetration of a high frequency current within a conductor is a result of magnetic flux lines linking with only part of the conductor. Those parts of the cross-section which are linked with the largest number of flux lines will have a higher inductance, and therefore reactance, than other parts of the conductor. The result is a current distribution over the cross-section such that those parts near the centre having the highest reactance will carry the least current. The difference in reactance of the inner and outer current paths is of significance at high frequencies, because both would be relatively large by comparison with the purely resistive component of the path impedances.

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3. Work Coil Design

Work coil design in relation to an electronic heating installation governs the degree of success with which a desired heat pattern is established in the work. It controls the geometry of the electromagnetic field associated with the coil and, therefore, its suitability for a particular application.

Although the size and shape of a work coil are suggested by the physical dimensions of the work, a certain amount of trial and error usually plays an important part in the design of such a coil. It is not always possible to calculate with any degree of accuracy the precise shape and ampere turns required for heating a particular type of work. This is especially the case when the work is of an irregular or complex shape. Constructional details are almost unlimited, and a varied choice of designs is available for different purposes.

The length-to-diameter ratio of a work coil is an important factor in determining whether a single or multi-turn coil should be employed for uniformly heating a given length of surface. With a small coil having a diameter not in excess of, say, $\frac{3}{4}$ in., a length-to-diameter ratio of 1 : 1 would produce uniform heating. As the diameter increases, the ratio should be reduced, so that, for example, with a coil of 4 in. diameter, the maximum length will not, as a general rule, exceed 1 in.

When multi-turn work coils of the external or internal type are used for hardening applications, it is important that the spacing between the coil turns is normally not greater than the diameter of the coil conductor. This is to ensure that a shadow effect of the coil does not appear in the heat pattern, with a consequent detriment to the hardening operation. Both the pitch and the coupling distance from the work to the coil have a direct bearing on the depth of heat penetration. A concentration of electromagnetic flux on the surface of the work, resulting from a fine pitch and close coupling, will produce a deeper layer of heat than is possible with an open pitch and loose coupling. With loose coupling, non-uniform heating is likely to occur, and the heat pattern on the surface of the work will follow the spiral of the coil. If a non-uniform heat

pattern should occur in work of a cylindrical form, it may usually be corrected by increasing the pitch at the centre of the coil relative to the pitch at the ends of the coil. Alternatively, the coil diameter may be varied where required so that a correction influence is applied to the electromagnetic field at the surface of the work.

During the heating of shaped parts, sharp edges formed by holes and keyways, etc., may become overheated as a result of a concentration of circulating r.f. currents at these points. In such cases, it is advisable to shunt the path of the r.f. currents with a copper plug or insert.

Hollow, high conductivity, copper tubing of circular, square or rectangular cross-section, which may be water-cooled, is usually employed for the manufacture of multi-turn work coils. The sizes of tubing used in general range from $\frac{3}{32}$ in. o.d. to $\frac{1}{2}$ in. o.d. The tubing is readily shaped to a desired contour and may be terminated in standard pipe fittings for providing a watertight seal.
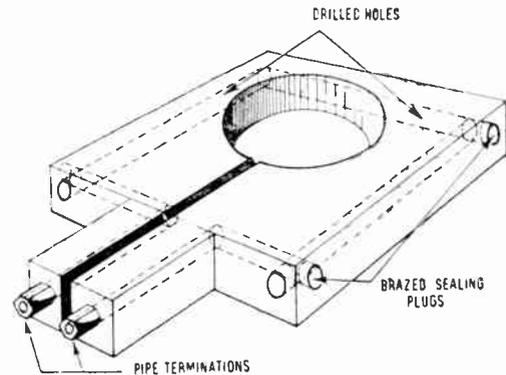
Fig. 2. Single-turn work coil fabricated from copper bar stock.

Many work coils of the single-turn variety are accurately machined from solid copper bar stock (Fig. 2). Water cooling channels are either drilled or milled in the copper stock or, alternatively, copper cooling tubes are brazed and soldered on to the flat face of the coil. Coils of this type will withstand hard usage with a minimum of maintenance. Where tight coupling between the coil and the work is necessary, they are suitable for precise surface hardening applications. With loose coupling,

they are ideal for brazing applications, where a good clearance between the work and the coil facilitates the cleaning of the coil of the effects of acid fumes, brazing flux and condensed water vapour.

In order that a work coil will be suitable for industrial operating conditions, it is essential that it is of a rigid construction. It should maintain its physical shape in relation to the work, as well as between turns in the case of a multi-turn coil. In addition, considerable electrodynamic forces which may exist between turns must be catered for when r.f. coil currents of a high value are being employed.

Turns spacers and supporting structures for work coils should be heat-resisting and combine mechanical rigidity with electrical insulation sufficient to withstand the maximum applied r.f. potential. Mycalex is a good example of a material suitable for this purpose.

Since the effective current flows only on the inside surface of an r.f. work coil, it is possible to attach supports, braces and suitable mountings to the outside surface without altering the path of the current. Where it is necessary to wind the turns close together or to have a small clearance between the coil and the work, an insulating varnish should be used, either alone or in conjunction with, say, sheet mica. For certain applications, it is preferable to insulate the coil with silicon glass sleeving, which is then impregnated with silicon varnish.

It is important with work coil circuits in general for ensuring maximum circulating current in the coil or coils that connecting leads which form part of the total circuit run close together in order to present a minimum of unwanted inductance.

3.1. Multi-turn coils for edge heating

Multi-turn work coils which are capable of high energy transfer rates into the area being heated may be effectively employed for the heat-treating of the edges of thin strips, such as the teeth of hacksaw blades, etc. Not more than six turns are normally used for applications of this nature. The spacing is kept relatively open between the middle turns to allow progressive motion of the work through the coil while close spacing is used between the end turns to reduce flux leakage.

3.2. "Hairpin" and "skid" coils

The form of work coil shown in Fig. 3 (a), which may be of the single or multi-turn type, is known as a "hairpin" coil due to its high length-to-width ratio. When this type of coil is used for heating the edge of narrow strip, it is often necessary to bend the ends of the coil upwards to prevent overheating on sharp corners of the work. An adaptation of the

Fig. 3. (a) Hairpin coil. (b) Skid coil.

hairpin coil, which is sometimes referred to as a "skid" coil (Fig. 3 (b)), has its ends turned up to form a bridge for use with progressive feed mechanisms. Coils of this type sometimes have their longitudinal axes curved when used in conjunction with rotary feed tables. If necessary, a straight coil can sometimes be employed with this type of table by using a stationary positioner to slide the work on to a fixed radius. The skid coil is often used for hardening the edges of parts such as ice skate blades, industrial knife blades and cutter bars. It also lends itself to parts of circular cross-section being passed upright through the coil as a result of induced circulating currents travelling around the circumference of the work.

3.3. Stepped coils

Where the part to be heated is conical, bevelled, or is stepped to two or more diameters, the amount of variation of the different diameters, as well as the power density required for the particular application, will determine whether a multi-turn or a single-turn work coil shaped to conform to the profile of the work should be employed. For power densities in excess of approximately 5 kilowatts per square inch, and where the variation in diameters is appreciable, a multi-turn work coil of the spiral helical type is usually preferable. It will enable uniform heating to be obtained over the length of the required heated zone and will ensure that the r.f. current does not concentrate on the inner surface of the coil section having the smallest inside

diameter. A relieved type of single-turn coil is satisfactory for lead screws, threaded shafts, etc., where the variations in diameter are small.

3.4. *Internal coils*

Applications such as the hardening of the internal walls of cylinders, the internal hardening of small dies and similar components, or annealing operations such as the shallow drawing of the inner surface of a hollow tube for subsequent machining, will usually require an internal type of work coil.

The relatively low heat transfer possible with internal coils should be taken into account in their design. The electromagnetic flux density of the opposite interior surfaces of a helical type of coil is greater on the inside than on the outside of the coil, and any flow of r.f. current will concentrate on its inside surfaces. This is in spite of a tendency for the induced current in the work to pull the coil current towards the outer surface of the coil. The effective coupling distance between the current-carrying path of the coil and the inner surface of the work will, therefore, be the sum of an air-gap plus the coil conductor diameter or width. The width of the conductors used in the design and construction of internal type work coils should, in consequence, be reduced to a minimum. Flattened tubing is usually employed with the permissible air gap restricted to not in excess of $\frac{1}{16}$ in., and less if possible.

Any lack of concentricity of an internal type of work coil assumes considerable importance due to the close coupling which must be maintained between a coil of this type and the work. With high power density heating applications such as internal surface hardening, it is common practice to rotate the work with respect to the coil. By this method, shadow effects are minimised, since the inner surface is, in effect, scanned, and uniform heating is achieved.

3.5. "Pancake" coils

Flat and other contours may be heated with the aid of a flat or compound curved type of work coil of the so-called "pancake" variety. High power densities are difficult to obtain with this type of coil, since it is only possible to utilize a relatively small amount of the electromagnetic flux associated with the coil.

When heating flat surfaces, the tendency for a pancake coil which is parallel to the surface of the work to cause minimum heating towards the centre is corrected by making the coil slightly conical, as shown in Fig. 4. The

Fig. 4. Pancake coil.

pancake coil is especially suitable for heating thin stock as a result of the eddy currents produced in the work tending to flow in the plane of the coil.

3.6. *Cored work coils*

When it is necessary to concentrate a heat pattern over a smaller surface area of the required shape than is possible by using a conventional design of work coil in close proximity to the work, a coil incorporating a ferrite core is sometimes employed. This type of cored inductor is very much more efficient than, say, a normal type of pancake coil used for the heating of a cold flat steel surface. It should be stated, however, that at the present stage of development most ferrite components are temperature-sensitive, and the question of cooling for this type of application, especially with small coils, constitutes a major design problem.

3.7. *Two-piece or split coils with integral quenching*

The shape of the work and the specified area to be heated do not always allow the work to be inserted longitudinally into a work coil. A typical example is where the bearings on the throw of a crankshaft require to be r.f. induction hardened by the single-shot method. It would be impossible to position a conventional design of helical coil at the correct location due to the offsets of the crank from the centre line of the shaft. For such applications, a split type of coil, which is hinged for opening and closing, is employed. The operation is usually effected by means of a pneumatic or hydraulic cylinder. It is quite convenient with a coil of this type to position it about the area to be heated, irrespective of the shape or mass of adjacent parts of the work.

When the diameter of the work is approximately 1 in. or greater, and the length of the zone to be heated is of a similar order of
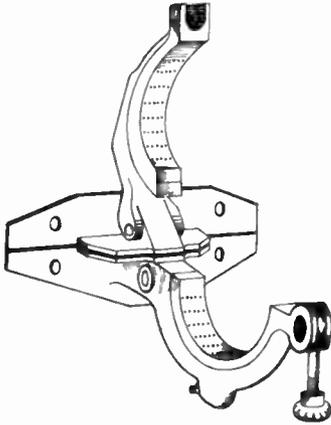

Fig. 5. Single-turn split coil with an integral quench.

magnitude, a single-turn split coil of the type shown in Fig. 5 will usually prove suitable. In cases where the desired heat pattern represents a length-to-diameter ratio greater than unity, or where the diameter is less than approximately 1 in., a higher frequency source of energy, in conjunction with a multi-turn type of split coil, will in all probability be required.

3.8. *Coil inserts*[2]

Frequent changing of single-turn work coils for accommodating parts of various diameters may be facilitated by constructing a master coil containing cooling channels and a counterbored hole for mounting removable inserts (Fig. 6).
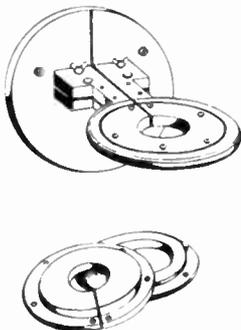

Fig. 6. Single-turn insert coil.

Each insert, which constitutes a specific coil of a given diameter and thickness, is slotted and drilled to correspond with slots and screw holes provided in the master coil.

3.9. *Multi-place work coils*

A series electrical circuit is employed for multi-place type work coils, which are frequently used for electronic valve outgassing and getter firing, as well as soldering and brazing applications. This is to ensure that the heating of each workpiece is identical. It is necessary with a coil of the type shown in Fig. 7 to make allowances for end-effect by equalizing the electromagnetic field patterns of the coil elements. With multi-turn coils, it is usual to increase the air-gap coupling distance of the end coil elements. With single-turn coils fabricated from copper bar stock, additional slots are milled on to the end coil elements.

The general proportions of multi-place work coils must be taken into consideration; otherwise, work placed within the coil openings may not receive the benefit of a surrounding coil as might be expected. Fig. 8 shows a multi-place coil of satisfactory proportions. The saw
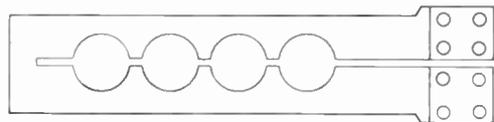
Fig. 7. Typical multi-place coil.
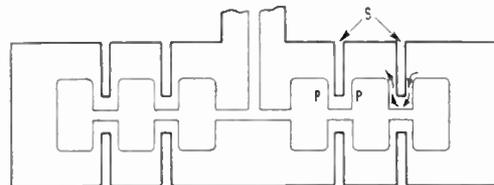
Fig. 8. Multi-place coil.

slots marked "S" ensure that the circulating r.f. currents will not by-pass the projections as at "P" but will follow the correct path as indicated by the arrows.

4. Work Electrode Design

The basic, although not necessarily the most common, form of electrodes used with electronic heating equipment consists of two flat plates made of either copper, aluminium or brass. Many other forms and shapes are employed, particularly in conjunction with plastics welding equipment.

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It is important with high voltage dielectric heating installations that work electrodes are smooth and have edge and corner radii sufficiently large to avoid any sharpness which might give rise to voltage breakdown and corona discharge. Under normal conditions, the electrode voltage will not exceed 15 kV peak. A grill or mesh type of electrode is used where voltage breakdown is likely to occur as a result of condensation caused by steam or solvent vapours.

Where uniform heating is required in a material of non-uniform thickness, it is generally possible to alter the electrode configuration in such a manner as to obtain the desired voltage gradient throughout the material.

4.1. Flat plate electrodes

Flat plate electrodes, usually of the mesh type, are widely used in plastics preheating equipment. Electrodes of this type also lend themselves to conveyorized applications. In such installations, the conveyor itself, fabricated from metallic chain or stainless steel sheet, is often employed as the lower earthed electrode.
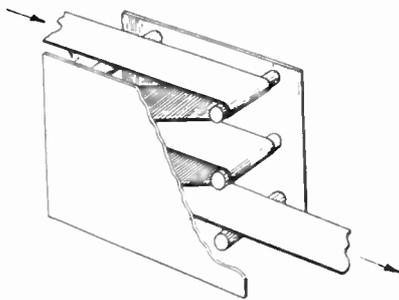
Fig. 9. Thin strip material passing between flat plate electrodes.

Flat electrodes of the type shown in Fig. 9 are sometimes used for the progressive dielectric drying of thin strip material. The work remains in the electric field between the plates for a sufficient time to become heat-treated by being passed back and forth over the insulating rolls.

4.2. Cylindrical electrodes

Where processes such as the dielectric heating of extruded rubber and plastics tubing are concerned, the work is sometimes placed
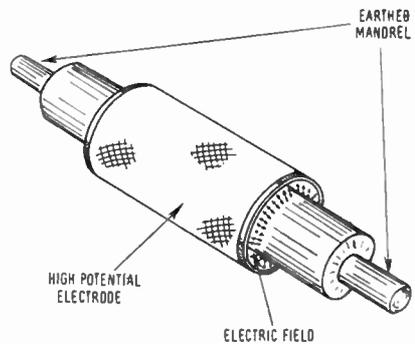
Fig. 10. Concentric electrodes.

between concentric electrodes, as shown in Fig. 10. The respective diameters of the electrodes and the spacing between them will govern the degree of concentration of the radial electric field at the surface of the inner electrode. If the material to be heated is extruded or spun on to a mandrel, the mandrel is often employed as the earthed electrode and at the same time preheated to prevent thermal flow away from the work. When this arrangement is used, an earthed enclosure made of not more than $\frac{1}{4}$ in. mesh is generally placed about the high voltage electrode. This prevents accidental contact with the "live" electrode, minimizes r.f. radiation losses, and at the same time reduces any condensation on the electrode which may occur as a result of gases being given off during the heating cycle.

4.2.1. Spiral electrode[3]

An adaptation of the cylindrical electrode, which is known as the "spiral" electrode, is shown in Fig. 11. This form of electrode is used for providing a high energy concentration as well as uniform heating of fluids such as
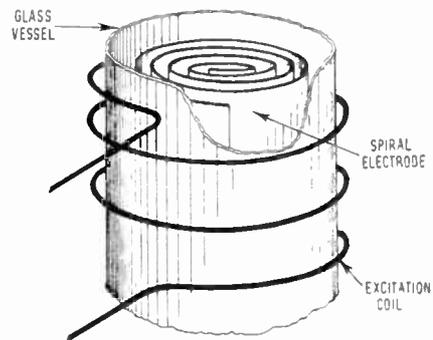
Fig. 11. "Spiral" electrode.

water and oil emulsion solutions when flowing in a closed system. The electrode is made of flat metallic strip of a given length, width, and spacing between the turns of the spiral, and represents, by virtue of its distributed inductance and capacitance, a resonant circuit. Excitation is obtained by placing the spiral within a resonant electromagnetic field. Any unit length of two adjacent turns provides, in effect, a small pair of flat plate type electrodes as a result of the potential differences set up along the length of the spiral.

4.3. Stray field electrodes

The electric field which extends outside the direct line between electrodes lends itself to surface or shallow-depth heating applications. A typical electrode arrangement which makes use of this stray field is shown in Fig. 12. A number of parallel conductors are embedded in polystyrene with adjacent conductors connected so that they are of opposite polarity. The backing board in this case is made of resin-bonded birch ply, and the work surface consists of a $\frac{3}{64}$ in. thick glass fibre laminate.
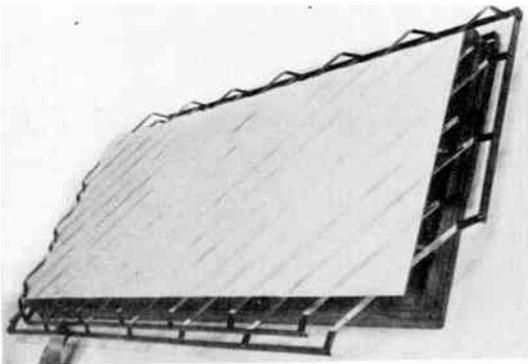
Fig. 12. Stray field electrode.

The depth of penetration of the electric field and the heat pattern developed within the work will be governed by the electrical properties of the work, the voltage developed between adjacent electrodes, the spacing between electrodes and the distance between the plane of the electrodes and the work. For a given electrode voltage and frequency, the wider the spacing between the electrodes, the deeper will be the heating, and, when this occurs, the effect

of the neutral zones directly beneath the electrodes is minimized. The width of the electrode determines the width of the neutral zone, and for this reason, narrow electrodes, such as $\frac{3}{8}$ in. × $\frac{1}{16}$ in. copper strips, are commonly used. If the neutral zone becomes an appreciable factor and cannot be controlled by adjustment of the electrode spacings, it can be eliminated completely by passing the work progressively under the electrodes on a belt
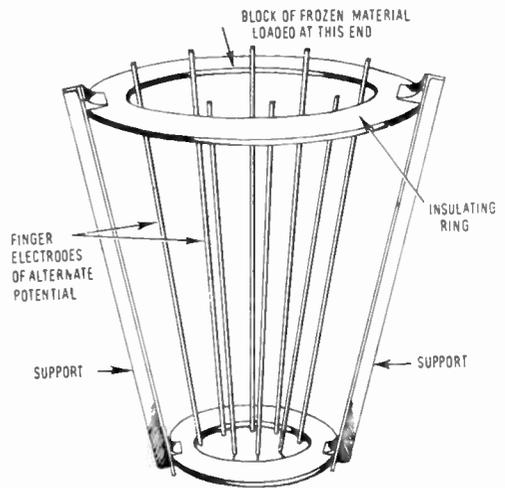
Fig. 13. Stray field electrode for dielectric defrosting.

conveyor. Some control of the depth of heating, as well as the rate of heating, for a given potential difference between the electrodes at a specified frequency, may be obtained by variation of the distance between the plane of the electrodes and the work.

A stray field heating electrode suitable for dielectric defrosting is shown in Fig. 13. The electrodes are placed radially to form the inner surface of a truncated cone. The frozen material is placed in contact with the electrodes at the top of the cone, and, as the outer surface of the block melts and falls into a container placed beneath the electrodes, the mass of unmelted material slides lower into the cone, thereby exposing more surface for dielectric heating. This continues until the mass has progressed through the electrode cone and is completely defrosted.

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4.3.1. "Cuff" electrodes

The electrodes shown in Fig. 14, and which are sometimes referred to as "cuff" or "collar" electrodes, lend themselves to the heating of tubular or rod-like material of various cross-section. This type of electrode arrangement makes use of the stray field heating technique, since the heating effect obtained utilizes the stray field on the inner side of the electrodes.
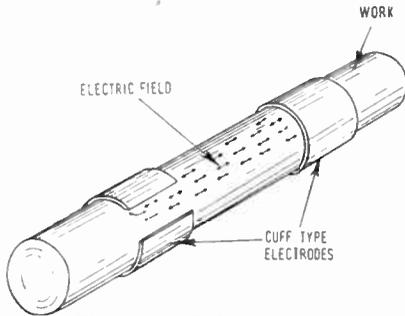
Fig. 14. "Cuff" electrodes.

The heat pattern can be varied, as far as depth of penetration and concentration are concerned, by adjusting the separation between the cuffs and their distance from the work.

4.4. *Plastics welding electrodes*

For plastics welding, an upper and lower electrode are used, with some means of applying transverse pressure. The upper electrode is often employed as the die and is generally made of brass, whereas the lower electrode may take the form of a platen, in which case it is usually made of aluminium. The die electrode is sometimes made of "T" or "L" section brass, with or without cutting edges, and mounted on an insulating backing material. Alternatively, it may be machined from solid brass for producing intricate patterns or where two-part dies are to be used for double-sided embossing.

Straight bar type electrodes are most frequently employed for welding long seams by making a number of welds consecutively along the seam path. For other than straight welds, one of the two electrode faces is usually contoured and shaped to conform with the dimensions of the area to be welded. In most cases, a high degree of accuracy in machining plastics welding electrodes is required, since materials with thicknesses ranging down to approximately 0·003 in. have to be welded.

4.4.1. Tear-seal electrodes

Tear-seal electrodes are nearly always used in conjunction with a flat plate type of lower electrode so that only one tear-seal die is required. The die electrode in this case is provided with a sharp outer cutting edge which cuts along the boundary of the weld and enables the unwanted material around the weld to be stripped away. With this type of electrode it is usual to cover the lower platen type of electrode with a suitable varnished fabric or p.t.f.e. barrier material to prevent short circuiting of the electrodes after the cutting edge has sunk through the plastics material.

5. Fixtures and Associated Mechanisms

Handling fixtures and associated mechanisms for electronic heating are made in a variety of forms to suit the particular type of heating application and the number of parts to be processed.

Mechanization in relation to r.f. induction heating usually involves the feeding and removal of the work to and from the work coil, the holding of the work in proper physical relationship to the coil to produce a pre-determined heat pattern, and the ability to repeat the function with uniform results. The fixture must be kept clear of the electro-magnetic field associated with the work coil to avoid itself becoming heated. A minimum distance of approximately 2 in. is usually required between the work coil and any extraneous metal objects. If the parts of the fixture or mechanism must be close to the work coil, they should be made of some non-magnetic or non-metallic material, depending on the field strength involved. Alternatively, the mass and shape of the parts should be altered where possible in order to lower their susceptibility to induced r.f. currents. In this connection, minimum surface contact between the work and the fixture can generally be arranged by the use of knife edge supports.

Mechanization associated with dielectric heating is generally concerned with the feeding and removal of the work to and from the electrodes, the possible application of pressure to the work and the removal of moisture or other volatiles that may be given off from the

work during the heating cycle. Care must be exercised to ensure that the presence of metal as part of the handling fixture does not distort or shield the electric field between the electrodes. The minimum spacing which should be maintained between the electrodes and a nearby metal fixture is not always readily defined, since the electrode shape, field intensity and the shape of the parts of the fixture are all determining factors. In practice, an attempt is usually made to keep the distance between electrodes and metal objects not less than the distance between the electrodes.

5.1. *Mechanization and R.F. Induction Heating*

5.1.1. Loading and ejecting the work

Where fixtures involve the assembly of components, remote loading by the use of interchangeable jigs is often utilized for reducing loading times. Mechanical or pneumatic type pressure clamping devices are usually employed for holding together the component parts of the work in correct relationship to each other. This is particularly the case where soldering and brazing of heavy parts are concerned. For light parts, spring clamps are sometimes used.

Various methods of ejecting the work from a fixture are employed as a function of handling, quenching, etc. In cases where it is possible to release the work through the base of the work coil, a fast-acting solenoid-operated trapdoor type of mechanism is sometimes used. The trip is then activated directly from a process timer which is used to control the heating period.

5.1.2. Moving the work with the work coil stationary

The basic mechanism employed for moving the work through the work coil and mounted beneath the coil is usually a roller drive or a conveyor with the rate of progression controlled by a variable speed motor.

Roller drive.—The progressive processing of parts of relatively light weight and thin cross-section such as hacksaw blades, as well as small diameter round stock and flat bars, may be facilitated by using power-driven pressure rollers. Two or more sets of rollers are mounted on a vertical axis to push the work through the coil. Variable tension spring loading for the rollers provides correct pressure for the drive, as well as ensuring a satisfactory earth connection to the work and rollers.

Conveyor drive.—Chain conveyors and belt conveyors of the friction-driven type, provided the speed of traverse is not in excess of, say, 10 ft per minute, are used for progressive heating applications. The soft soldering of the tops of sheet metal containers, brazing pre-assembled units and various annealing applications, etc., are frequently handled in this manner. It is sometimes convenient, with the chain type of conveyor, to drill and tap the cross links to provide a method of fastening jigs and fixtures for holding the work.

Progressive fixtures.—Vertical rather than horizontal fixtures are generally used for simplifying the application of a spray quench when the work is progressively passed through a work coil. Fixtures of this type are usually driven by a lead screw mechanism with a variable speed motor capable of being varied through a stepless speed range of approximately 7·5 in.–75 in. per minute. The lower work rest is usually fixed, while the upper support is made adjustable for accommodating various lengths of stock. For case hardening applications where the required depth of the hardened zone may be of the order of only 0·040 in.–0·060 in., the work should be perpendicular to the plane of the coil. The importance of having all the hardened areas of a uniform depth justifies rotating the work. A single rotational speed of approximately 90–120 rev/min is usually satisfactory for providing a uniform heat pattern.

The type of application will determine whether the motion in a vertical direction should be continuous or intermittent, constant or accelerating. For hardening the entire length of the work, a continuous constant speed with a fast return mechanism is usually required. For the single-shot hardening of small areas only of the work such as small bearing points, an intermittent motion is desirable. Suitably located limit switches actuated by "dogs" which move with the carriage are responsible for stopping the motion, energizing the work coil, applying the quench and then energizing the motor drive to the next limit switch. For

progressive zone hardening, limit switches, in conjunction with dogs on the carriage, ensure that the carriage moves rapidly to the point where the first zone to be hardened enters the work coil, when the speed of traverse is slowed down to a predetermined value for processing. The work coil is energized, and a solenoid-operated quench valve is opened. After the carriage has traversed the zone, the work coil is de-energized and the quench valve is closed. The sequence of events is then repeated. For work which exhibits small differences of diameter along its length, a single work coil may often be employed for hardening the surfaces of the different diameters by arranging for the speed of traverse to be altered as some inverse function of the diameter being processed. Components such as tapered shafts of relatively short length which require a continuous accelerating motion through the work coil are usually accommodated by linking the work with a rotating cam. The contour of the cam is then shaped to control the rate of travel and consequent heat pattern.

Turntable fixtures.—Turntable type fixtures, which are often made of stiffened aluminium plate and associated with a variable speed drive or indexing type of pneumatic cylinder, are rotated, either continuously or intermittently, in accordance with application requirements.

An adaptation of the turntable fixture frequently involves the automatic release of the work through the turntable into a quench bath if the part is being heated for hardening, or into a basket for convenience of handling. It is sometimes advantageous to place the turntable type of fixture in a vertical plane. The work, after passing through work coils, often of the hairpin variety and located on either or both sides of the turntable, reaches a dropping point for transfer to subsequent processing operations.

5.1.3. Moving the work coil with the work stationary

The work to be heated may be of a relatively large mass or contour as would be experienced, for example, with the progressive surface hardening of the guideways of a lathe bed. In such a case, it is usual to feed the work coil through flexible r.f. current-carrying leads and

move the coil and quench along the stationary work. The path of traverse of the work coil carriage may, in applications of this nature, be independent of the part being heated or controlled directly by being in contact with the work.

5.2. *Mechanization and Dielectric Heating*

It is important with dielectric heating installations that any metal employed as part of a work handling fixture does not, by virtue of distributed capacitance between itself and the electrodes, assume a potential above earth and cause distortion to the electric field between the electrodes. Vapour-removal manifolds or air ducting which may be in close proximity to the electric field should be made of some non-metallic material of low loss factor such as polystyrene.

5.2.1. Applying pressure to the work

The simultaneous application to the work of mechanical pressure and r.f. power is often required with processes involving dielectric heating.

Independent hydraulic or pneumatic presses using shaped and curved electrodes are frequently encountered in the wood-gluing field for the manufacture of furniture, etc. In such cases, the lower platen of the press may be operated at earth potential and be in the form of a die conforming to the desired contour of the finished part. The upper matching platen would incorporate a high potential electrode backed by a suitable insulating material such as, for example, a laminated block of maple, approximately 6 in.–12 in. thick, depending on the magnitude of the applied r.f. voltage. In this manner, equalized pressures are obtained over the curved surfaces when the press is closed. Where a number of places in the work require independent applications of pressure, as in a predetermined sequence for simplifying the mechanical assembly of various component parts, pneumatic cylinders are invariably used.

Plastics welding and dielectric embossing presses, apart from some small foot-operated plastics welding machines, are usually of the pneumatic or hydraulically-operated type. A high degree of mechanical accuracy and the maintenance of rigidity are important factors to be associated with the design of plastics

welding presses, owing to the relatively thin sheets of plastics material which require welding. Total thrusts of up to 30 tons and more are used with some of the larger independent types of plastics welding and dielectric embossing presses, which usually operate at a frequency of the order of 20 Mc/s. Smaller presses, operating at approximately 36 Mc/s, generally have the r.f. generator built into the press itself for the purpose of minimizing lead inductance when employing other than co-axial feeding between the r.f. generator and the press.

5.2.2. Conveyor drive

Several factors (including the effect of the electric field on the conveyor belt, the nature of the material being carried by the belt, the amount and composition of any volatile substances given off by the work during the heating cycle, the method of handling, traverse speeds, etc.) must be taken into account when choosing a belt material suitable for a conveyorized dielectric heating handling fixture.

In order that the conveyor belt will ride smoothly over the lower electrode, it is usual to raise the electrode by approximately $\frac{1}{16}$ in. above the infeed and outfeed guides to the electrode area.

Of the non-conducting conveyor belt materials, canvas duck is generally satisfactory, as it does not normally absorb too much heat energy when exposed to the alternating electric field between the electrodes.

Metal belts, either of thin sheet or of chain mesh construction, and made of either plain carbon steel or stainless steel, are extensively used. In such cases, they become in effect the lower earthed electrode. A satisfactory contact surface should be provided between the conveyor belt and the support base and guides to prevent any localized heating of sections of the conveyor. At the same time, the frame of the fixture should be bonded in such a manner as to present a low overall return impedance to circulating r.f. currents

The choice between a conveyor belt of the sheet metal or chain mesh type will depend upon the particular application. If the material to be heated contains a high percentage of moisture or corrosive solvents, the belt should

be of the stainless steel variety. Similarly in the food processing field, where the food may be in direct contact with the belt, stainless steel is generally preferred. In dielectric heating equipment for foundry core baking, on the other hand, chain mesh belts are used, since they permit of the ready removal of the sand.

6. Generators

Electronic heating generators suitable for industrial applications operate in general within the frequency spectrum of 100 kc/s–200 Mc/s. Output powers range from a few hundred watts at the highest frequencies for applications such as spot gluing and cellulose acetate welding, to output powers of up to approximately 500 kW for the case hardening of steel, etc. The overall efficiency of most r.f. heating generators is of the order of 50 per cent.

R.f. induction heating generators generally use frequencies between 100 kc/s and 1 Mc/s. Equipments with output powers not higher than, say, 3 kW, tend to utilize frequencies between 500 kc/s and 1 Mc/s, whereas the majority of medium to high power generators with output powers of approximately 5–50 kW use a frequency of operation of the order of 450 kc/s. Higher power generators, i.e. with output powers in excess of 50 kW, generally operate at frequencies between 100–300 kc/s.

Dielectric heating generators operate at various frequencies between 1 Mc/s and 200 Mc/s, with the nature of the work to be heated usually determining the particular operating frequency. R.f. generators for the woodworking industry operate in general at frequencies between 10 Mc/s and 15 Mc/s. Some applications require frequencies in the region of 20 Mc/s, whilst others, such as edge bonding applications, require the selective heating which is obtainable by using frequencies of the order of 1 Mc/s. Plastics preheating and plastics welding generators usually operate at frequencies between 25 Mc/s and 100 Mc/s. In the United Kingdom the majority of equipments of this type operate at approximately 36 Mc/s. Many other frequencies are used for general dielectric heating applications, and, as suitable power oscillator valves become available, there is an increasing tendency to utilize the higher frequencies.
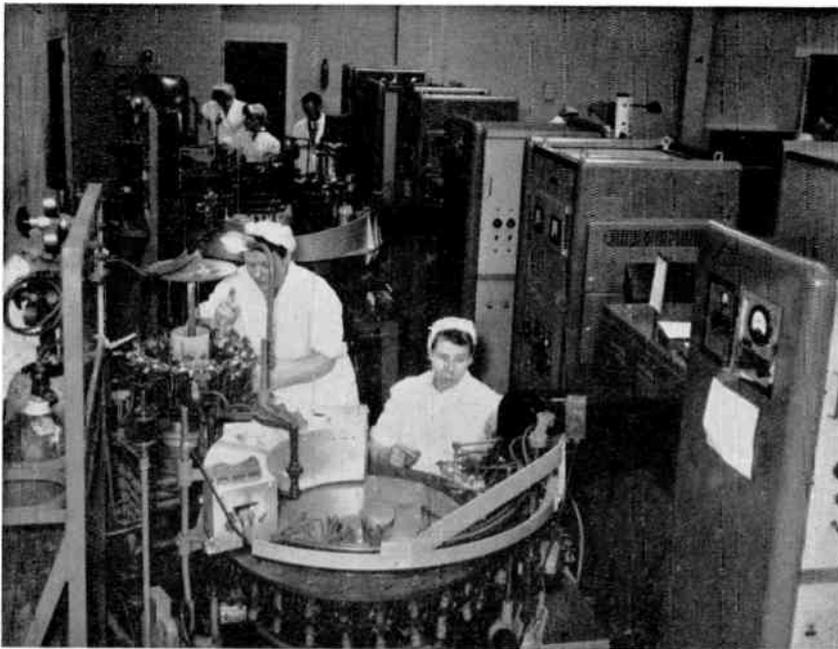
Power oscillators of the feedback class are used with the various types of r.f. heating generators. The principal circuits in everyday use which are determined mainly by the frequency of operation of the equipment are the Hartley, Colpitts and reversed feedback.

7. Industrial Applications

Electronic heating lends itself to automation not only because it provides the fastest rate of heating so far known, but also because of the precision with which it may be controlled. Heating takes place within the work itself, the amount of heat depending only upon the power input to the work and its duration, both of which may be accurately controlled. Furthermore, this quantitive control of heating need not be confined solely to the intensity and amount of heating but may also be applied to heating selected parts only of the work.

To ensure that consistent heat-treatment and processing may be repeated for an indefinite number of operations, the r.f. generator may include built-in devices for providing constant supply voltages as well as continuously variable impedance matching. By such means, a fluctuating mains supply is catered for and compensation provided for variations of the electrical characteristics of the work during the heating cycle. One such method makes use of the change of anode current loading for producing an error signal for comparison with a fixed reference, the resultant being used to energize a motor-driven impedance matching device. An alternative method, which incorporates a closed-loop servo system, employs a controlling signal from an electronic pyrometer arranged to view the work. This system also lends itself to controlled heating as a function of process variable information which may be fed back from separate automatic inspection devices[4] situated at various stages along the production process.

Automatically-controlled heat-treatment installations incorporating electronic heating equipment are being used on an increasing scale by industry for the processing of large quantities of materials and components. The flow of work to and from the heating operation is handled automatically, and the heating operation itself is maintained to pre-set standards.

In the applications which follow, the equipment described may be adapted to form part of a flow line production system by integrating the individually controlled heating processes and associated mechanical handling equipment into larger automatic transfer groups.

7.1. R.F. Induction Heating

7.1.1. Outgassing and getter firing electronic valves

One of the earliest applications of electronic heating was for outgassing and getter firing electronic valves, and this is now almost universally employed in the radio valve industry. Selective heating of the elements of the valve for driving out occluded gases during the evacuation process generally takes place in the temperature range of 700°C–1300°C. Any remaining traces of gas are reduced by physical and chemical reaction by firing the getter after outgassing and evacuating have been completed.

Special purpose mechanical handling equipment, usually of the multi-position rotary pumping and sealing type, is employed for large scale electronic valve production (Fig. 15). With equipment of this type small r.f. units, arranged to feed individual work coils and mounted directly on the turntable mechanism, are sometimes preferred to a single larger source of r.f. power. By this method, ionization, if undesirable, may be prevented by the employment of a low work coil-to-earth applied r.f. voltage and unwanted radio interference minimized.

7.1.2. Petrol tank soldering

A special purpose machine employing r.f. induction heating for the soft soldering of fittings to commercial vehicle petrol tanks in one operation is shown in Fig. 16. The
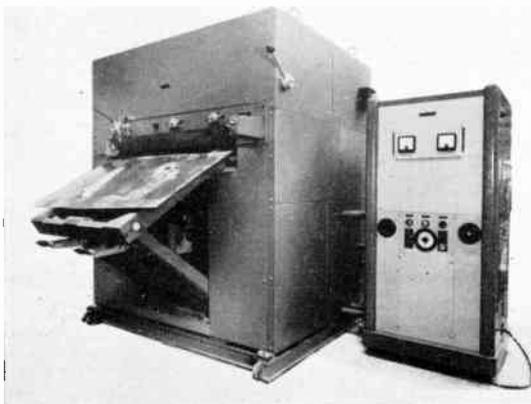
Fig. 16. Machine and associated r.f. generator with loading carriage down and petrol tank sheet and fittings in position. (Courtesy Vauxhall Motors Ltd.)

soldering is carried out on the flat sheet prior to bending and forming. Several sizes of sheet with various fittings can be accommodated. Tin-plated steel sheet is loaded on to the carriage, where tin-plated steel components such as the petrol tank filler, drain plug, draw-off pipes, etc., solder preforms and flux are placed in position. The carriage, which is power-assisted, is moved into position by an electro-pneumatic system. Stripper arms lift the sheet off the carriage into the heating position, when the carriage is withdrawn for reloading. Initiation of an automatically-timed heating cycle of 25 seconds takes place, after which cooling air is applied and the sheet is automatically ejected from the rear of the machine. R.f. power is fed to series-connected pancake type work coils from a 9 kW 450 kc/s generator.

Before electronic heating was employed, a time of up to about 10 minutes per completely soldered sheet was taken. The machine described reduces the floor-to-floor time to half a minute per completely soldered sheet.

7.1.3. R.f. induction hardening plant for starter ring gears

In a special installation which incorporates a 30 kW 450 kc/s r.f. generator, provision is made for hardening three sizes of starter ring gears. The diameters of the rings, which are made from 0·35–0·40 per cent. carbon steel, are 10·25 in., 14·5 in. and 15·125 in. respectively. Thicknesses of the rings range from $\frac{5}{16}$ in. to $\frac{1}{2}$ in. The hardness obtained is 52–54 Rockwell C to a depth of 0·125 in. below the root of the teeth. The heating cycles for the small, medium and large rings are 17 seconds, 32 seconds and 56 seconds respectively, with corresponding floor-to-floor production rates of approximately 144 per hour, 90 per hour and 56 per hour.

After a starter ring gear has been placed on the loading station, heating and quenching cycles are completely automatic. The work is mounted on a hydraulically-operated carriage, which brings it into position beneath a single-turn work coil at the hardening station. The three work coils for the three sizes of rings are mounted one above the other. Carried centrally above the coils is a hydraulically-operated gripper mechanism which moves
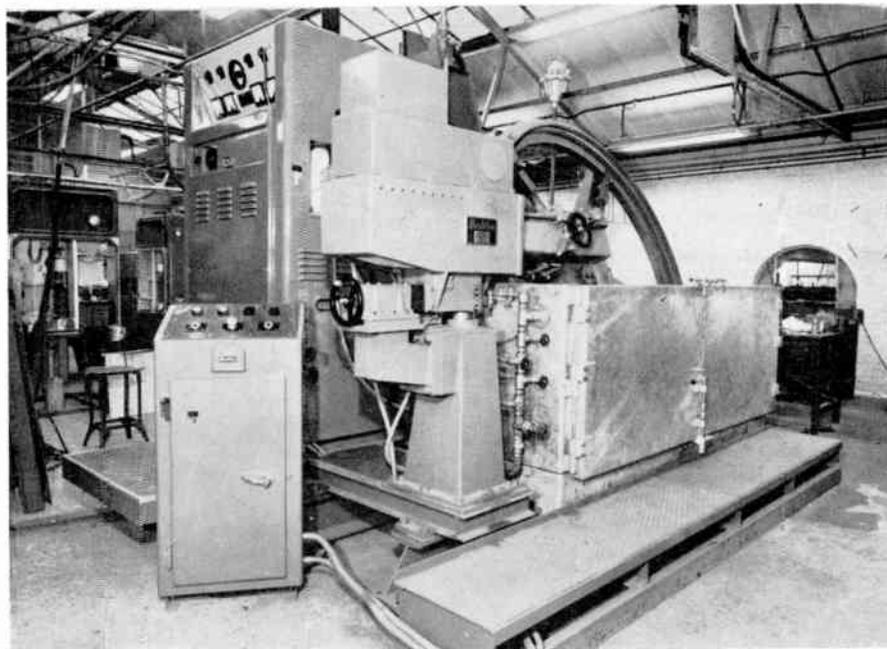
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down, picks up the work from the carriage and lifts it into position within the appropriate work coil.

The base of the plant incorporates a temperature-controlled water quench tank in which is immersed a cross-slatted wire mesh conveyor. At the termination of the heating cycle, the gripper arms are released and the work drops on to the conveyor, where it is carried beneath the transfer carriage to emerge at the ejection platform at a temperature of approximately 200°C for stress relief.

Six process timers are provided for controlling the heating cycle, two for each size of ring. The first is set to provide the required overall heating time, while the second serves to switch in power factor correction capacitors for generator re-matching when the heated steel reaches the Curie point.

### 7.1.4. Hardening large ball-race tracks

An example of the r.f. induction hardening of the track of a relatively large ball-race of 7 ft 6 in. in diameter is shown in Fig. 17. The ball-race is made from a direct hardening steel of 0·40–0·45 per cent. carbon content and clamped to a spider on an assembly which is rotated by a motor drive in conjunction with a speed reduction box. For this application the scanning technique is employed. A specially shaped work coil is energized via an r.f. current transformer fed from a 30 kW 450 kc/s generator. The coil, and a water quench jet which is situated $\frac{5}{8}$ in. immediately beneath it, are mounted on a "follower" mechanism which holds the spacing between the work coil and track face to 0·02 in. ± 0·0005 in. With this equipment, a consistent hardness of 57 Rockwell C is obtained to a consistent depth of 0·09 in. below the face of the track.

7.1.5. Hardening rocker pads, cam followers and tappet screws

The electronic heating installation shown in Fig. 18 consists basically of two independent hardening units housed within a common framework. It is used for hardening valve rocker pad faces and cam follower cup ends at one work station and tappet screw heads at the other. A 9 kW 450 kc/s r.f. generator is employed as a common power source for the two units.

Rocker pads of 0·40–0·45 per cent. carbon steel are loaded on to a pneumatically-operated 12-position indexing turntable situated on the left-hand unit. As the rotary head indexes round in a clockwise direction, r.f. power is applied to a pancake type work coil. After a
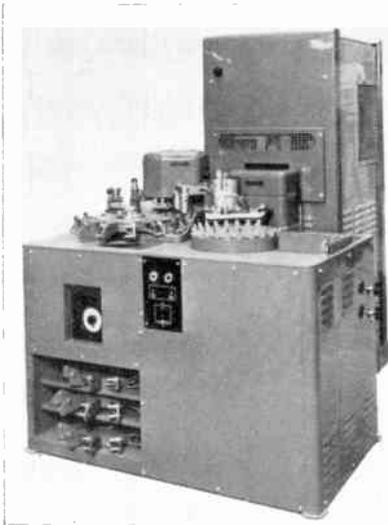
Fig. 18. Installation for hardening rocker pads, cam followers and tappet screws (Courtesy of The Rover Co. Ltd.)

component has been located beneath the coil for a predetermined heating period, it is moved round under dual-water quench jets for complete quenching prior to unloading. The unit, which is capable of maintaining a continuous production rate of 10 rocker pad faces hardened per minute, attains a minimum

hardness of 58 Rockwell C to a depth of 0·100 in. below the surface of the pad face. For cam follower cup ends where the production rate is six per minute, the pancake-type work coil is replaced by a skid type of coil and the operational procedure as for rocker pads is repeated.

Actuation of an r.f. changeover switch to supply r.f. power to the right-hand unit causes an elongated type of pancake work coil to be energized via a built-in r.f. current transformer. Tappet screws of 0·50–0·60 per cent. carbon steel are loaded on to pivoted component location blocks mounted on a 24-position turntable. The table, which employs a geared motor drive, rotates continuously to enable the components to be passed beneath the work coil, which is of sufficient length to heat four tappet screw heads simultaneously. Subsequent to heating, the work is subjected to a drop quench in oil. The continuous production rate of the unit is 22 tappet screw heads hardened per minute. The minimum hardness obtained is 58 Rockwell C to a depth of 0·12 in. below the apex of the spherical surface contour of the head of each component.

7.1.6. Crankshaft hardening

Induction heating at frequencies of the order of 10 kc/s has been employed on an industrial
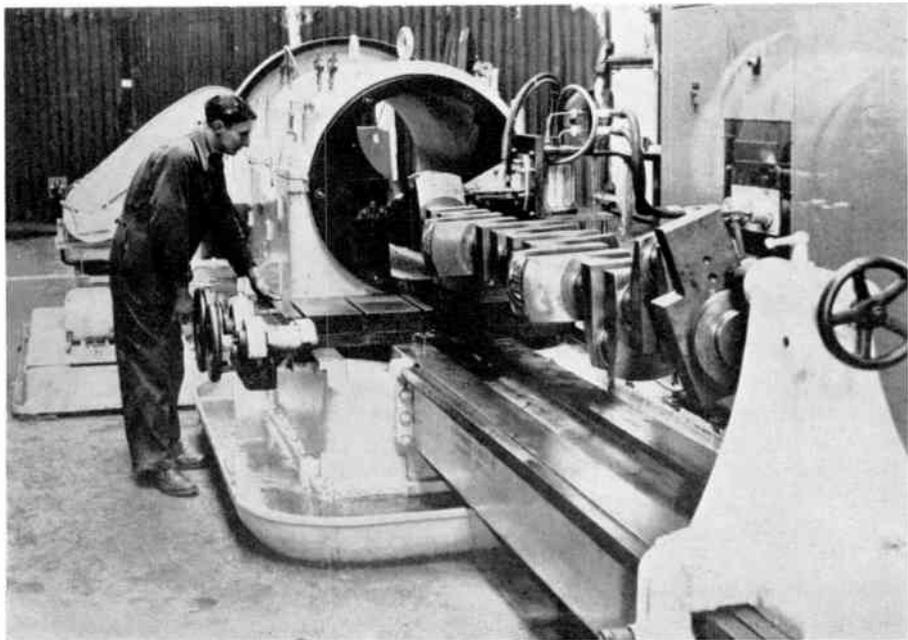
Fig. 19. Crankshaft hardening installation. (Courtesy of Mitchell Shackleton & Co. Ltd.)

scale for many years for the surface hardening of the crankshafts of diesel engines. Constant increases in the power of engines and increasingly high pressures resulting therefrom on the bearings of crankshafts has resulted in exacting hardness requirements. Many of these surface hardening applications are now proving to be better suited to hardening by large valve-driven generators than by rotating machines.

Figure 19 illustrates what is possibly the largest present-day example of an installation for crankshaft hardening as a function of electronic heating. The r.f. generator employed is capable of a continuous output power of 125 kW at 225 kc/s. A wide range of crank-shafts may be hardened with this particular equipment. Relatively small multi-throw crankshafts having pins of up to 3·0 in. diameter × 2·0 in. long may be single-shot hardened. Large marine diesel engine crank-shafts of 25 ft. and more in length, with pins of the order of 8·0 in. diameter × 10·0 in. long, are hardened by employing a scanning technique with a following oil quench. The crankshaft shown being handled, prior to hardening, and which is mounted on an off-throw type of lathe, is made of 0·40–0·45 per cent. carbon steel. The minimum hardness obtained to a depth of 0·100 in. is 58 Rockwell C. The pins being processed in this particular case, which are 6·0 in. diameter × 3·25 in. long, rotate at a hardening speed of 10·5 in. per minute. For this crankshaft, tempering subsequent to hardening is achieved by turning off the quench, reducing the r.f. power and increasing the scanning speed.

7.2. Dielectric Heating

7.2.1. Manufacture of moulded wood products from wood waste[5]

In a large installation for the utilization of wood waste, moulded wood products of various shapes are manufactured, with the aid of electronic heating for curing, from a mixture of wood shavings and synthetic resin glue. In the first part of the installation wood shavings of suitable size are dried to a moisture content of less than 10 per cent. in a gas-fired rotary type of dryer, after which the dried shavings are air-blown along a feed pipe to cyclone hoppers mounted above a mixing platform. At this stage, the shavings

are passed to a series of rotating drum type mixers, where they are mixed with approximately 15 per cent. of liquid urea formaldehyde and a separate hardener. After mixing, the agglomeration is fed by way of gravity chutes for pressing into mould boxes. The mould boxes containing the compressed agglomeration are then passed along roller conveyors to electronic heating cages, where r.f. power is applied via electrodes attached at suitable positions on each mould box for through-heating the work. The r.f. power is applied for a predetermined time, after which the mould boxes move forward on roller conveyors to unloading bays and inspection tables.

7.2.2. Welding plastics sachets

Electronic heating in conjunction with special purpose automatic packaging machines is being used on an increasing scale for the manufacture of liquid filled sachets. In a typical machine employed for making shampoo sachets, gripper arms draw roller-fed p.v.c. sheeting vertically downwards, where it is folded in half and subsequently guided around a liquid feed pipe. The sheeting is then passed down to a photo-electrically controlled location between a pair of "U" shaped pressure-applying welding electrodes. The electrodes close about the p.v.c. sheeting, when r.f. power is auto-matically applied to the work causing the bottom and two upright sides of the sachet to be welded. At this stage, a predetermined quantity of shampoo is injected into the sachet. The electrodes then open, allowing the next downward stroke to take place. The electrodes close and weld the three sides of the following sachet, the bottom weld of which is arranged to form the top weld of the previous sachet. The sequence of operation is then repeated. The overall production time per sachet, allowing for welding and dwell periods, is 2 seconds. R.f. power in this particular application is obtained from a 1 kW 36 Mc/s generator.

7.2.3. Dielectric embossing

Dielectric embossing is being employed for the single-shot embossing of complete car and coach door panel trims, car bench type seats, cushions and backs, roof linings, perambulator and soft furnishing upholstery, etc. Plastics materials are available, such as fibroceta

acetate fibre wadding which have been specially formulated for dielectric embossing operations. This particular type of material is suitable as a resilient padding or interlining between sheets of, say, p.v.c. coated hardboard and various types of fabrics, all of which may be rapidly embossed with the aid of electronic heating. The development of fibroceta wadding and similar materials has enabled continuous lengths of welded, quilted and embossed p.v.c. materials to be produced.

Production times for dielectric embossing depend on a number of factors, including the actual area to be embossed and, to a certain extent, the size of the press and associated r.f. generator used for the application. A typical equipment, for example, will emboss in 20 seconds up to approximately 100 square inches of a car door panel consisting of a $\frac{3}{16}$ in. thick phenolic impregnated wadding sandwiched between a plastics coated board 0·08 in. thick and a 0·02 in. thick coated fabric vinyl. The equipment consists of a hydraulically-operated 30 ton press with a platen area of 6 ft 3 in. × 3 ft 3 in. and an associated r.f. generator having an output power of 20 kW at 18·5 Mc/s.

7.2.4. Moisture removal from foodstuffs

Apart from defrosting, one of the most important applications to date of electronic heating in the food industry is the removal of moisture from food during processing. Certain types of biscuit baking ovens, for example, which hitherto employed conventional heating only and were hundreds of feet in length, are now becoming available with a greatly reduced length as a result of the application of dielectric heating as an adjunct to the existing forms of heating.

An equipment for continuously drying high protein-low starch bread rolls is a typical example. The rolls, which are cellular in texture, measure 2·25 in. in diameter and weigh approximately 1 ounce. After conventional oven baking, the rolls have their moisture content reduced from 19 per cent. to 9 per cent. in 15 seconds by being passed between plate type electrodes placed above and below the conveyor of a dielectric heating installation.

The peak r.f. electrode potential in this particular application is approximately 15,000 volts obtained from a 10 kW 20 Mc/s r.f. generator. The conveyor speed is maintained at 6 ft per minute, and the rolls pass between the electrodes at a rate of 200 per minute. Controlled warm air is used to remove the moisture extracted from the rolls. After drying, the rolls are ready for immediate packing. Prior to the application of electronic heating, the part of the process described took approximately three hours and required the use of large steam-heated dryers.

8. Conclusion

Electronic heating is playing an important part in the modernization of many industrial heating processes as well as in the evolution of entirely new forms of heat-treatment and processing. Existing and potential applications are as wide as industry itself, and now that electronic valves and components are being designed and manufactured specifically for this class of service, the advantages which will accrue to users of this electronic aid to production are assured.

9. Acknowledgments

10. References

1. L. L. Langton, "Radio-Frequency Heating Equipment," p. 21 (Sir Isaac Pitman and Sons, Ltd., London, 1949).

2. F. W. Curtis, "High-Frequency Induction Heating," p. 124 (McGraw-Hill Book Company, Inc., New York, 1950).

3. J. W. Cable, "Induction and Dielectric Heating," p. 369 (Reinhold Publishing Corporation, New York, 1954).

4. J. A. Sargrove, "The Automatic Factory—What does it Mean?" p. 95 (The Institution of Production Engineers, London, 1955).

5. M. T. Elvy, "Electronic Heating and the Woodworking Industry," *J. Brit.I.R.E.*, **14**, p. 561, November 1954.

6. L. Hartshorn, "Radio-Frequency Heating," p. 55 (George Allen and Unwin, Ltd., London, 1949).

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11. Appendix

In addition to the data and formulae quoted in the body of the paper, the following information is relevant to electronic heating applications in industry.

Thermal power requirements of the work.

$$P = 17 \cdot 6 \, mc\Delta t$$

where P = thermal power requirements of the work in watts

m = weight of work in pounds heated per minute

c = specific heat of the work

Δt = temperature rise of the work in °F.

Table 1

Depth of Current Penetration δ for Typical Metals[6]

Metal	Resistivity microhm-centimetres	Permeability μ	Depth of current penetration δ in inches		
			10 kc/s	100 kc/s	1 Mc/s
Copper	1·7	1	0·026	0·008	0·003
Brass	7	1	0·052	0·017	0·005
Steel, hot (above 780°C) ...	120	1	0·216	0·069	0·022
Steel, hot (below 780°C) ...	40	40	0·020	0·006	0·002
Graphite	800	1	0·600	0·170	0·060
Tap water	2000	1	0·870	0·280	0·087

Table 2

Heat Factor σ for Various Dielectric Materials

Material	Heat Factor	Material	Heat Factor
Phenol formaldehyde (wood flour filled) moulding pellet	0·29	Oak (8% moisture)	0·68
Urea (fabric filled) moulding powder	0·62	Birch (10% moisture)	1·15
		Phenolic glue mix	11·00
Window glass	0·37	Urea glue mix	14·30
Pyrex glass	0·02	Cellulose acetate sheet	0·44
		P.V.C. (plasticized)	0·25
Spruce wood (10% moisture) ...	1·63	Rubber (hard)	0·08
Beech wood (10% moisture) ...	2·80	Slate	0·25
Walnut (15% moisture)	1·80	Mycalex	0·03

. . . Radio Engineering Overseas

A selection of abstracts from European and Commonwealth journals received in the Library of the Institution. All papers are in the language of the country of origin of the journal unless otherwise stated. The Institution regrets that translations cannot be supplied.

621.315.212.011.1

An iterative method for calculating electromagnetic fields. A. REDHARDT. *Archiv der Elektrischen Ubertragung*, 11, pp. 227-230, June 1957.

It is assumed that the inner conductor of a coaxial line is cut off at a certain point in a plane perpendicular to the axis, while the outer conductor is continued. When waves pass through this transmission line, stray fields come about at the point of discontinuity, with the transversal and longitudinal components of the electrical field passing continuously through the interface. The resultant composite field can be established successively by adding fields alternately at the one and the other side of the interface, while satisfying in each case one of the two boundary conditions. The method involves but moderate computing work.

621.317.321

Measurement of transmission distortion in frequency-modulated radio links. H. HARTBAUM. *Archiv der Elektrischen Ubertragung*, 11, pp. 239-252, June 1957.

A measuring method is described with which the transmission distortions of frequency modulated systems can be determined separately by static and dynamic nonlinearities. The method can be applied to individual elements of radio links such as modulators, demodulators, etc., but the distortion of complete systems can be measured in service as well.

621.317.33

The accuracy of a method for measuring series capacitances and inductances. H. RUHL. *Nachrichtentechnische Zeitschrift*, 10, pp. 297-302, June 1957.

Investigations concerning the accuracy, which can be obtained from a method developed by Herzog for measuring the series capacitance and inductance of crystals, have been carried out. A modified version of the method of measurement, which leads to a simple formula for the determination of the series capacitance is explained.

621.372.5

On the design of four-terminal interstages for pulse applications. A. K. CHOUDHURY AND N. B. CHAKRA-BARTI. *Indian Journal of Physics*, 31, pp. 193-210, April 1957.

The present work is devoted to the design of four-terminal networks having prescribed input and output capacitance for a transient response with little or no overshoot. The requirements for such a performance are first studied. The conditions that the response of the network has no overshoot, and the bounds on the time response set by the capacitances have been obtained. The pole configurations that may achieve the desired characteristics are described. Methods for realizing the required pole distributions are formulated, and some circuit arrangements are suggested.

621.372.51.029.64

The dielectric disc as transformation quadripole in the magnification of node displacement measurements. L. BREITENHUBER. *Archiv der Elektrischen Ubertragung*, 11, pp. 223-226, June 1957.

An earlier paper discussed the introduction of a transforming piece in transmission lines used for measuring purposes, in order to magnify small displacements of the voltage nodes for greater ease of measurement. In regard to the small node displacements resulting in measuring the permeabilities of ferromagnetic materials in Lecher wires this possibility was illustrated by reference to a specific example.

This paper deals with the case of a dielectric disc on the basis of the transmission line equations, and the analytical representation of the maximum attainable node displacement is derived as a function of the thickness and the dielectric constant of the disc. The discussion reveals that the magnification of the displacement becomes a maximum when the disc shifts the phase by 45° (quarter-wave piece). In this case and for very high dielectric constants the magnification of the node displacement is directly proportional to the dielectric constant.

621.372.512:621.385.1

Induction in electromagnetically coupled systems. W. DAHLKE. *Archiv der Elektrischen Ubertragung*, 11, pp. 231-238, June 1957.

Each compound system consisting of primary system with electromagnetically coupled secondary system can be represented at its input end by a parallel-connected primary admittance and induced admittance or by a series-connected primary impedance and induced impedance. The apparent power introduced into the compound system consists accordingly of primary power plus induced power. Dependent upon whether input voltage or input current is here considered as the independent variable, different expressions are found for these apparent powers. They are derived from Maxwell's equations and explained by reference to the examples of the magnetic coupling and the conducting diode.

621.372.56

A microwave attenuator which is not frequency sensitive and has a constant phase shift within very wide limits. R. STEINHART. *Nachrichtentechnische Zeitschrift*, 10, pp. 294-297, June 1957.

The disadvantages of attenuators with transversely moved vanes and T-network attenuators are discussed and a rotary attenuator is described which is not frequency sensitive and has a constant phase shift up to a certain limit. Figures for this limit are given and an error calculation is included.

621.372.831.4

Slots in an imperfectly conducting waveguide. R. CHATTERJEE. *Indian Journal of Physics*, 31, pp. 278-282, May 1957.

A theoretical analysis on the slot radiators in a waveguide has been carried out, taking into account the finite conductivity of the waveguide walls. It has been found that with a slight decrease in conductivity from the perfect conductivity condition, the equivalent shunt conductance of the slot increases by a small amount. But with further reduction in conductivity, it falls off rapidly, almost in direct proportion with the reduced conductivity.

463

621.373.4 : 621.373.8

Valves with delay lines. F. W. GUNDLACH. *Nachrichtentechnische Zeitschrift*, **10**, pp. 265-276, June 1957.

Electron beam valves with waveguides of a periodic structure are used for the amplification and generation of microwaves. A theory, which is very similar to the known cascaded network theory in communications and which is a comprehensive representation for the properties in forward and backward operation, can be derived for these valves when the periodic waveguide is subdivided into sections of a cascaded network.

621.376.5 : 539.07

A nuclear induction spin-echo apparatus. B. M. BANERJEE, S. K. GHOSH and A. K. SAHA. *Indian Journal of Physics*, **31**, pp. 211-226, April 1957.

A very flexible apparatus with Bloch's crossed-coil probe for the detection of spin-echo signals is described in detail. A fixed 1 Mc/s master oscillator allows the frequency of the final gated amplifier to be set at different values by proper selection of the harmonic in the harmonic generators. The pulse generators produce a sequence of pulses, the number, durations intervals and the repetition rates of which can be adjusted independently. Using Hahn's method, both the spin-lattice relaxation time T_1 and the spin-spin relaxation time T_2 have been measured for protons in glycerine as an illustration.

621.383.8 : 621.387.46

Improved performance of photomultipliers in scintillation counters. A. ASHMORE, B. COLLINGE AND S. K. SEN. *Indian Journal of Physics*, **31**, pp. 261-264, May 1957.

The use of a cathode follower to reduce the effective capacitance to earth of the collecting electrode of a photo-multiplier, enables bigger voltage pulses to be obtained for the same degree of non-linearity in the photomultiplier. The investigation has been made of the improvement obtained with a 6260 photomultiplier under typical operating conditions.

621.396.676

Design applications of electrostatic cages in airborne antenna research. A. WEISSFLOCH AND C. ANCONAH. *Onde Electrique*, **37**, pp. 599-604, June 1957.

The author goes over basic principles of electrostatic cages as applied to mock-up testing of sense antennas in radio-direction finder systems (effective height, curvature factor, axis of equivalent dipole). The method has been improved in various ways to facilitate testing and to improve measurement accuracy. It has been extended to testing of antennas operating on the r.f. range (2 to 20 Mc/s). At the lower end of that band, antenna-to-matching unit efficiency varies as the square of effective height multiplied by antenna capacitance. This principle is employed in the case of a suppressed antenna designed for Caravelle aircraft. Results obtained for that particular antenna are given in the paper.

621.396.932/933.22

Direct vision type direction finder for high frequency operation. K. MIYA. AND T. SASAKI. *Journal of the Institute of Electrical Communication Engineers of Japan*, **40**, pp. 429-436, April 1957.

This paper describes a sensitive direct-vision type direction finder for high frequency, with which multiple signals or scattering signals can also be measured. The principle of the finder is a so-called differential output method using an electrical time division system. The measurable minimum field intensity in the h.f. band is estimated at -27 to -40 db above $1\mu V/m$. The bearing of the incoming wave is indicated by a sharp unidirectional figure on a c.r.t. The working principles and circuit of the direction finder are explained in detail and the nature of error peculiar to the finder discussed theoretically.

621.396.812.5

Reflection of short and ultra-short waves by the aurora. G. LANGE-HESSE. *Archiv der Elektrischen Ubertragung*, **11**, pp. 253-261, June 1957.

This is a summarizing report on observations and findings obtained so far in the field of reflection of h.f. and v.h.f. radiation at northern lights. Systematic research into this phenomenon which was discovered for the first time in the years immediately preceding World War II was made above all in the past ten years. Observations of reflection were made both with emitted pulses and with continuous waves. The importance of the results for practical radio communications, radio navigation, and the general observation of northern lights is covered in detail. This report covers approximately the state of research in this field at the beginning of the International Geophysical Year (July 1, 1957 to December 31, 1958) and refers to further research planned during this period.

621.396.933

Single sideband communication in aeronautics. M. MARQUIS. *Onde Electrique*, **37**, pp. 586-588, June 1957.

The author reviews basic principles of s.s.b. operation and examines the advantages of the system for air-to-ground communication. An airborne s.s.b. transmitter-receiver equipment is described. For only 10 watts transmitter power, this equipment assures reliable r.t. contact over distances of several hundred kilometres. Other outstanding features are very light weight and small size. Details on operation and performances are given.

621.396.933.2

R.A.N.A. hectometric navigational aid—an assessment of R.A.N.A. system accuracy. J. AUBRY. *Onde Electrique*, **37**, pp. 571-585, June 1957.

R.A.N.A. hectometric radio navigation aid systems operate on a phase-comparison principle. Ground absorption and the interferential effect of ground irregularities affect the precision of the system. From an analysis of this interference, certain conclusions can be derived regarding R.A.N.A. network calibration. System accuracy can be assessed directly from continuous receiver readings.

681.142

Electric correlators. K. STEINBUCH AND H. ENDRES. *Nachrichtentechnische Zeitschrift*, **10**, pp. 277-287, June 1957.

Electric correlators are required for evaluating relations, which cannot be expressed algebraically but only by tables, in digital data evaluating systems. Typical examples of applications, general points of view and possibilities of realization are discussed and the paper is concluded by one example of a practical electric correlator.