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

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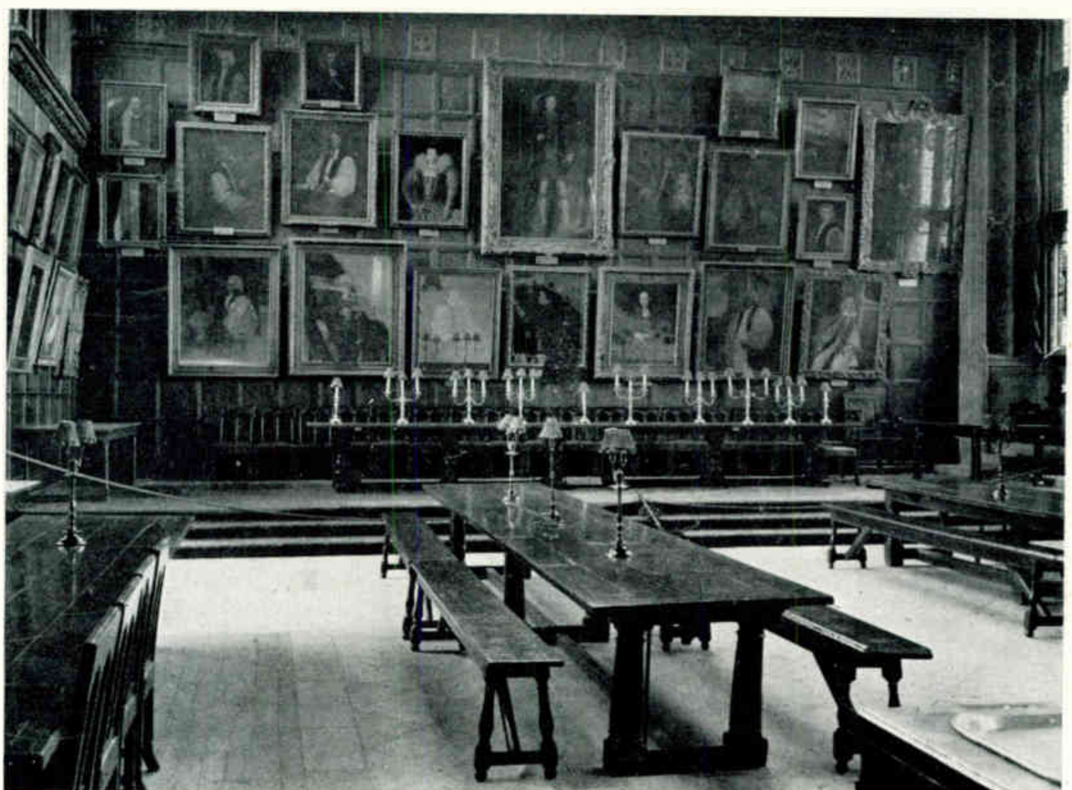
THE CONVENTION BANQUET

On Friday, July 9th, the Institution will hold a Banquet in the Hall of Christ Church, Oxford. The Hall offers much of interest to the visitor, and our photograph draws particular attention to the exhibition of portraits.

Next to the Queen's collection and the National Portrait Gallery, the Christ Church collection of portraits is probably the richest in Britain, and the best part of it can be seen in the Hall. Apart from the two founders—Cardinal Wolsey, who founded Cardinal College in 1525, and King Henry VIII, who converted it into Christ Church in 1536—and Queen Elizabeth, who associated Christ Church with Westminster School in 1561, the portraits all represent former members of the college.



Photograph by Walter Scott, Bradford

CHRIST CHURCH HALL

SESSION 1 — 1954 CONVENTION

Summaries of selected papers to be presented and discussed on Thursday, July 8th, commencing at 2.30 p.m.

518.5 : 621.389

The economic use of digital computers.—R. K. LIVESLEY.

The paper considers the factors which determine the economic use of an automatic digital computer for scientific and engineering problems. The two types of problem (*a*) involving a small amount of repetition work, (*b*) involving an indefinite amount of repetition work are dealt with, and the necessity for treating the problem by the correct technique is stressed. Recommendations are made for the use of standard programmes which are adaptable to a variety of problems.

518.5 : 621.389

Electronic computers and industrial mathematics.—B. D. DAGNALL and R. L. MICHAELSON.

The basic theory and mode of operation of a high-speed digital computer is described in functional terms, without reference to details of electronic circuitry. A complete "programme of instructions" to cause a typical computer to carry out a simple job is given and the programming of two representative engineering calculations is discussed briefly. The factors which an industrial organization must take into account before deciding to purchase a computer are considered.

518.5 : 621.389

Some comparisons between analogue and digital computers.—W. E. SCOTT and A. C. D. HALEY.

The paper discusses the reasons for using computers in industry and the considerations which should apply to the choice of machine for different types of work. Examples are given of both analogue and digital machines and the uses to which they can be put. The advantages and disadvantages of each type are mentioned, with the aim of encouraging a rational approach to the specification and design of computing devices.

518.5 : 629.13

Electronic computers in aircrew training apparatus.—A. E. CUTLER.

After discussing the economic advantages of training on simulated equipments, some of the problems solved by the computers in flying trainers, engine trainers and track recording will be described. The relative complications of a full flight simulator computer using digital and analogue methods are considered and the analogue type found to be most suitable. The use of the building brick principle is dealt with and details of utilization, running time and percentage serviceability given. Further applications of analogue methods to training equipments are discussed.

518.5 : 621.389 : 657.4

The application of electronic digital calculating methods to punched-card machines.—J. H. LUCAS.

Electronic calculating methods used to replace mechanical methods in punched-card machines are described with reference to a type of machine now coming into production, known as the Electronic Multiplying Punch (Emp). An outline of the calculating systems used in sterling and decimal machines is given. The general design principles and some features of the circuit design are described.

518.5 : 621.52

Statistical computers as applied to industrial control.—P. HUGGINS.

The need and use of statistical methods for quality control of a continuous industrial process is discussed and some examples of quality control based on statistical technique, but employing a "human" controller, are described. The advantages and disadvantages of automatizing such control from the engineering and economic points of view are considered. An outline of some of the circuit techniques employed is given. Two practical examples are quoted—one in the bakery industry and one in cable manufacture—of the application of automatic statistical control.

518.5 : 621.389 : 657.4

Applications of a high-speed electronic computer to business accounting problems.—A. ST. JOHNSTON and S. L. H. CLARKE.

The use of a high-speed electronic computer is described in two systems of equipment for carrying out invoicing, customers' accounts, stock control and wages computation for an organization having 30,000 customers and 2,000 employees. The first system gives the more complete solution to the problems, using equipment which is not yet fully developed. The paper goes on to describe how the problems can be solved by a system using equipment commercially available.

518.5 : 621.389 : 657.4

Application of electronic computers to clerical work.—T. R. THOMPSON.

The nature of clerical work and the fundamental requirements of the equipment for doing it automatically are considered. The types of clerical work and circumstances in which an electronic calculator can be used with advantage are described and details are given of experience gained from operating a particular equipment. Finally, problems which remain to be solved are discussed.

SESSION 2 — 1954 CONVENTION

Summaries of selected papers to be presented and discussed on Friday, July 9th, commencing at 9.30 a.m.

534.2 : 620.179

A method of ultrasonic gauging.—F. M. SAVAGE.

The paper describes a method of measuring wall thickness accurately, although only one surface is accessible. A variable frequency oscillator is employed and standing waves are set up between the transducer and the reflecting surface. At the resonant frequency and its harmonics the oscillator anode current increases and the measurement of the frequency interval between these peaks enables the thickness to be calculated.

534.23 : 620.179

Improvements in ultrasonic flaw detection.G. BRADFIELD.

The paper describes improvements in pulse systems of ultrasonic flaw detection in three fields: (1) A mode changer (to change longitudinal waves to shear waves) which is made of heavy material in the form of a laminated assembly and gives better efficiency and better discrimination than the usual device. (2) Damping, loading and circuitry for piezo-electric crystals to give improved discrimination and to reduce the adverse effects of rough surfaces. Additional monitoring means are described which assess and display the extent of the adverse effects of the rough surfaces. (3) Devices enabling beams of mechanical waves to be steered from chosen sites to search for flaws.

534.23 : 667.2 : 675

Some new applications of ultrasonics with special reference to its use in the tanning and dyeing industry. —F. GUTMANN.

The basic theory of vegetable tanning and chrome tanning and differences due to particle size involved are discussed and the effects of ultrasonic fields described. Practical problems both in the laboratory and in subsequent large-scale industrial application are dealt with. Parallels are drawn between tanning and dyeing, and ultrasonic washing mentioned. Details are given of the transducers and oscillators used.

621.389 : 534.614 : 533.27

The analysis of binary gas mixture by a sonic method. —E. W. PULSFORD.

The operation of the instrument described is based on the variation of velocity of sound in a mixture of two gases with the proportions of the mixture. The velocity of sound is determined at a fixed temperature by measuring the resonance frequency of a double Helmholtz resonator containing the mixture. The source of sound is a diaphragm driven electromagnetically from a variable frequency oscillator; a similar transducer followed by an amplifier and rectifier form the resonance detector. The method of continuous recording of the mixture proportions is also described, and a simple servo-mechanism is used to maintain the condition of resonance and to operate the recorder.

621.386.1 : 620.179

Some typical circuits for industrial X-ray apparatus. —J. J. BLISS.

The nature of X-rays and their use in non-destructive testing is briefly outlined. Suitable X-ray tubes and the associated h.t. generators are described and problems of exposure control and timing referred to. A typical 250-kV industrial X-ray generator is described in some detail, special attention being paid to the control equipment.

621.386.8 : 621.384.62 : 620.179

Industrial radiography and the linear accelerator.— C. W. MILLER.

The most important factors in obtaining maximum sensitivity of flaw detection in the radiographic examination of thick specimens are the energy of the radiation and the size of the source, while to obtain reasonably short exposure times a large X-ray output is required. It is shown that optimum results may be expected with equipment operating at an energy of the order of 4 MeV. The development of the travelling wave linear accelerator, which is briefly described, has made possible compact equipment and its suitability for industrial radiography is discussed.

621.386 : 621.771

An X-ray thickness gauge for the measurement of hot-rolled strip steel.—F. H. GOTTFELD and D. TIDBURY.

The increased demand for close control of rolling tolerances in hot or cold strip and sheet mills has led to the development of special X-ray thickness measuring equipment. It functions by measuring the absorption of X-rays in the material, and from the results thus obtained, highly accurate deductions can be made regarding the thickness of the strip. A description of the radiation source, differential detection equipment and reference wedges is given.

621.386.832 : 620.179

Industrial X-ray fluoroscopy with particular reference to ultra-fine focus X-ray equipment.—E. W. KOWOL.

The development of fluoroscopy as an inspection method and as an aid to radiography is discussed and the economics of both applications, their advantages and limitations, considered. A 150-kV mobile fluoroscopic X-ray unit and a 150-kV fine focus unit, which permits an enlargement of the image, are described. Typical users include light alloy foundries, electrical engineering and the food industry. Special problems of fluoroscopy are discussed, such as the protection and fatigue of the operator, and the subjective element which is introduced by the method.

SESSION 3 — 1954 CONVENTION

Summaries of papers selected for presentation and discussion on Friday, July 9th, commencing at 2.30 p.m.

621.387.42

The alpha gauge.—E. N. SHAW.

The apparatus described is for the measurement of weight per unit area of very thin materials, such as capacitor paper. An alpha source is used in conjunction with an ionization chamber backed off by a similar system. The algebraic sum of the currents is fed into a stable d.c. amplifier, and the out-of-balance reading calibrated in terms of weight. The sources of error are investigated, together with methods of compensation. Results obtained under factory conditions are also discussed.

621.387.424 + 621.317.7

A combined beta and dielectric gauge.—R. Y. PARRY.

The performance of beta gauges is normally extremely satisfactory for most applications, but suffers from not having a very fast response. On the other hand, dielectric gauges suffer from a number of drawbacks, but do have a high speed response. The paper describes composite equipment with the stability of a beta gauge and the fast response of a dielectric gauge which has been developed for use in weighing individual cigarettes and controlling the average weight at a rate of 40 per second. The beta gauge uses a balanced double ionization chamber system.

621.387.46

The practice and scope of gamma-radiography.—L. MULLINS.

The relative merits of gamma-rays and X-rays are discussed with special reference to the practice and scope of X-rays. It is shown that the methods are to a large extent complementary and that gamma-radiography has special features which have assisted to the rapid expansion of the radiographic inspection of castings and welds.

621.387.46 : 621.771

A gamma ray thickness gauge for hot steel strips and tubes.—G. SYKE.

A prototype gamma ray thickness gauge for hot milled rolling steel strip of 0·05 in to 0·30 in thickness is described, which uses a scintillation detector and provides distinct reading at short time intervals. Each reading represents the mean thickness of the strips during the preceding interval. The result is displayed on a lamp board and gives a visual picture of the longitudinal profile of each strip. Automatic standardization whilst no strip is passing through the measuring head is incorporated. Results obtained and performance of the instrument are presented and discussed. An adaptation of the above instrument for gauging the wall thickness of hot steel tubes is described.

621.385.5 : 621.318.562.5

Multi-electrode counting tubes.—K. KANDIAH.

Multi-electrode counting tubes have made it possible to count in decimal figures in a manner which is considerably simpler than those systems which use a multiplicity of single thermionic or cold cathode tubes. It is now possible to use these tubes in equipment for counting of nuclear particles and radiations and for various counting applications in industrial process control with the advantages of direct indication of the number stored, high counting speeds and simple zero resets. The flexibility of the counting tubes and their reliability has encouraged their use in even wider applications. It is the purpose of this paper to assess features of these tubes which make them suitable for some unusual applications.

621.387.46

The scintillation counter in industry.—J. S. EPPSTEIN.

The characteristics of scintillation counters for detection of high and low energy gamma rays are discussed. Stability problems are shown to be caused by changes in e.h.t. voltage and a circuit is given for minimizing the effects of these and so making the counter suitable for industrial use.

621.387.4

Instruments for radiation protection.—R. B. STEPHENS.

The paper discusses the general requirements with special reference to some equipments having wide application. The design principles of these instruments are discussed, emphasis being placed on such features as reliability, ease of handling and simplicity of control. The influence of these features on the circuit design is then considered. Mention is made of the various types of circuits employed and future design trends discussed.

621.387.4

Nucleonic instruments in industry.—D. TAYLOR.

The paper discusses the servicing of nucleonic instruments under factory conditions and considers some of the problems which have arisen in the British Atomic Energy Project. The annual failure rates of some of the standard instruments are given and attention is called to the component failures. It is noted that much progress has been made in improving the reliability and life of some of the newer components, e.g. Geiger-Muller counters, and that the failure rates are highest for the more orthodox components, e.g. thermionic valves and resistors. Experiences are quoted from British, American and Canadian sources. Reviewing the analyses presented, an attempt is made to lay down a number of guiding principles to follow when designing complete instruments.

SESSION 4—1954 CONVENTION

Summaries of papers selected for presentation and discussion on Saturday, July 10th, commencing at 9.30 a.m.

621.314.214.5 : 620.08

Differential transformers for mechanical measurements.—L. W. BLICK.

A description is given of a typical differential transformer, together with a brief outline of the principles underlying its operation and design. Circuits for use with the type of differential transformer described are given, and the influence of the source of energization is discussed. A means of shifting the electrical zero is shown, together with methods for achieving high mechanical sensitivity. A number of standard production transducers employing differential transformers are illustrated, and these transducers are compared with their mechanical counterparts. Some complete systems employing transducers are then briefly described, and a number of uses outlined.

621.383 : 62

Optical transducers and some industrial applications.—J. A. SARGROVE.

After a brief survey of the principles and characteristics of photocells and electron multipliers, the advantages of various optical arrangements for different applications are considered. Sharp focus light spot transducers for reflectometers and light scatter transducers for nephelometric determinations are described. Reference is made to transducers for particle detection in liquids, goniometric applications such as high-speed weighing, line following and edge alignment equipments.

621.383.5 : 614.84

Photo-electric smoke detection and test techniques using barrier-layer cells.—R. W. J. COCKRAM.

The methods advanced are developed from a common basis of arranging for calibration of a photo-cell either for each test or from a substandard illumination. Providing the cell characteristics are met in the control circuits, the methods provide a new approach to photometric problems as experienced in production to-day.

620.172/3 : 681.26

Load-cell force transducers.—D. L. JOHNSTON.

The electrical load cell is basically a form of extensometer applied to a tensile or compressive specimen. Any form of extensometer or micrometer indicating device could be employed, but the electrical resistance wire strain gauge is the most convenient for large loads. These load cells are compared with other forms of transducer in terms of energy level and conversion efficiency, so that the most suitable type may be chosen for a particular application. Measuring circuits are discussed including those using magnetic amplifiers and transistors, together with automatic self-balancing bridges of high accuracy.

537.228 : 620.179.22

Piezo-electric vibration pick-ups.—S. KELLY.

The paper deals with the development and use of displacement pick-ups and accelerometers using Rochelle Salt and barium titanate. By suitable design the units can be produced with constant sensitivity from 1 c/s to better than 20 kc/s, the law being either constant amplitude, constant velocity or constant acceleration. Typical examples are: (*a*) barium titanate accelerometer—sensitivity 20 mV/g from 5 c/s to 12 kc/s; (*b*) rochelle salt vibration pick-up—equal output voltage 1 c/s to 600 c/s for constant displacement. Details of matching networks to ancillary equipment will be given although specific amplifier design will not be dealt with.

620.172.222

Wire strain gauge transducers for the measurement of pressure, force, displacement, and acceleration.—J. L. THOMPSON.

The theory of operation and the construction of resistance wire strain gauges for the measurement of pressure, vibration, acceleration, force and torque are discussed. The special applications of unbonded gauges are considered. Practical details are given of strain gauge technique and special reference is made to methods of fixing gauges to the structures under examination.

Session 5 arrangements are given overleaf but additional papers for Sessions 4 and 5 may be included in the final programme.

Demonstration of equipment will take place in the Electrical Laboratories after each session.

SESSION 6

Final and summing-up Session will be held on Sunday, July 11th, at 5.30 p.m. Short papers will be contributed to the debate on "Electronics is the key to improving and increasing production."

SESSION 5 — 1954 CONVENTION

Summaries of papers selected for presentation and discussion on Saturday, July 10th, commencing at 2.30 p.m.

621.791.9 : 621.389

Electronic control of resistance welding.—C. R. Bates.

The electronic circuits commonly used for single-phase welding controls may be classified into two basic types, (1) leader-follower circuits, (2) feedback-trigger circuits. Details of these circuits are given after a brief description of the requirements for control of resistance welding processes. The various welding techniques and applications are explained, together with the electronic control of weld-heat for spot and seam welding. A discussion of various control circuits follows, including "slope control" for welding aluminium and its alloys. In this, the rate of change, or slope, of the weld-current is accurately governed and yet may be easily varied or adjusted. Circuits for automatic variation of weld-current to compensate for changes in supply voltages or welding conditions are described.

621.389 : 535.331

Electronics in automatic direct reading spectrometers.—F. Holmes.

This 30-channel instrument is a rapid routine production control unit in the making of non-ferrous alloys. The circuit employs several entirely new features not previously used in this type of equipment. A special feature is the use of a "dekatron" counter circuit and a printing recorder to register the counts corresponding to the intensity ratios of the selected spectral lines of the constituent elements being measured. The concentrations are then determined from working curves established experimentally for each measuring channel to give the concentration as a function of the count for the corresponding element.

621.375.5 : 674

Electronic heating and the woodworking industry.—M. T. Elvy.

The paper describes some of the commercial applications of electronic heating in respect of wood which have developed in the furniture and utilization of wood waste branches of the woodworking industry. Consideration is given to applications covering the seasoning of timber, the bonding of laminated structures, flat, curved and moulded plywood sections, tapeless veneer splicing, edge gluing of panel and core stock, spot gluing and assembly gluing. The principal methods of applying r.f. dielectric heating are recalled, with particular reference to the use of synthetic resin glues. Jig and electrode design are discussed. Aspects of the design of suitable electronic generators are outlined in conjunction with practical systems for coupling and matching the work.

545.82 : 621.389 : 661.721

The automatic indication and recording of minute concentrations of organic gases in air.—H. A. Thomas.

The presence of methanol in an industrial plant is detected by its catalytic conversion to CO_2 and estimation by infra-red gas analysis. The equipment continuously and sequentially samples the atmosphere from 10 points in the plant and gives automatic warning when the methanol concentrations at these points exceed 200 and 1,000 parts in 10^6. A continuous record is also provided.

621.384.622.1 : 615.4.678.742.2

Applications of high energy electrons to the sterilization of pharmaceuticals and the irradiation of plastics.—C. W. Miller.

The travelling-wave linear accelerator provides a source from which a beam of electrons having an energy of several MeV can easily be extracted at a reasonably high power level. Bacteria and viruses can be killed by such irradiation and experiments are described which have determined the dosage required. A wide range of contaminated substances can thus be sterilized without undesirable reaction in the material itself. The process is performed after the product has been sealed in its final container and eliminates the risk of contamination. The sterilization of food is also possible. Changes in molecular structure occur when certain polymeric substances are irradiated. In polyethylene this improves resistance to solvents and eliminates the melting point. Some possible processes are mentioned and experiments to determine the basic physics and chemistry are described. Difficulties encountered in dose measurement, particularly when dealing with insulating materials, are briefly indicated.

621.52

The replacement of the human operator by non-specialized programmed machines.—G. T. Baker.

Typical processes carried out by human personnel are assembly operations and the feeding of powered machines. Electronic technique provides a means whereby the parameters defining the motion can be specified in a manner that can be rapidly programmed to meet any particular operation. Some of the flexibility of the human hand can be provided by detachable elements which the machine selects automatically during a programme. The remainder of the problem can be reduced to two elements, a joint and a power source, i.e. a muscle. Typical designs are given and the solution is well within the scope of existing manufacturing technique. Convenient methods of programming include telephone-type apparatus, punched paper tape and the magnetic drum.

MICROWAVE MEASURING EQUIPMENT*

by

P. M. Ratcliffe†

Read before the Institution in London on May 5th, 1954. *Chairman: Mr. E. A. H. Bowsher (Member)*
Also read before the West Midlands Section in Wolverhampton on January 26th, 1954.

SUMMARY

Due to the large amount of work that has been undertaken in the fields of radar and communication engineering, particular emphasis has been laid upon the design and utilization of measuring instruments for the 10-cm and 3-cm bands that are suitable for field and factory as well as laboratory use. The concept of measurement in the band is considered, and the measurable quantities shown to be wavelength, power and normalized impedance. The following instruments are described: capacitance-loaded line and resonant cavity wavemeters; thermistor-type milliwattmeter; a neon-tube tester for measurement of standing-wave ratio; directional couplers for s.w.r. measurement; spectrum analyser; noise generator. A 3-cm waveband radar test set incorporating signal generator, power monitor, spectrum analyser and cavity wavemeter is described.

1. Introduction

The microwave band is generally considered to occupy that section of the radio frequency spectrum which extends from 1,000 Mc/s (30 cm) to 300,000 Mc/s (1 mm), being normally further subdivided into the centimetre (30 cm to 1 cm) and millimetre (10 mm to 1 mm) bands. This range of frequencies is characterized by the phenomena that the wavelengths involved are comparable in magnitude with the dimensions of the apparatus used; it is this fact which gives the distinctive separation from the lower frequency u.h.f. region and the higher frequency region of the infra-red spectrum where the technique becomes closely allied to that of optical practice.

The concept of measurement at microwave frequencies differs mainly in the quantity that it is possible to measure, the absolute measurement of impedance in terms of voltage and current being replaced by the measurement of normalized impedance in terms of electric and magnetic field. The emphasis in power measurement is on the heating effect instead of the product of voltage and current, while measurement of wavelength rather than frequency is considered to be preferable.

In designing measuring apparatus for any frequency spectrum the designer is concerned with the effect the apparatus will have upon the equipment under test and the ease with which it can be inserted to perform its necessary function. Increase in frequency increases the difficulty of this task, reaching a climax in the microwave band where it is often necessary to remove a section of waveguide and replace it by a similar section which is coupled to the measuring apparatus. Because of the laborious nature of this procedure the apparatus is sometimes built into the system so that reference may be made to it at will. With certain types of measuring apparatus it is, fortunately, still possible to use coaxial line inputs, even at wavelengths of 3 cm, and the coupling to the waveguide is usually via coaxial-to-waveguide transformers and directional couplers: the only proviso is that the coaxial section be kept to a minimum length to avoid large attenuation.

Due to the added impetus of the war the development of microwave equipment has forged ahead rapidly in the fields of communication and radar, and has also found other applications in the fields of dielectric measurement, spectroscopy and radio astronomy. Much has already been written about the general design of microwave measuring apparatus,[1,2,3] and no paper of reasonable length could give a comprehensive survey of the various methods available. Hence the scope of this paper has been confined to a description of the design of measuring instruments with which the author and his colleagues have been associated, and that are produced commercially to meet the requirements

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†Marconi Instruments, Ltd., St. Albans, Hertfordshire.

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in the fields of communication and radar. Owing to the large amount of work that is being undertaken in the S- and X-bands (10 cm and 3 cm respectively), the majority of commercially available instruments fall into one of these classifications, and emphasis is laid upon those instruments which are suitable for use in field and factory besides the laboratory. The three major quantities to be measured in microwave work are frequency, power and impedance, so the instruments considered in this paper will be classified into one of those groups with a further section on special instruments peculiar to radar working. Certain sections of the apparatus contain much normal electronic circuitry, and in such cases the description has been confined to an absolute minimum.

2. Frequency Measurement

For frequency measurements of the greatest accuracy, the conventional low-frequency standard employing a highly stable quartz crystal oscillator can be extended for operation into the microwave region, by multiplication and heterodyning. Such a system would have a primary standard vibrating at a fundamental frequency in the region of 1 to 10 Mc/s, and a multiple of that fundamental would be used to calibrate a high-frequency variable oscillator. A harmonic of this oscillator could, in turn, be heterodyned with the unknown frequency to determine its value. Due to the difference in frequency between the unknown and the primary standard, the apparatus will of necessity be complex in construction and operation, being only ideally suited for laboratory use. It is, therefore, essential to have simpler if less accurate methods available for normal measurement purposes. The measurement of wavelength or frequency by loosely coupling a parallel-tuned circuit, consisting of a coil and variable capacitor calibrated in frequency, to the unknown source of energy, is a well-known method of measurement at ordinary frequencies. Although such lumped circuit elements lose their utility at microwave frequencies, they have their counterpart in resonant cavities or lines.

2.1. *Resonant Lines*

The formation of high-impedance resonant sections by short-circuiting a length of line one-quarter wavelength long in order to produce a maximum standing-wave ratio is well known from transmission line theory. This immediately suggests a simple method of determining wavelength by the measurement of successive minima in a slotted line by means of a travelling probe; this will give the value of one-half the line wavelength from which the frequency may be

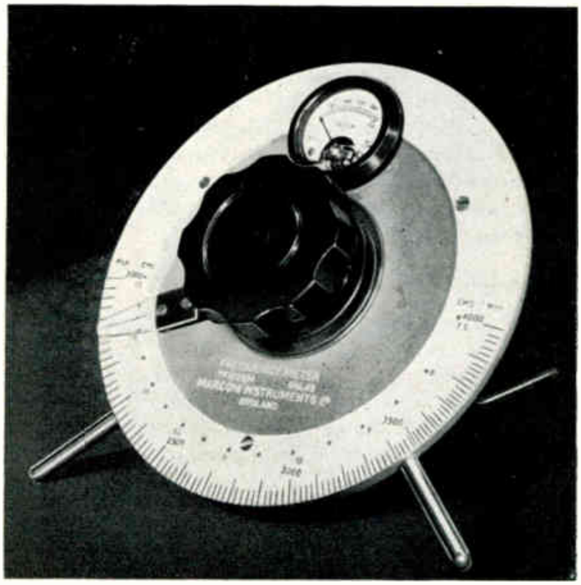


Fig. 1.—2000 to 4000-Mc/s frequency meter.

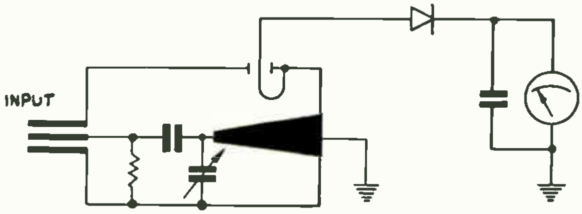


Fig. 2.—Frequency meter circuit diagram.

calculated from a knowledge of the velocity of propagation in the line. Although this method is frequently used, as slotted lines are normally readily available for the purpose of impedance measurement, there is an improved method which has been developed to form a useful wavemeter whereby the output coupling loop is fixed and the length of the inner conductor varied to form the quarter wavelength line.

2.1.1. Capacitance-loaded Lines

The disadvantages of the majority of coaxial line wavemeters are the difficulty of supporting the inner conductor when in a horizontal position, and their size and shape. The length of the line must always be such that it is possible to obtain at least two resonances, while the upper frequency limit occurs when the mean value of the circumferences of the inner and outer conductors is less than one wavelength. These two requirements determine the physical form the instrument will take and hence the final result is a long instrument of small cross-sectional area. In order to overcome the normal failings of such wavemeters, a series of four instruments covering the frequency range 250 to 4,000 Mc/s have been developed, the latter two falling within the microwave band, which can each be housed in a case of cubic form, thereby producing a compactness which, if possible, is always desirable in any design.

The resonant system of the wavemeter, shown in Fig. 1, comprises a concentric line short-circuited at one end, and its electrical length is altered by tuning at the open end by means of a variable capacitor. This capacitance is constructed by the projection of vanes from the inside wall of the outer conductor to form a stator assembly; a corresponding rotor is formed by the free end of a robust shaft mounted axially with respect to the line and at right angles to the front frequency scale. The rotor plates have been shaped to give a linear law over the frequency range which gives a coverage of 2 : 1 over a scale of approximately 180 deg. As can be seen from the functional circuit diagram in Fig. 2, the input is via a small capacitor in order to ensure a minimum of pulling over the frequency range, and to make the calibration independent of the form of input, whether it is a coaxial feeder or a short stub aerial. The detector follows normal practice and consists of a small, robust microammeter having a full-scale deflection of 250 μA mounted on the front panel, which is inductively coupled with a small loop to the line via a silicon crystal, thereby producing maximum direct current in the meter at resonance. This type of construction ensures that the line is fully enclosed thus providing excellent screening, and assists in keeping the Q-value high, there being no losses due to radiation. Provided the materials are suitably chosen so as to give good mechanical stability and a low temperature coefficient, the ultimate accuracy will depend upon the degree of discrimination that can be obtained with dial reading. On these instruments the effective length of the scale is 9 in (23 cm), and it is considered feasible to measure frequency to an accuracy of one part in a thousand. Unlike a normal coaxial wavemeter this instrument is not self-calibrating, due to the unknown value of the stray residual capacitance of the variable capacitor, and each instrument has to be calibrated individually against a crystal oscillator in the same manner as its low-frequency counterpart. Once this has been accomplished, however, it gives a direct reading in frequency without the necessity for arithmetical operations or reference to calibration charts.

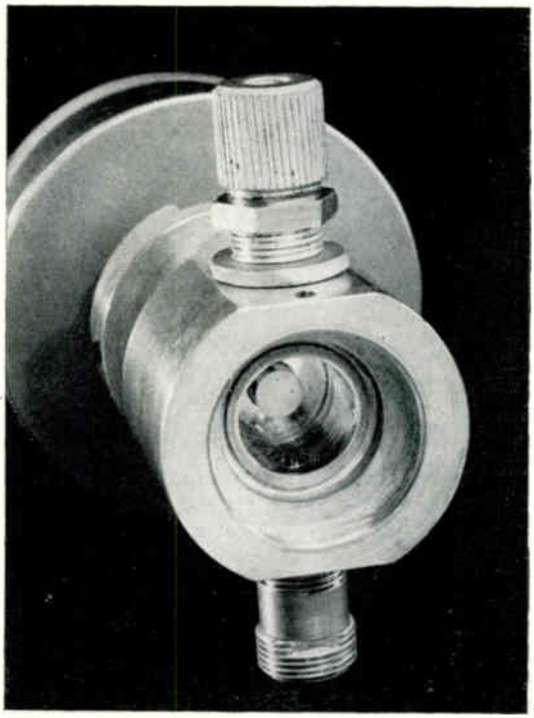


Fig. 3.—Experimental model of type E_{010}—EH resonant cavity.

2.2. *Resonant Cavities*

The practical upper frequency limit for the capacitance-loaded coaxial wavemeters described above was found to be in the order of 4,000 Mc/s;

therefore, to extend the same measurement technique further in frequency it is necessary to resort to the hollow resonant waveguide cavity, an example of which is shown in Fig. 3. Here the situation is further complicated by the choice of mode that will be used, as departure from the coaxial line is synonymous with departure from the transverse electromagnetic (TEM) mode with its unambiguous indication of frequency. There are several modes of resonance which can be employed in a cavity wavemeter, and the choice will depend mainly upon the function the instrument is to perform. The other variable factor to be considered is the type of input to the instrument, either coaxial or waveguide, which will depend upon its application.

2.2.1. Type E_{010} Wavemeter

For general-purpose use the widest frequency cover is desirable, consistent with freedom from unwanted modes of resonance liable to lead to ambiguity of reading. It has been shown[4] that the most suitable mode to meet these requirements is the E_{010} mode equipped with an axial plunger which, when fully extended into the cavity, becomes a TEM or EH mode, hence it has received the designation E_{010}–EH hybrid mode. The theoretical frequency cover is 3 : 1, and correct selection of dimensions will ensure that the wanted mode is dominant and obviate spurious responses due to higher modes.

The highest frequency is obtained when the plunger is fully withdrawn from the cavity, the wavemeter then operating in the E_{010} mode with the resonant frequency determined only by the diameter of the cavity, and equal to $2{\cdot}3 \times 10^4/D$ Mc/s where D is the diameter in centimetres. At the minimum frequency of resonance the plunger is fully inserted making a coaxial line, the length of the cavity then being the frequency-determining dimension. The ratio D/L should be made greater than one in order to ensure that the wanted mode is dominant (L is the length of the cavity). The plunger should be of the non-contact type with the smallest possible clearance in order to obtain a low impedance path without the necessity of a good sliding electrical contact. The power may be coupled into the cavity inductively, and extracted by the same means with the detector taking the form of a sensitive d.c. microammeter fed via a silicon crystal.

In order to obtain maximum sensitivity from the instrument it is essential that the Q-factor be kept high. In a cavity this may be expressed as

$$Q = 2\pi \frac{\text{Energy stored/cycle}}{\text{Energy dissipated/cycle}} .$$

The energy stored is proportional to volume and the energy lost is proportional to surface area $\times\ \delta$ where $\delta =$ depth of penetration of current. Hence for high Q-factor the ratio of volume to area surface must be kept as high as possible, and is improved by silver plating and highly polishing the interior of the cavity to obtain maximum reflection from the walls. Due to the wide frequency cover of 4,000 Mc/s–10,000 Mc/s obtained with this particular instrument it was visualized as being for general-purpose use, and as such would not be permanently coupled into a waveguide system; it was therefore designed to have a coaxial input for ease of connection to other apparatus. Here again the wavemeter was not self-calibrating, although the frequency could be calculated with a fair degree of accuracy from the physical dimensions, the only unknown quantity being the effect of the input and output coupling loops. Therefore it was calibrated against a crystal by heterodyne methods, and as the plunger was attached to a micrometer head a calibration chart of depth of penetration against frequency was obtained.

3. Power Measurement

At low frequencies power is normally measured indirectly by observing the amplitude of current flow in a known impedance, whereas in the microwave band the fundamental method of absorbing the whole or a known fraction of the power as heat in a load is, with few exceptions,[5] the only method possible. The apparatus required to absorb the heat will, in general, depend upon the level,[6, 7] but as it is possible to attenuate any high level down to a measurable quantity by means of a resistive pad or directional coupler, only a low-level method is described here. This particular wattmeter is designed for use in the X-band and will record c.w. powers between 0·1 mW and 2 mW using a bead-type thermistor as the power-absorbing element, and measuring the resistance change in a d.c. bridge circuit. For any accuracy to be achieved by this method it is essential that all the power propagated from the source is absorbed by the thermistor, and the design resolves itself into one of matching the thermistor to the waveguide.

3.1. *Thermistor Mount*

The bead thermistor is mounted in a length of standard 3-cm waveguide with its leads parallel to the electric field, hence the r.f. currents set up in the lead wires also flow through the element thereby transforming the power to heat energy.

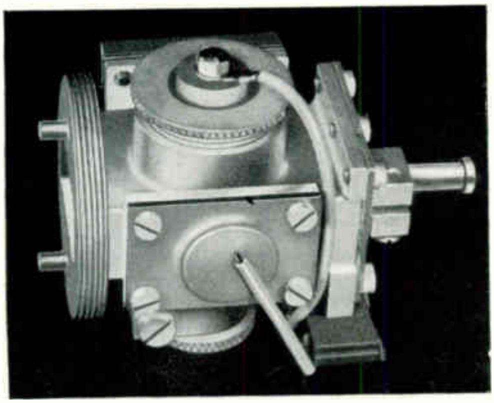


Fig. 4.—Thermistor mount.

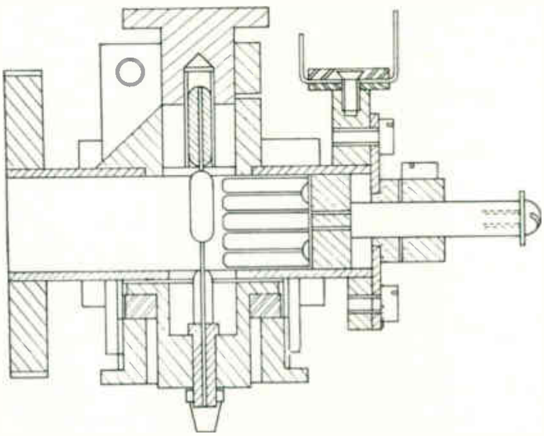


Fig. 5.—Cross-sectional diagram of thermistor mount shown above.

Figs. 4 and 5 illustrate the method of mounting; the leads are soldered into pins which protrude from the waveguide and one is insulated by a washer which forms an r.f. by-pass capacitor and enables a d.c. connection to be made to the thermistor. The other pin forms the inner conductor of a short-circuited coaxial line which is adjustable in a vertical plane to assist in the matching. A second matching device is provided by the adjustable non-contact-type plunger which tunes out the reactive element of the bead. The resistive component is adjusted for optimum value by varying the direct current flowing through the thermistor. It was found by experiment that the thermistor required to be between the values of 100 and 300 Ω to be matched to the waveguide, hence with no r.f. power applied it is set at 300 Ω with a given direct current, and the application of r.f. power allows the resistance to be driven down by 200 Ω before any serious mismatch occurs.

To determine the position of the two adjustments the mount is connected as a load on a standing-wave detector which is fed by an oscillator set at mid-band frequency. The two adjustments are set to give a minimum standing-wave at this frequency and a curve is then taken over the whole band in which the mount is required to operate. Fig. 6 shows the degree of match obtained over a 16 per cent. band, the maximum loss of power being only 3 per cent. at the band extremities. These two adjustments, once having been set up for a particular thermistor, will not have to be altered unless the thermistor is replaced.

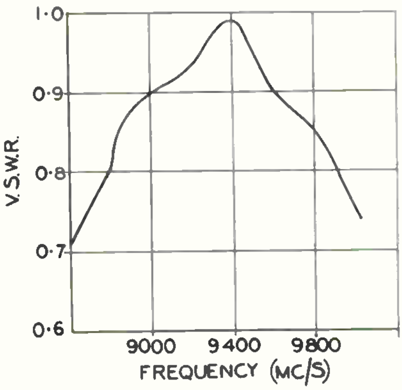


Fig. 6.—Degree of match obtained with thermistor to the waveguide.

The negative temperature characteristic of the thermistor causes the instrument as a whole to exhibit an interesting overload performance, in that it makes the burn-out power of the thermistor when used in this manner greater than its d.c. value. If the r.f. power is increased to such a value that it approaches the d.c. burn-out figure the ohmic resistance of the thermistor will naturally be driven to a very low value, which will cause it to become badly mismatched to the waveguide. Hence, instead of absorbing all the r.f. power, a large quantity, depending upon the degree of mismatch, will be reflected from the rear-short circuit thus causing less harm to the thermistor.

3.2. *Bridge Circuit*

The bead thermistor is connected in one arm of a Wheatstone bridge, and a galvanometer is employed to measure the out-of-balance current as the bead resistance varies with the r.f. power applied, so that the meter may be calibrated directly in milliwatts. Initially, the bridge supply voltage is adjusted so that the bridge is balanced when the current through the bead is such that its resistance is 300 Ω.

As the thermistor bead is sensitive to small changes in current it is essential to ensure that the voltage source for the bridge is held stable. Also, as the bead is sensitive to ambient temperature changes, the bridge circuit must be compensated for changes of sensitivity and drift with ambient temperature. These compensations are achieved by the use of further temperature-conscious elements in the form of plate-type thermistors.

Sensitivity compensation is achieved by connecting a plate thermistor in series with the meter, thereby making use of the fact that bridge sensitivity can be controlled by adjustment of the meter arm resistance. Drift compensation is made possible by connecting a further plate thermistor in parallel with the bridge. The success of design of this type of compensation depends upon the resistance/temperature characteristics of the two plate thermistors employed. Unfortunately these characteristics are never such as to allow perfect compensation over the entire temperature range. However, by placing the plate thermistor in a network of ordinary ohmic resistors, it is possible to compensate at several points in the temperature range, and arrange to have small errors at temperatures which lie between these points. The circuit of Fig. 7 will maintain the sensitivity constant to within 0·5 db over a 70°C ambient temperature range. The drift compensation is of the order of half full-scale deflection at a full-scale sensitivity of 2 mW. The maximum slope of the drift curve is approximately 3 per cent. of full-scale deflection per degree centigrade.

From the circuit it will be seen the bridge sensitivity is standardized by selecting the correct value of meter shunt for the bead used. Since the parallel combination of meter and shunt is small compared with the resistance of the series plate thermistor, this calibration technique has very little effect upon the accuracy of the sensitivity compensator. It has been found desirable to earth the drift-compensating thermistor directly to the waveguide mount, thus ensuring good thermal contact between the bead and the plate thermistor. In this mount, both the drift and sensitivity thermistors are fitted, as shown in Fig. 4. It will be observed that the sensitivity thermistor is isolated from the waveguide due to circuit arrangement.

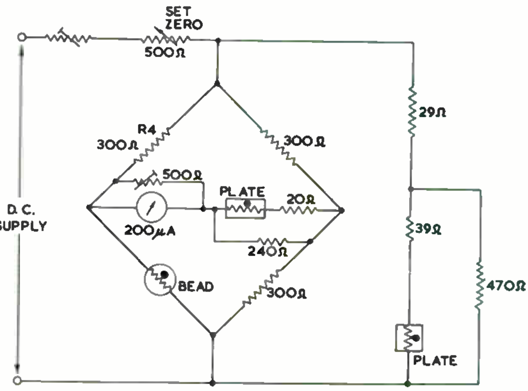


Fig. 7.—3-cm milliwattmeter circuit diagram.

The d.c. supply to the bridge can be obtained either from a 6-volt battery or a power supply which should be stabilized against mains fluctuations.

The bridge described above is direct reading over the range 0–2 mW, the first indication being at 0·1 mW, whilst it is possible to discriminate to 0·05 mW. When set up correctly, the accuracy of this type of bridge will be 2 per cent. at half full-scale deflection, the accuracy falling to 6 per cent. at extremes of the scale.

The method of measurement is virtually a comparison of the heating effect due to r.f. power and to d.c., hence the apparatus may be adjusted to read correctly by the measurement of direct voltages across known values of resistance in the following manner, assuming that the thermistor absorbs all the r.f. power available within the guide.

With no r.f. power applied, the bridge is balanced by means of the preset zero, thereby ensuring that the thermistor has a resistance equal to the other resistors in the bridge arms, and the voltage across R_4 measured with an infinite impedance voltmeter to obtain value V_1.

$$\text{Power in thermistor, } P_0 = \frac{V_1^2}{R_4}$$

R.f. power is applied to the bridge to produce a suitable deflection on the meter, say P_1 mW, and the balance restored by decreasing the direct current; the voltage across R_4 is measured again to obtain V_2.

$$\text{R.f. power in thermistor} = \frac{V_1^2 - V_2^2}{R_4}$$

The meter is restored to read P_1 again and the shunt adjusted to the true power as calculated from the two voltage measurements. The instrument is then ready for operation and will not normally require any further adjustment.

4. Impedance Measurement

4.1. *Normalized Impedance*

At microwave frequencies the transfer of power from a source to a load, where the distance and power level necessitates, is achieved by a hollow metal waveguide, as the normal coaxial line has high insertion loss and low power-handling capacity. If minimum loss is to be obtained within the transmission system some knowledge of the impedance of the component parts of that system must be known. It is indeed fortunate that a complete analogy between waveguide and normal transmission line theory is possible by considering the fundamental quantities of electric (E waves) and magnetic (H waves) fields to replace the derived concepts of voltage and current. It has been shown[8] that the value of the waveguide impedance is given by the ratio of E/H, and using the M.K.S. practical system of units with E measured in volts/meter and H in amperes/meter, Z will be given in ohms.

The absolute value of waveguide impedance, however, is of little practical value; what is required is the impedance of the load that is to be connected at the end of the waveguide in terms of the waveguide impedance. The ratio of these two impedances is known as the normalized impedance, which may be found from a knowledge of the distribution of the electric or magnetic fields in the guide between the source and the load, being unity when the load is matched.

4.2. *Necessity for Impedance Measurement*

In any microwave equipment, be it a communication system, radar or laboratory measuring apparatus, it is essential that each component part be matched to the characteristic impedance of its neighbour over the frequency band in which it is to operate. An example of such a system is a high-powered radar transmitter where the match between the aerial array and waveguide run has to be as perfect as possible for the following reasons:—

(1) The power-handling capacity of the waveguide run is limited by the peak working voltage of the insulation, and any standing waves produced will decrease the amount of power that it is capable of transmitting.

(2) The efficiency of power transfer to the aerial is greatest when it presents a perfect match to the guide.

(3) The input impedance to the waveguide run, and hence the power input and output is less sensitive to small changes of frequency or length of line, as the impedance tends to become purely resistive.

(3) There is less danger of frequency pulling of the magnetron or other oscillator of the transmitter when it is connected directly to the waveguide.

The instrument used for measurement must be so designed that it can be inserted without adding further discontinuities or subtracting appreciable power from the transmitter.

There are in existence two basic devices for the measurement of the impedance of lines or aerial arrays, namely the slotted guide and the directional coupler. The main difference between the two techniques is that, whereas the latter only gives the modulus of the impedance, the former also gives the phase angle, thereby specifying completely the normalized impedance of the load being measured. The choice of the two systems will in general depend upon whether a knowledge of the phase angle is required, and the following sections will discuss the methods and choice of apparatus for this task.

4.3. *The Slotted Guide*

The slotted guide, using a single travelling probe, is the most commonly used piece of apparatus for actual impedance measurement at a fixed frequency, as it gives by far the greater accuracy as well as the most information. It is usual to tune the probe to the frequency of measurement so as to produce maximum sensitivity in the detector and to present a high shunt impedance across the guide thereby, introducing very little discontinuity. The probe is moved up and down the line and the maximum and minimum voltage developed across the probe due to the electric field is noted, from which the voltage standing-wave ratio may be calculated.

The design of various slotted lines or guides has been described in numerous papers[9, 10] and it would be superfluous to repeat it here. There is, however, a useful piece of direct-reading apparatus for high power measurements which functions in a similar manner, without the disadvantage of a complicated moving probe but with a sacrifice in accuracy, which is known as an S-Band Neon Tester (see Fig. 8). It consists of a set of six evenly spaced glass tubes filled with neon at reduced pressure, each of which protrudes into a waveguide through one of six holes in the broad face of the guide. The set of tubes extends along the length of approximately half a guide-wave-length at 10 cm. Each tube is sheathed by a pair of semi-cylinders which are spaced to leave a longitudinal slot in front through which the tubes may be viewed. A perspex cover-plate carrying numbered horizontal lines is fixed in front of the set of neon tubes, and the whole device may be inserted into the waveguide run where the v.s.w.r. is to be measured. When power is propagated along the guide each neon will sample the electric field at one point and a discharge will occur, the amplitude of which will depend upon the strength of the electric field. For a perfectly matched load the amplitudes in all tubes will be equal, while for a mismatch the standing wave ratio can be found by taking the ratio of the minimum and maximum amplitudes. For the tester to give a true picture of the standing wave the neons must either be perfectly matched and inserted an equal amount into the guide, or any six neons can be used with means to alter the depth of penetration until a uniform discharge is obtained with a matched load at all powers.

Measurement of voltage standing wave by one of the above methods to obtain a knowledge of impedance is very suitable at a fixed frequency, but has certain disadvantages when used on a radar transmitter.[11] If a long waveguide run is connected between a source and aerial array which is badly mismatched the magnetron will tend to produce more than one frequency. The standing wave pattern produced at the probe or probes by these various frequencies will depend upon their phase relationships; in general, the minimum and maximum amplitude of each frequency will not coincide, and these two amplitudes when measured by the probe may be respectively increased and decreased.

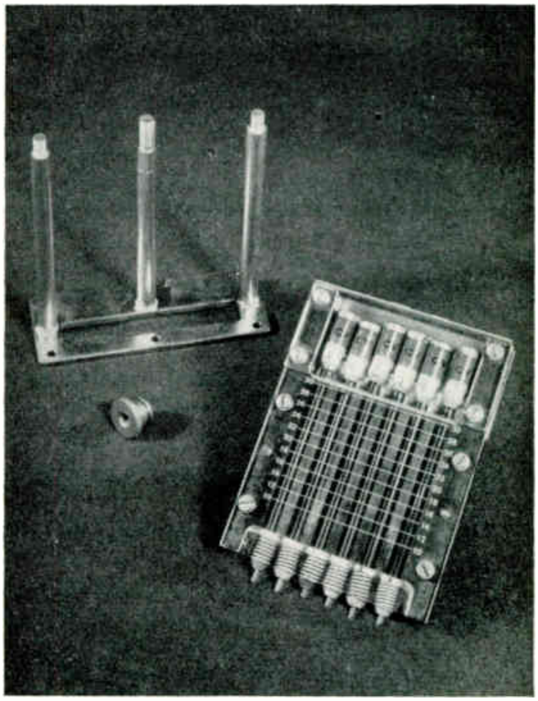


Fig. 8.—S-band neon tester withdrawn from case.

Thus the observed wave pattern will not necessarily indicate the true nature of the impedance, but rather an apparent match that changes as the frequency deviation alters.

4.4. *The Directional Coupler*

Due to its ability to separate the incident and reflected powers the directional coupler is unaffected by the phase relationship of the various frequencies present, and if these powers are measured or compared by a suitable device the v.s.w.r. may be found. It also has the further advantage that no complicated travelling probe is required thereby simplifying measurements, but with a sacrifice in accuracy. There have been numerous designs of directional couplers,[12, 13] but the general method of construction is to commence with two waveguides of the same dimensions as the run into which it will be inserted, thereby ensuring the impedance of the measuring apparatus is equal to that of the line. The broad faces of the two guides are bonded together and a number of slots cut in the common wall, positioned one quarter guide wavelength apart so that the propagation in the subsidiary waveguide will add in one direction and in the other cancel. The size and number of these slots will depend upon the required directivity, attenuation and frequency band over which it is to operate. For measurement purposes, the directional coupler is inserted into the waveguide run at the appropriate position such that all the power launched into the transmission line flows through the main waveguide (see Fig. 9). Due to the method of construction a small portion of the incident power will be coupled into arm 1 of the subsidiary waveguide, and likewise a small portion of the reflected power will be coupled into arm 2. The figure of merit for a directional coupler is its directivity, which is defined as the ratio of the power in arm 2 to the power in arm 1 due to the incident wave, or the inverse ratio due to the reflected wave. The other figure to specify completely the performance of the directional coupler, apart from its frequency range, is the attenuation between the main and subsidiary waveguide which is the ratio of the power in arm 1 to the incident power, or conversely the ratio of the power in arm 2 due to the reflected power.

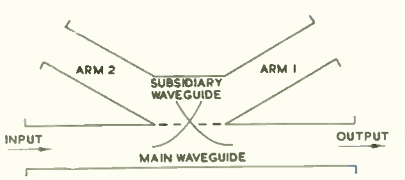


Fig. 9.—Directional coupler circuit.

With the normal type of directional coupler in which both of the subsidiary arms are on the same side of the waveguide the directivity and attenuation will be the same for both the incident and reflected waves, provided the construction is symmetrical. Therefore, a knowledge of the power in arm 1 and arm 2 will specify the voltage standing wave ratio produced by the load, provided the directivity is high. The voltage standing wave ratio is derived from the two power measurements by the following method:—

$$\text{By definition v.s.w.r.} = \frac{E_{min}}{E_{max}} = \frac{E_I - E_R}{E_I + E_R}$$

where E_I and E_R are incident and reflected voltages respectively

$$= \frac{2}{1 + \dfrac{E_R}{E_I}} - 1$$

As the two voltages are developed across a common impedance $\dfrac{E_R}{E_I} = \sqrt{\dfrac{P_R}{P_I}}$ where P_I and P_R are incident and reflected powers respectively.

$$\text{Therefore, v.s.w.r.} = \frac{2}{1 + \sqrt{\dfrac{P_R}{P_I}}} - 1$$

Hence, the absolute value of the two powers is not required, but merely their ratio, thus simplifying the requirements for the detectors in the subsidiary arms of the directional coupler.

4.4.1. Measurement of V.S.W.R.

The operation of measuring the voltage standing wave ratio can be simplified by comparing the values of the two powers instead of measuring them separately. This can be achieved by feeding the power from the subsidiary waveguide into two attenuators, being fixed for arm 1 and variable for arm 2. The maximum value of the variable attenuator can be equal to that of the fixed attenuator, and its value will be determined by the maximum v.s.w.r. that is to be measured. The variable attenuator can then be adjusted to give an equal power output to that of the fixed attenuator, the point of equality being found by a null detector connected between the outputs of the two attenuators. Reference to Fig. 10 will give the v.s.w.r. in terms of the difference in attenuation, or the variable attenuator can be calibrated in v.s.w.r. directly. For example, if the main waveguide is terminated in a short-circuit, then the incident and reflected powers will be equal, giving $P_R/P_I = 1$, thus giving a v.s.w.r. of zero in the above formula.

4.4.2. Accuracy of Measurement

The design of an instrument, as described above, will depend for its accuracy on the directivity of the directional coupler, and the reflection coefficient of the two attenuators.

Consider first the directional coupler:

If the directivity is infinity, the voltage appearing in arm 2 $= E_2 = E_R = E_I \frac{(1-R)}{(1+R)}$

where R is the voltage standing wave ratio of the load.

But if the directivity is D where $D>1$, then there will be an additional voltage of E_I/D appearing in arm 2. These two voltages will add or subtract according to their phase relationship, giving a maximum or minimum voltage of

$$E_2 = E_I \frac{(1-R)}{(1+R)} \pm \frac{E_I}{D}$$

Therefore, the error in the voltage amplitude

$$= \frac{\text{Unwanted voltage}}{\text{Wanted voltage}}$$

$$= \frac{(1+R)}{(1-R)} \frac{1}{D}$$

The actual voltage standing wave ratio measured

$$= \frac{1-\left(\frac{1-R}{1+R} \pm \frac{1}{D}\right)}{1+\left(\frac{1-R}{1+R} \pm \frac{1}{D}\right)}.$$

This gives the lower limit of reading for a given standing wave ratio as

$$\frac{2R - \frac{1}{D}(1+R)}{2 + \frac{1}{D}(1+R)}$$

and the upper as

$$\frac{2R + \frac{1}{D}(1+R)}{2 - \frac{1}{D}(1+R)}$$

Inspection of the above results shows that the error in measurement increases directly as the increase in true standing wave ratio, and is independent of the incident voltage amplitude. Hence, the directivity sets the upper limit of measurement that can be made for a given accuracy. Also it should be noted that whilst the ratio of unwanted to wanted voltage in arm 2 may be very large, the error in standing wave may still remain within reasonable limits. For example, a reasonable value of directivity that can be maintained over a broad band is 30 db, and although the error in the voltage amplitude for a load of 0·9 voltage standing wave ratio is $\pm$ 60 per cent. the limits of the reading that would be recorded in the standing wave measurement are only 0·845 to 0·960.

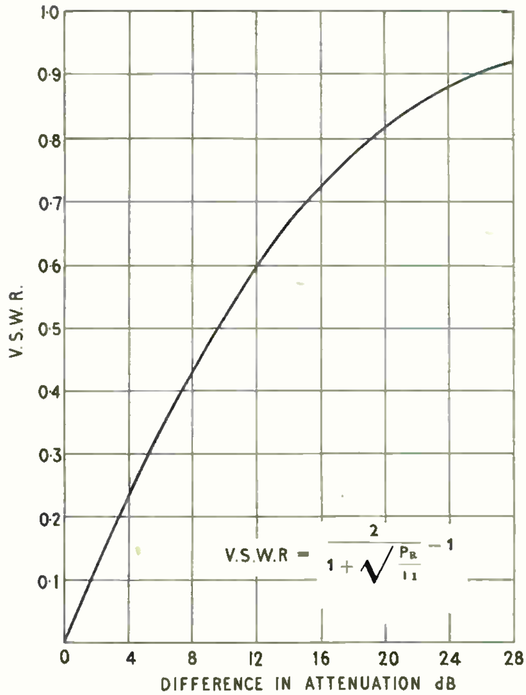


Fig. 10.—Variation of v.s.w.r. as a function of the ratio of reflected to incident power P_R/P_I.

There will, of course, also be an unwanted voltage produced in arm 1 from the reflected wave due to the imperfect directivity, but as the amplitude of the reflected wave is always less than that of the incident wave, it will only produce a second-order error which will be negligible when measuring loads with low reflection coefficients.

The incident and reflected waves which pass into arms 1 and 2 respectively should be totally absorbed by the attenuators in these arms, and any reflections will pass directly into the opposite arms, thereby producing further unwanted signals. When measuring loads with voltage standing wave ratios approaching unity the reflected signal is small, hence it is the reflection from arm 1 that is of primary importance.

If the directivity is infinity, and the reflection coefficient of the impedance in arm 1 of the coupler zero, then again the voltage in arm 2

$$= E_2 = E_1 \frac{(1-R)}{(1+R)}$$

If, however, the impedance in arm 1 has a standing wave ratio of A there will be an additional voltage reflected into arm 2 of amplitude

$$E_1 \frac{(1-A)}{(1+A)}$$

Therefore, the total voltage in arm 2 will have a maximum or minimum value of

$$E_l \frac{(1-R}{(1+K} \pm \frac{1-A)}{1+A)}$$

Thus the measure v.s.w.r. =

$$\frac{1-\left(\frac{1-R}{1+R} \pm \frac{1-A}{1+A}\right)}{1+\left(\frac{1-R}{1+R} \pm \frac{1-A}{1+A}\right)} = \frac{2R \mp \rho(1+R)}{2 \pm \rho(1+R)}$$

where ρ is the reflection coefficient of arm 2 impedance, and the

$$\frac{\text{Unwanted signal}}{\text{Wanted signal}} = \frac{(1-A)}{(1+A)}\frac{(1+R)}{(1-R)} = \rho\frac{(1+R)}{(1-R)}$$

Here again, the error of measurement increases with increase in the standing wave ratio of the load, and also of course with arm 1 impedance.

When measuring low standing wave ratios the reflected wave will be comparable with the incident wave, and the reflection from arm 2 attenuator will also begin to introduce errors. Owing to the difficulty of building attenuators with a sufficiently low reflection coefficient, it is unwise to utilize the two arms of a directional coupler for measurement purposes.

There are two methods by which this difficulty can be overcome, at the expense of the simplicity of the instrument. The more usual method is to use two directional couplers with their main waveguides connected in series, and utilize one coupler to measure the incident wave and one to measure the reflected wave. This will leave two arms, one per coupler, unused and these can be terminated in a matched load with a low reflection coefficient; a figure such as 0·0025 might be considered reasonable, as then the accuracy of the instrument would depend upon the directivity only. Great care must be taken to ensure that the two couplers are identical, particularly in the amount of attenuation between the main and subsidiary waveguides, otherwise additional errors will be introduced. The other solution is to use a double directional coupler, having four arms, two on each side of the waveguide. One side can then be used for measuring the incident power and the other side for measuring the reflected power. This system has the advantage of giving twice the attenuation of the coupler between the arms being utilized for measuring purposes thereby, giving adequate decoupling. Here again, matched loads of the same degree of perfection would be required to terminate the unused arms.

4.4.3. Measurement of Attenuation

It is also worth noting that a system such as the one described above is capable of differentiating between loss of power due to the load mismatch, and that due to the actual attenuation of, for example, a waveguide run. If a short-circuit is placed at one end of the waveguide run under test, the incident power will be equal to the reflected power, provided there is no attenuation. Any loss in the guide will attenuate the power on its forward and return path, hence by adjusting the power outputs of the two arms to be equal, the attenuator of the instrument will indicate twice the attenuation of the waveguide run. If the short-circuit is made movable in a length of waveguide a perfect instrument will indicate the same value of attenuation when the short-circuit is moved through a half guide wavelength, but any imperfections will be indicated by a change of attenuation from a maximum to a minimum as the short-circuit is moved.

5. Special Instruments

5.1. *Spectrum Analyser*

The use of pulse modulation in the application of microwaves to radar demands methods for analysing the spectrum of such pulses to determine the frequency distribution of the sidebands. Pulse modulation on oscillators will produce a bandwidth of frequency which under favourable conditions will depend only

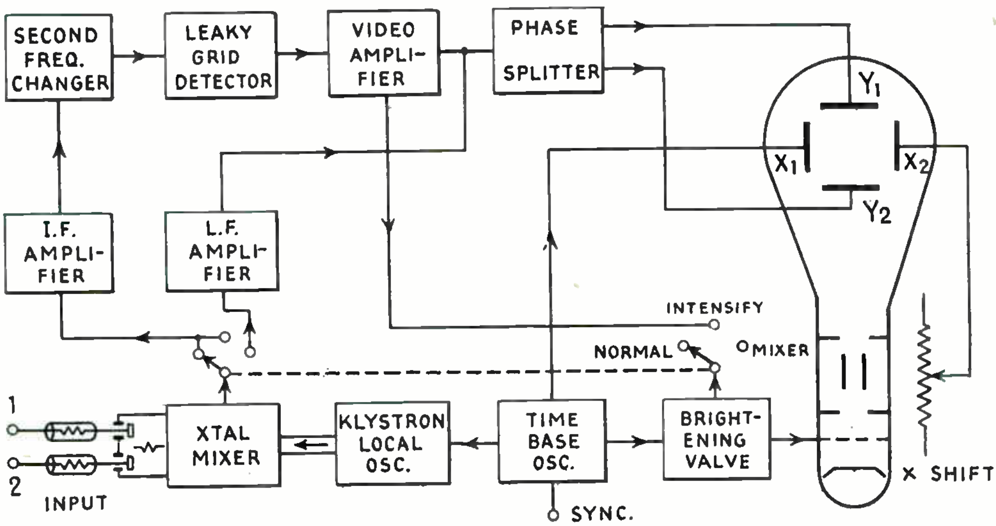


Fig. 11.—S-band spectrum analyser—block diagram.

upon the shape and width of the modulating pulse. This bandwidth will be further increased if frequency modulation occurs during the pulsed condition which is highly probable when the generator is feeding a line or aerial array containing a reactive component. Hence it is essential to have some means of displaying the frequency distribution of the sidebands when the oscillator is operating.

Instruments for performing this task are known as spectrometers or spectrum analysers, and are basically narrow-band superheterodyne receivers.

5.1.1. S-Band Analyser

A block diagram of a typical S-Band analyser is shown in Fig. 11; the pulse modulated r.f. signal to be analysed is fed via a length of attenuating coaxial cable into the instrument where it is coupled into a waveguide by means of a coaxial-to-waveguide transformer. The output from the local klystron oscillator is also coupled into the same waveguide, the two signals being applied to a crystal mixer mounted across the waveguide. The klystron is swept through the frequency spectrum of the input signal by means of a sawtooth voltage applied to the reflector, the same voltage being used to produce a horizontal sweep on the screen of an oscilloscope. The resulting heterodyne output from the crystal mixer, which is frequency modulated at the same rate as the local oscillator, is applied to a narrow band i.f. amplifier, and after detection and amplification is applied to the Y-plates of the oscilloscope. Provided the detector has a square law response the vertical deflection will be proportional to the power input of the signal, and since the deflecting voltage applied to the X-plates is also used to frequency-modulate the klystron, the horizontal deflection will be proportional to frequency. The determination of spectrum width and the centre frequency of the signal under test is facilitated by the provision of a calibrated local oscillator tuning control. By operating this control the trace is moved across the screen in a horizontal plane, and the width of the frequency spectrum can be found by noting the change in the local oscillator frequency required to move the display through its own width.

The analyser is also equipped with a brightening valve to intensify the trace for the duration of each single transient, when the oscilloscope beam is moving at high speed. Facilities are also available for checking the correct operation of the klystron oscillator and, in particular, to ensure that it is oscillating in one mode only. By applying the klystron directly to the crystal mixer and detecting and amplifying the output it may be displayed on the screen of the oscilloscope. Provided it is operating correctly in one mode the trace displayed will be a continuous line of variable amplitude depending upon the magnitude of the klystron output.

5.1.2. Design Features of Spectrum Analysers

Analysers for any frequency band function in the same manner as that described for S-band working, but differ in detail due to the different frequency range, pulse length and repetition rate of the signal to be examined as it is found in practice that for a given band there are preferred values of pulse length and repetition rates used in operational equipment. In general, as the carrier frequency is increased, the pulse duration is shorter but of greater repetition rate. The local oscillator frequency range must be such as to cover the range of the signal to be analysed, and the frequency modulation applied to the klystron should cover the particular region of the spectrum. As an empirical rule, it is considered that a frequency band at least three times the reciprocal of the pulse length should be displayed on either sides of the carrier frequency to ensure a true picture of the sideband distribution.

Owing to the wide bandwidth of a pulse modulated signal it would not be practical to view one particular transmitter pulse, hence the local oscillator is swept at a frequency which is considerably less than the lowest repetition rate. At each pulse the analyser samples the amplitude at one particular frequency within the bandwidth thereby building up a complete plot of the spectrum over a number of pulses and giving a display of a number of vertical transients, with the envelope giving the amplitude of power distribution. The separation and number of transients displayed will be determined by the sweep length (b in cm), the pulse repetition rate (f_r in pulses/sec) and the sweep frequency of the receiver (f_s in cycles/sec) giving:

$$\text{Number of transients displayed} = \frac{f_r}{f_s}$$

$$\text{Separation of pulses in cm} = \frac{bf_r}{f_s}$$

The number of transients considered necessary for an adequate display is thought to be a minimum of 50. As an example the S-band analyser described above has a minimum time-base frequency of 4 c/s making it suitable to display pulses down to a repetition rate of 200/sec, whilst the instrument designed for X-band working sweeps at 8 c/s, thereby increasing the minimum repetition rate to 400/sec. The choice of intermediate frequency and bandwidth is dictated by the shortest and longest pulse lengths respectively in order to achieve adequate separation of the image spectra and resolution. If the pulse length is τ seconds then the i.f. bandwidth should be at least one-tenth of $1/\tau$ c/s, whilst the i.f. should have a minimum value of $4/\tau$ c/s. Thus the S-band analyser with an i.f. of 22·5 Mc/s and a bandwidth of 100 kc/s can handle pulses from 0·2 μsec to 1 μsec wide: however, it is possible to view pulses outside these limits with a decrease in accuracy of the display.

5.2. *Noise Generators*

The modern technique of determining the sensitivity of receivers by noise factor measurements is now well known, and has been extended to the microwave band of frequencies by utilizing the wide band spectrum of noise that is generated by mercury vapour discharge lamps. At first attempts were made to construct microwave noise sources with the diode type of noise generator, which was so successful at lower frequencies, or with a klystron. Unfortunately neither of these methods leads to the simplicity and reliability which was desirable, and it was shown by Mumford[14] that it was possible to construct a noise source using an ordinary vapour discharge lamp mounted in a length of waveguide. The experiments he actually carried out were done in the 6-cm band, but further work showed that this type of tube was also applicable to S- and X-band generators.

The tube when operating in a waveguide acts as a passive resistance working at an effective temperature of 11,400°A, thus giving an absolute noise power output at approximately 15 db above that due to the same passive resistance at 290°A; this figure of temperature is taken as the zero reference level for noise factor measurements. Such lamps have now been specially constructed in a size suitable for this purpose, being about 9 in. long and ⅝ in. in diameter. They are filled with a mixture of mercury and argon at a pressure of 30 mm, and their power consumption for reliable operation is in the order of 10 W d.c. A filament is fitted at each end, one being heated from an a.c. supply to assist in starting the discharge, which is slightly in excess of 6 in. in length.

The noise power available is almost independent of the d.c. power being dissipated in the lamp and its temperature coefficient is negligible.

The discharge tube when operating has, in common with all generators, an output impedance, which in this case is both reactive and resistive, and has to be matched to the waveguide into which the noise power is to be launched. The necessity for matching is not only to ensure that the maximum power is available from the source, but also to ensure that the receiver under test is fed from the correct source impedance. This latter reason sometimes places more stringent matching requirements in the design than does the former, and generally speaking any loss in power due to this mismatch will detract from the accuracy of the instrument.

5.2.1. The Noise Source Head

The problem of mounting the tube into a standard rectangular waveguide so as to form a good impedance match offered two basic solutions: one is to mount the tube across the broad faces and the other to mount it across the narrow faces of the waveguide. The former is termed an E-plane and the latter an H-plane mount and numerous variations are obtainable for each depending upon the angle of insertion with respect to the waveguide. If the tube is introduced gradually at an oblique angle to the waveguide faces, the discontinuity is less as has so often been proved in the case of tapered waveguide dummy loads. The only proviso is that the length of the load should be several guide wavelengths long.

This method lent itself readily to the construction of the X-band mount the tube being inserted in the E-plane of the waveguide at an angle of 10 deg to the direction of propagation of the signal. This was considered the smallest angle that could be used consistent with sound mechanical construction. The longitudinal length of waveguide occupied by the discharge tube in this mount gave a taper of approximately two and a half guide wavelengths long at the lowest frequency; measurements of v.s.w.r. never fell below 0·85 over the frequency range 8,500 Mc/s–9,700 Mc/s. It was interesting to find that the position of the short-circuiting plunger at the rear of the discharge tube made no difference to the degree of match obtained owing to the large amount of attenuation through the tube. This plunger could therefore not be used to obtain a very good value of v.s.w.r. at any particular frequency of use and therefore an adjustable reactive tuning screw was fitted between the tube and the output flange of the waveguide. By adjustment of the longitudinal position and penetration depth of the screw it was possible to obtain a v.s.w.r. better than 0·95 with a bandwidth sufficient for normal noise measurement purposes. This made a compact instrument which could be used for normal types of measurement without any adjustments being made, but which could also be used for very accurate laboratory purposes with a small amount of additional work before taking measurements.

Design of the S-band noise head seemed to call for a different method of attack as the length of the discharge with this particular

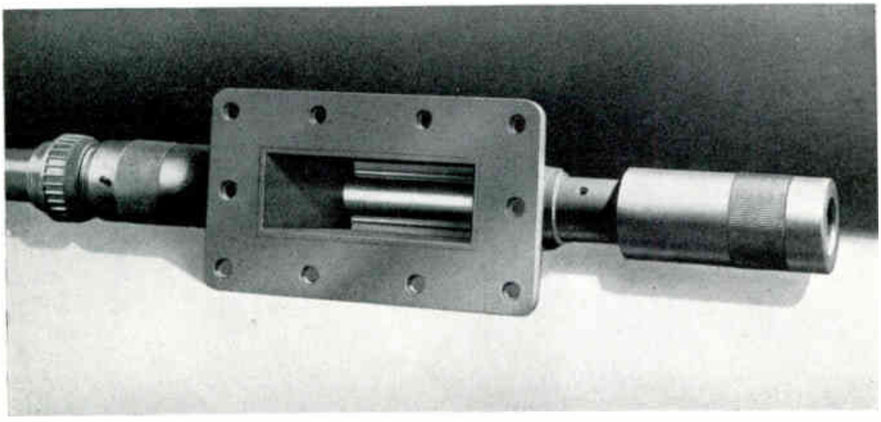


Fig. 12.—Operating S-band noise head.

tube was not several wavelengths long. As a first attempt an H-plane mount was constructed with the tube at right angles to the narrow wall of the waveguide, as shown in Fig. 12. By filling the air gap between the tube and the broad guide walls with two irises a good match was obtained; the particular frequency band depended upon the very critical positioning of the short-circuiting plunger behind the tube. Over the frequency range of 2,850 Mc/s to 3,160 Mc/s a figure of v.s.w.r. not worse than 0·8 was obtained. Experiments were made with an S-band E-plane mount, and it appeared that a superior result with less critical dimensioning of the plunger position would be possible, especially if a longer discharge tube were used. The problem was not pursued, however, as the performance of the H-plane mount was considered ample for all but the most accurate measurements. In both the X- and S-band noise generators the ends of the discharge tube which extend beyond the waveguide walls are contained in cylindrical metal shields, which behave electrically as waveguides beyond cut-off frequency. Thus noise energy is prevented from reaching the filaments, it being confined to that part of the discharge which is actually within the waveguide.

5.2.2. Power Requirements

The design of the power unit was dictated by the striking voltage and power consumption of the tube when in operation, being the same for both X- and S-band working. The minimum current rating for reliable operation was stated by the tube manufacturers to be 160 mA, and it was found when using an S-band H-plane

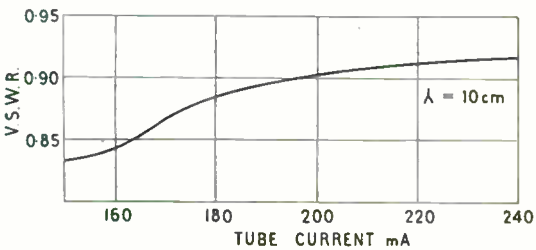


Fig. 13.—Degree of match obtained with variation in tube current.

mount that the impedance match to the waveguide improved with increase in current (see Fig. 13). As this factor was not extremely critical a value of 180 mA d.c. was selected as being sufficient without being wasteful. The d.c. power necessary was obtained from an ordinary full-wave rectifier circuit which was fed to the discharge tube via a series resistance and a low inductance choke. For starting purposes the end of the series resistance was joined to earth with the discharge tube disconnected, and in breaking this circuit a high voltage surge was produced by the choke which was sufficient to commence operation of the discharge.

5.2.3. Practical Measurement of Noise Factor

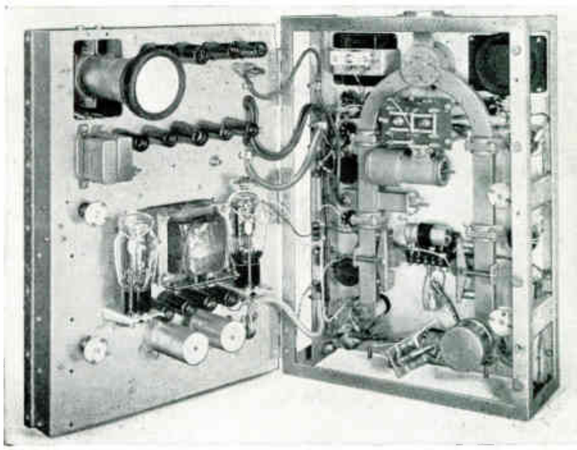
As has been stated the noise generator will deliver an absolute noise power output approximately 15 db above zero level. For measurement purposes this source can be made variable by the insertion of a calibrated variable attenuator between the discharge tube and the receiver under test provided the attenuator has a reasonable value of reflection coefficient. When measuring noise factor the noise generator is connected to the receiver via a variable attenuator which should be set at a maximum attenuation to suppress completely the noise output from the generator. The gain of the receiver can then be adjusted to record a suitable output on a power meter which for simplicity, should have a linear power law. The attenuator of the noise generator should then be decreased until the power output from the receiver is doubled. If the amount of attenuation now present between the receiver and the generator is subtracted from the maximum available power output the noise factor will be given directly. It should be noted that the generator must never be switched off with no attenuation between the receiver and the generator, as the receiver would then have its input terminated in a reactive impedance whose value would depend only upon the length of short-circuited waveguide connected to the input.

5.3. *A 3-cm Radar Test Set*

This test set is considered to embody all the apparatus required for aligning complete radar equipments for optimum performance, and for the location of faults. A detailed description of its capabilities have appeared elsewhere,[15, 16] so only brief details of its operation will be given here. Basically it consists of a signal generator covering the frequency range of 9,000 to 9,680 Mc/sec with a maximum c.w. output of greater than 4 mW, a power monitor capable of measuring mean powers up to 50 W, a spectrum analyser with oscilloscope display, and a cavity wavemeter.

5.3.1. Design Details

The mechanical design feature of main interest is the method by which normal electronic circuitry and waveguides have been combined to form a compact unit with a large section of the waveguide mounted within the main framework of the instrument. Fig. 14 shows a view of the front panel with the controls brought out from the interior waveguide, and also the external section of waveguide which in operation would be mounted in the main waveguide run to sample the signal to or from the aerial. Fig. 15 gives an interior view illustrating the method of mounting the waveguide with the normal type of components. This waveguide assembly, shown in Fig. 16, has three arms which meet at a 120-deg Y-junction guide switch which allows full coupling to be established between any two arms with attenuated coupling to the third arm. The latter coupling is via a small hole in the rotating partition giving an attenuation of 30 db. The right-hand arm contains the klystron and attenuator, whilst the other arm contains a thermistor mount, a crystal mixer, a cavity wavemeter and a further attenuator.



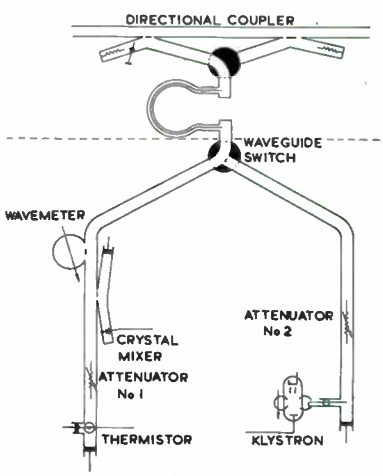


Fig. 14 (above).—Radar test set.

Fig. 15 (top right).—Radar test set—interior.

Fig. 16 (bottom right).—Waveguide assembly.

5.3.2. Signal Generator

A reflex klystron is used as the signal source, the frequency being continually variable by a mechanical drive on the front panel. The control is uncalibrated, as the frequency is determined by the wavemeter mounted in the opposite arm. The output is fed via a calibrated attenuator which consists of a vane of suitable dielectric material coated with a thin film of carbon. This vane is mounted along the length of the guide parallel to the electric field and the attenuation is varied by inserting the vane further into the guide, the maximum attenuation being obtained in the centre where the intensity of the field is greatest. The metal push rods connecting the vane to the mechanical drive protrude from the guide via iron dust cores which effectively reduce any leakage which might otherwise occur. In order to set up the frequency and level of the generator it may be switched directly into the opposite arm where the power can be measured with the thermistor mount as described in section 3, and the frequency found by the cavity wavemeter. It is also possible to modulate the klystron to produce a frequency-sweep signal for spectrum analyser use, or to produce a pulse modulated signal.

5.3.3. Power Monitor

Complementary to its function as a generator the test set may be utilized to determine the standing wave ratio of a waveguide run in a similar manner to that described in section 4.4. The external length of waveguide which is mounted in the main waveguide run consists basically of two directional couplers with a two-position switch such that either the forward or backward power can be diverted into the instrument. The detector for these powers is the thermistor which by means of the variable attenuator may be set to give equal readings for both powers; the v.s.w.r. is given by the difference in attenuation.

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LONDON SECTION DISCUSSION

L. C. Walters (*Associate Member*): In the section dealing with resonant cavity wavemeters it was stated that the E_{010} mode was commonly used, and that the resonant frequency for a cylindrical cavity depended only upon the diameter of the cavity; which of course it does. The speaker then went on to say something which may have been misunderstood, namely that the frequency of resonance is altered by using a close-fitting non-contact type plunger. In actual practice the only way in which an axial plunger can alter the frequency, in this mode of oscillation, demands that it has a relatively small diameter compared with the inside diameter of the cavity.

Secondly, on the subject of power measurement with a thermistor as the power-absorbing element, something might be said about the losses that occur in practical thermistor mounts. For this instrument to work accurately all the applied power must be absorbed by the thermistor bead and, as investigations on practical mounts have shown, this is very difficult to achieve. There is usually some power lost in the ceramics and other materials used to construct the thermistor and its mount.

E. G. Hamer (*Associate Member*): The schematic diagram of the capacitance loaded line wavemeter (Fig. 1) shows a coaxial line which is short-circuited at one end. From this drawing it would appear that the inner conductor of the line is in the form of a cone rather than the more conventional cylindrical shape. It would be of interest to know why this is so.

E. M. Wareham: The relationship existing between the glow height and the field strength in this type of neon tube may be of interest. The original investigation was carried out at the Radar Research Establishment about 10 years ago, and, due to the fact that it was not possible to cover a wide range of powers, it was concluded that the glow height was approximately proportional to the square of the field strength.

This, however, is not the case, for more recent work has shown that the glow length is proportional to the logarithm of the field strength at the probe. This was predicted to be the case by considering the glowing column of gas as a lossy conductor in a transmission line. In such a line, the field strength falls exponentially along its length until it is below the ionization potential of the gas, when the glow stops. Since the field strength at the end of the glowing column and the attenuation per centimetre of the discharge are fixed, the length of the discharge is proportional to the logarithm of the exciting field strength.

In a short pulse system where the ionization time is large compared with the pulse length and short compared with the interval between pulses, the excitation of the gas is directly proportional to the mean energy content of the pulse. Thus, for a given pulse energy the glow length is independent of both of the shape of the r.f. envelope, and the pulse repetition frequency.

Mr. Walter's comments on the thermistor mount are confirmed by work conducted at the Radar Research Establishment on the S.T & C type E bead thermistor. The power lost to the thermistor is dissipated in the glass envelope and the wire connectors within the envelope. The actual loss at 9,000 Mc/s was found to be about 0·4 db, and a loss of about 0·3 db was recorded at 3,000 Mc/s. Work carried out at Q-band frequencies has produced very conflicting results, power losses from 1·0 db to 3·0 db being quoted.

C. S. Fowler (*Associate Member*): In the resonant cavity type of wavemeter what is the minimum percentage deviation of frequency as calculated from the cavity dimensions to that obtained in practice due to the coupling loop? I am assuming that the minimum coupling to the cavity is used.

M. Gammon (*Associate Member*): The radar test set mentioned at the end of the paper was said to contain resistive attenuators, with the absorbing element consisting of a carbon film. It would be of interest to have some indication of the stability of this film, as it is generally considered that nichrome or precious metal films on glass produce a more stable attenuator.

E. M. Wareham: The reported instability of the carbon film attenuator element may be largely attributed to water absorption by the porous material on which the film is deposited. All such attenuator vanes will of course have the temperature coefficient of carbon, but the relatively large variations in attenuation that have been reported showed that some other factor was predominating and causing instability. Work that I have carried out indicated that this was in fact due to water absorption. Thus, if the Morganite-type materials that are usually used are impregnated with a suitable varnish a much greater degree of stability may be expected.

P. M. Ratcliffe (*in reply*): The axial plunger used to alter the frequency of resonance of the cavity-type wavemeter has a diameter which is small compared with the diameter of the cavity itself, the actual ratio being 2·35 to 1. The small clearance mentioned is due to the difference in diameter between the plunger and the hole in the cavity wall through which it is inserted. In the oscillatory mode used there is a current flow between the plunger and the end wall of the cavity, so ideally the plunger should be merely a continuation of this inner wall. However, due to the necessity of rotating the plunger to alter its penetration depth there must be some break in the continuity. Originally a series of spring fingers were used to maintain the circuit, but difficulty was experienced in obtaining a material which would give a reliable electrical contact and withstand the constant friction that was produced by the rotation, so the non-contacting type of plunger was adopted.

If the plunger inserted into the cavity is considered as a coaxial line, the characteristic impedance looking into the line will be determined by the ratio of the two diameters and is about 50 ohms. At the point where the plunger leaves the cavity the diameter of the outer conductor of the coaxial line is suddenly reduced to almost the same diameter as the inner conductor, and the characteristic impedance will approach zero, thus giving an effective short circuit without any actual d.c. contact.

The deviation from the calculated frequency of resonance as given by the formula in Section 2.2.1 will be due to the effect of the two coupling loops, and it is not possible to state a figure for this deviation as it will depend upon the depth of their insertion into the cavity. Naturally this is kept to the absolute minimum required to give a reasonable indication on the meter, but this in turn will depend upon the amplitude of the signal and the efficiency of the detector circuit. The latter is easily altered by changing the sensitivity of the indicating meter. The most important point to observe is that the input coupling loop is not inserted to such a depth that the external circuit connected to this loop has any marked effect upon the frequency.

In reply to Mr. Hamer, the inner conductor of the line is in the form of a cone, mainly for ease of mechanical construction. The complete inner conductor assembly rotates so that to obtain an efficient electrical contact at the short-circuit end of the line the diameter of the inner conductor is increased and is joined to a coin silver washer which moves against the wall of the outer conductor and provides a lossless contact. As has been stated, the fixed plates of the variable capacitor are formed by projecting vanes from the inside wall of the outer conductor; therefore to maintain the frequency range of the instrument at a maximum the inner conductor is narrowed.

Mr. Wareham's information on the logarithmic response of the discharge tube is of interest, but it would appear that when used as a standing wave indicator the errors will only be serious when the mismatch is large, as it is at the extremes of the scales that a square law deviates widely from a logarithmic law.

The figures quoted in the paper for the absolute accuracy of the thermistor mount concern first of all the accuracy of the bridge circuit purely from a d.c. viewpoint, and secondly the microwave power lost due to the mismatch of the mount. An investigation into this power loss in comparison with a water calorimeter gave the following results: At 3,000 Mc/s with a measurement accuracy of $\pm 2\frac{1}{2}$ per cent. the thermistor was recording 96 per cent. of the power, whilst at 10,000 Mc/s with an accuracy of ± 4 per cent. it was measuring 92 per cent. of the power measured by the water calorimeter. These figures appear to be slightly worse than those found by Mr. Wareham: no comparable figures are known for Q band. There is now available the torque vane wattmeter,[5] which gives power in terms of the fundamental quantities of mass, length and time by measuring the deflection of a reactive vane supported by a quartz fibre in a waveguide. The instrument has a measuring accuracy of ± 1 per cent. for powers greater than 10 W, so that comparisons between this wattmeter and the other methods will give results with smaller experimental errors.

AN ELECTRONIC RANDOM SELECTOR*

by

R. W. Walker (*Student*)†

Read before the North-Eastern Section in Newcastle upon Tyne on January 13th 1954

SUMMARY

Some of the requirements for producing a random series are discussed. Mechanical and electronic devices have been constructed that try to produce randomness in selection, but very few pass the rigorous tests applied by the statisticians. Three types are mentioned and an electronic method is described in detail. Reference is made to the use of the selector in psychical research.

1. Introduction

The word "random" is often applied to anything where no definite order appears to exist. For example, a person may draw a number out of a hat, or select the name of a horse by sticking a pin into paper and these things could be done "at random."

Statisticians, however, require a number of tests to be made to ensure that an allegedly random series is in fact random. For practical purposes the following four tests[1] can be applied and hereinafter the word random will be used when referring to a series of digits that appear to pass these tests.

(*a*) *Frequency Test.*—This must show that all digits shall occur an approximately equal number of times.

(*b*) *Serial Test.*—Requires that no digit shall tend to be followed by any other particular digit.

(*c*) *Poker Test.*—If digits are arranged in blocks of, say, five, there will be a certain expectation of the numbers in which the five digits are all the same, the numbers in which there are four of one kind, and so on. Referred to as poker test from the analogy with the card game.

(*d*) *Gap Test.*—There are certain expectations in regard to the gaps occurring between the same digits in the series. For instance, if one digit (0-9) is taken, say zero, in about one-tenth of the cases the first zero will be followed immediately by a second zero, and there will be no gap. In about nine-hundredths of the cases there will be one digit between two zeros. In about eighty-one-thousandths of the cases there will be a gap of two digits between successive zeros, and so on.

The four tests should be used, as one test on its own may show the series to be "random" whereas, in fact, there may be a definite order in which the digits are produced.

An allegedly random series can consist of any number of "tries" (or throws of a die for example). If a series consists of a number of tries in excess of, say, 200, then it is safe to state that a different series will be produced each time. If, on the other hand, a series is made up of a small number of "tries," say six, it is quite likely that the digits will appear in a particular order more than once depending on the number of series recorded.

2. Production of a Random Series

It is not easy to produce a random series of digits, and many methods, mostly mechanical, have been tried. One of the most important points in random selection is the elimination of the "human element." There is a great tendency for a human being to try to avoid making a choice which may favour one or more groups of samples in a given population and in so doing may set up a bias towards another group.

The throwing of dice to produce a random series of digits between one and six is very unsatisfactory as it is extremely difficult to produce a die which is not "loaded" to some slight degree. It is also necessary to make sure that the throw is not made to the advantage of one digit more than another and a mechanical thrower may be used for this purpose.

A further effect that may have to be taken into account is that due to psycho-kinesis,[2] which is the moving of material objects by a non-physical means.

A semi-mechanical method of producing the digits 0 to 9 was devised by the statisticians M. G. Kendall and B. Babington Smith.[3] It consisted of a rotating disc divided into 10

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† Physics Department, King's College, Newcastle upon Tyne.

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sectors, each sector being marked with a different digit 0 to 9. The disc was made to revolve at 2,500 r.p.m. and illuminated by a free-running neon flash operated at a variable 3- to 4-second period. The illumination from the neon lamp made the disc appear stationary, the digit being read off against a fixed pointer.

The method, although good, was fatiguing and errors might easily be made after a long spell of working.

In any electrical or mechanical system that has to produce a random series of digits the shuffling process has to be very fast compared with the interval between each choice. For example, in the Randomizing Machine mentioned above, the disc rotated approximately 40 revolutions per second and the flashes occurred at about 3- or 4-second intervals; that is, about one flash for every 160 revolutions of the disc. If one wanted to record a digit, say every 2 seconds (remembering that a set of tables of random numbers may contain thousands of digits), then the relationship would be about one flash in 100 revolutions.

Electronic devices for shuffling at high rates have been constructed in an attempt to overcome the disadvantages of the mechanical systems. The type with which the writer has had experience is of the "four digit" pattern which is used for the randomization of targets in psychical research.[4]

A similar electronic random selector to that described by Wilson[4] was constructed at the request of Dr. G. D. Wassermann,* who is conducting a series of experiments into psychical research. It was found, however, that slight but significant bias always persisted on one of the four digits that the equipment selected. The bias could be removed from one to any of the other three digits, but could not be reduced to conform to the requirements of the Frequency Test. Also, this selector was not easy to test electrically.

An electronic random selector designed by Dr. J. F. W. Bell† was then constructed that appears to be satisfactory in performance[5] and is described below.

* Mathematics Department, University of Durham, King's College, Newcastle upon Tyne.
† Now at Physics Department, Royal Naval College, Greenwich.

It works on the principle of a pulse being applied to a "gate" circuit, the gate being opened and closed at a regular rate. Any pulse passing through the gate triggers a bistable multivibrator which is in turn coupled to a pair of mechanical registers.

Two such circuits make up the complete selector enabling four mechanical registers to operate.

3. Construction

The equipment, which is shown in Fig. 1, consists of four main parts:—

(i) Unit A, which houses the power pack, seven 3,000-type relays, four P.O.-type mechanical registers and a double triode valve.

(ii) Unit B contains two almost identical circuits each consisting of a thyratron, a gate valve with diode clamper, a free-running multi-vibrator and a bistable triggered multi-vibrator.

(iii) A small metal box containing a locking/non-locking P.O.-type key.

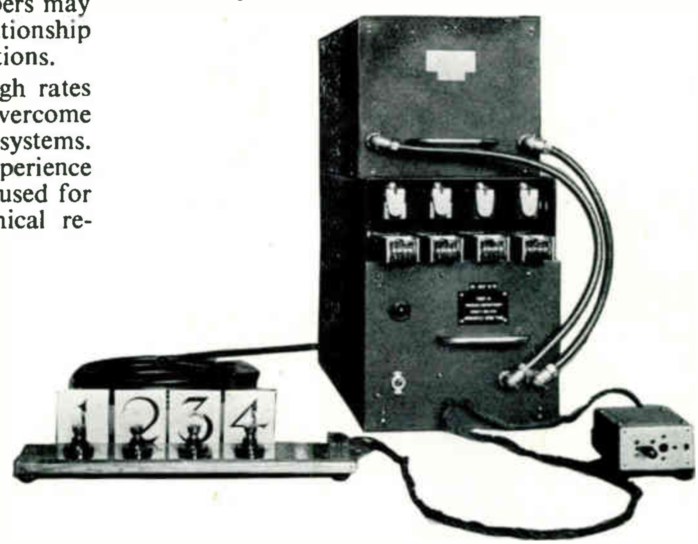


Fig. 1.—The electronic random selector.
The lamp operating relays (relays RL1 to 4) can be seen at the top of unit A with a register below each relay. Unit B is mounted above unit A. In the foreground the box containing a locking/non-locking P.O. type key is shown and, on the other side, the four indicator lamps which light one at a time. These have been numbered 1 to 4, but of course could be associated with any letter of the alphabet, suit in a pack of cards, etc.

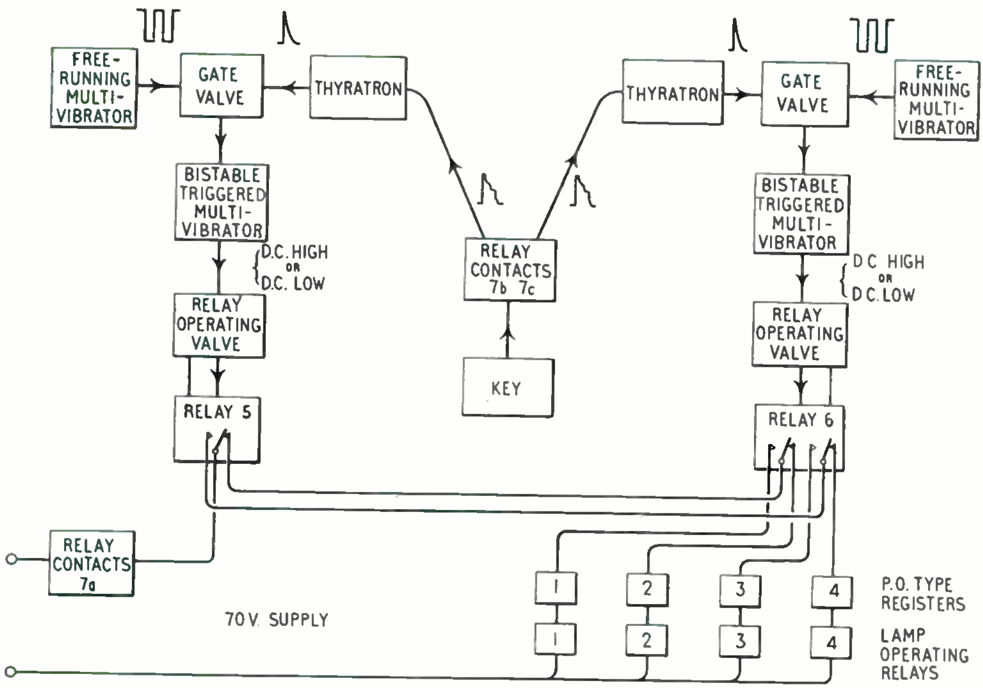


Fig. 2.—Block diagram of the electronic random selector.
(Note.—A detailed circuit diagram is given in Fig. 5.)

(iv) Four 8-V 4-W M.E.S. lamps mounted on a wooden baseboard, each lamp being identified with a digit one to four.

Referring to the block diagram in Fig. 1 and commencing at KEY in centre, then, when the key is operated to "normal working" position, relay 7 is energized and contact units 7b and 7c close, with 7a closing slightly afterwards.

Consider only the left-hand circuit for now and that the h.t. line has been connected via 7b through a resistor and small capacitor to the thyratron Mullard EN31. This "fires," producing a sharp pulse at its cathode, the pulse being positive-going with respect to earth and applied to the control grid of a Mullard valve type EF50. The suppressor grid of this valve is joined via a capacitor to the output of a free-running multi-vibrator (6SN7GT) which produces a wave of good rectangular form at about 500 complete changes per second. The "mark/space" ratio of the wave is approximately 1 : 1, although it is not essential that this be accurate. Ratios of 2 : 3 and 3 : 2 have been used with no noticeable change in the final results.

Using the EF50 as a gate valve its suppressor grid is clamped electrically to earth via an EA50 diode during a "mark" and is held about 100 V negative with respect to earth on "space." The pentode is thus made to conduct for a millisecond and cut off for a millisecond. The pulse on the control grid of this valve will only appear at the anode if its injection coincides with a conducting period of the valve. In Fig. 3 pulse (*a*) appears at anode and pulse (*b*) does not. Pulse (*c*), being on the borderline between the two conditions, may appear as a pulse reduced in size at the anode, depending on the width of the grid pulse and the steepness of the suppressor grid wave-form.

(*a*) A pulse that gets through the gate is made to trigger a bistable multi-vibrator, the d.c. output of which is passed on to the grid of a triode valve (one-half of Brimar double-triode 6SN7GT). This valve has a positive bias of 75 V with respect to earth applied to its cathode. If the direct voltage on the grid is higher than the bias the valve conducts operating relay 5, and if lower the relay remains in the "not operated" position.

(*b*) When the pulse does not appear at the anode of the gate valve, the bistable multi-vibrator and relay 5 remain in the position set by the previous triggering pulse.

(*c*) A small pulse of a certain size will tend to trigger one-half of the multi-vibrator in preference to the other, due to very small differences in capacitance, inductance and resistance of the two halves. Hence there will be a tendency for relay 5 to show a bias towards one state.

To reduce the occurrence of pulse (*c*) the width of the rectangular wave (t_2) is made large compared with the pulse width (t_1). A complete change in 2 milliseconds for the rectangular wave has been found best and this gives a ratio t_2/t_1 of 100 : 1 for a 20-μ sec pulse.

The pulse, which is initiated by operating the key (Fig. 2), can be made to occur at a maximum rate of one pulse per second, but for normal working a rate of one pulse every 2 or 3 seconds (t_3) is more convenient. The ratio t_3/t_2 is about 1,200 : 1 which can be compared with the 160 : 1 ratio (disc revolutions per flash) of the Randomizing Machine.

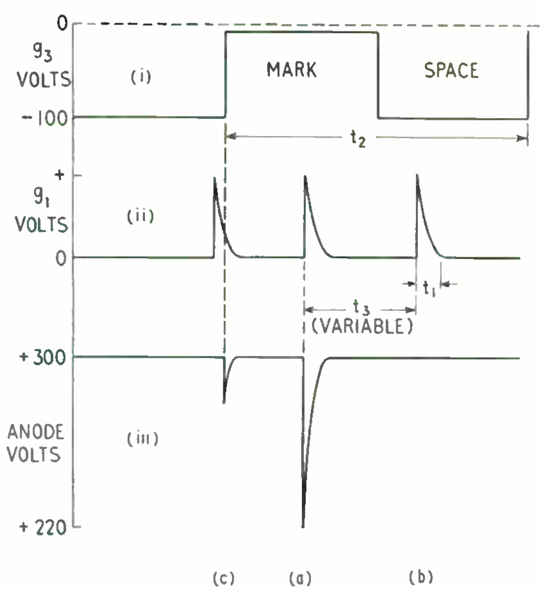


Fig. 3.—Voltages with respect to earth at three electrodes of the gate valve.

Referring again to Fig. 2, the right side of the diagram is similar to the left except that the free-running multi-vibrator works at a slightly

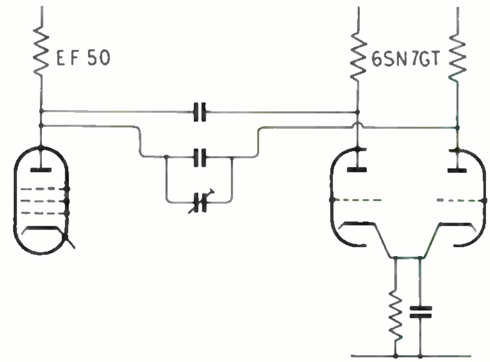


Fig. 4.—The triggered multi-vibrator circuit.

different rate to its "opposite number" and that relay 6 has another contact unit as shown.

The spring-sets of relays 5 and 6 are interconnected to give four possible combinations of switching. About 100 milliseconds after these have been determined (by chance), contact unit 7a "makes," allowing one register and one lamp relay to operate, and thus indicating any digit one to four.

By throwing the key handle to the second position, that is "continuous working," the selector produces the digits automatically, this being brought about by an additional resistor in relay 7 circuit causing the relay to pulsate about once per second. In general, the "continuous working" position is only used when testing the equipment for faults, although if a four-channel pen recorder be fitted to record the occurrence of each digit a proper analysis of the series can be made after the automatic recording.

The tables of random numbers compiled by Dr. Wassermann were all recorded by the key being operated in the "one digit" position and each digit written down by hand.

4. Initial Setting Up—Testing

At first it was found that a bias existed towards two of the digits, but this was overcome by balancing the two feeds from each gate valve to its respective bistable triggered multi-vibrator. Although the capacitances in each arm (Fig. 4) are not necessarily equal, the effect at the final adjustment is to make both halves of the multi-vibrator accept the smaller pulse of Fig. 3 (*c*) in an *almost* unbiased manner. It is not possible to have the perfect condition just as it is not possible for a die to be completely unbiased, but as long as these inequalities are kept to a reasonable minimum the final results will probably conform to the requirements of the four tests for randomness.

When balancing feeds from the left-hand gate valve (Fig. 2), relay 6 is made inoperative by fixing its armature in one position, thereby allowing only two lamps to light. If the circuit is properly balanced these lamps should produce a random series of the two digits illuminated. The same procedure is carried out when balancing the right-hand circuit, this time rendering relay 5 inoperative.

To check if the pulse from the gate valve triggers the bistable multi-vibrator correctly, the suppressor grid of the EF50 should be earthed and the free-running multi-vibrator disconnected. Every pulse must now cause the relay armature (5 or 6 depending on the circuit under test) to change its position, and by putting the key to "continuous working" the two registers in circuit will record this automatically.

When removing the earth from g_3 of the gate valve and applying instead 100 V negative with respect to earth, the pulse should not be conducted through the valve, hence causing the relay to remain in one position.

When both circuits have been balanced and tested individually, and the appropriate relay armatures released, the four final relays should operate the lamps and produce a random series of digits.

No stabilization of the power supply is employed, the a.c. mains input being approximately 240 V. During tests the input was altered from 225 V to 255 V with no apparent change in the randomization process. A valve warming-up period of about 10 minutes is usually allowed before a series is recorded, although the selector can be used, if necessary, one minute after switching on the valves.

5. Use of the Selector in Psychical Research

Reference was made earlier in this paper to psychical research and it may be wondered what the connection is between that and an electronic random selector.

Psychical research covers the study of phenomena that cannot be explained completely by the application of the known physical laws of nature. Telepathy and clairvoyance are typical instances coming within this category of phenomena and are sometimes classed together under the heading of Extrasensory Perception.[6] For definitions and details of experiments carried out reference should be made to some of the many books and papers published on the subject. (For example, ref. 6.)

It has been found that if two people are separated by some distance, with no means of communication whatsoever in the physical sense, one may perceive impressions set up by the other. Many experiments have been carried out using a number of different simple designs or pictures or shapes, known in psychical research as targets. These are viewed separately by an agent at equal short intervals of time, the percipient at some distant point attempting to name the targets.

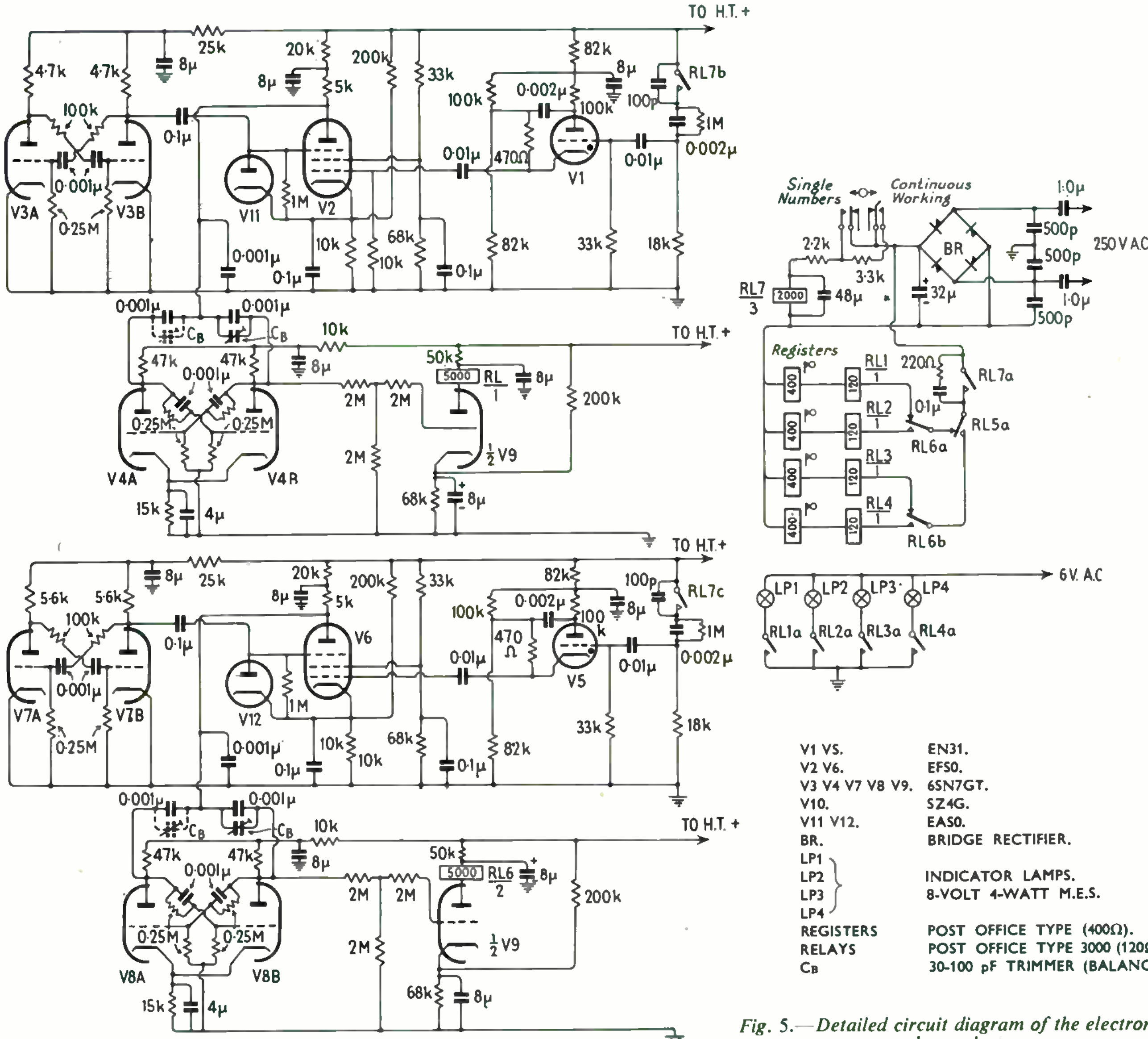
When *chance only* is allowed to govern the naming of targets the probability of obtaining a correct *guess* can be worked out mathematically. In E.-S.P. experiments it has been found that a percipient may be able to name most of the targets at the time they are viewed by the agent, the probability of this happening by chance alone being possibly millions of millions to one against.

The targets used in these experiments are required to follow a random sequence. For example, if simple designs are used, say a circle, cross, rectangle, wavy lines and a star, each printed on a separate card, these cards must be randomized to conform to the requirements of the tests for randomness.

Cards bearing these designs have been used for many years, there usually being five cards of each design making 25 cards to a pack. These cards may be viewed thousands of times by the agent during a series of experiments for it is only by taking a large number of targets that any significant information can be gained.

A successful series of experiments involving long-distance telepathy was conducted by Dr. S. G. Soal and his colleagues between London and Antwerp in June, 1949, showing among other things that distance does not appear to diminish the ability to perceive information in E.-S.P. experiments.[7]

Many people believe that the "inverse square law," familiar to physicists and radio engineers, does not apply in E.-S.P. and for this reason a



V1 V5.	EN31.
V2 V6.	EF50.
V3 V4 V7 V8 V9.	6SN7GT.
V10.	SZ4G.
V11 V12.	EA50.
BR.	BRIDGE RECTIFIER.
LP1 LP2 LP3 LP4	INDICATOR LAMPS. 8-VOLT 4-WATT M.E.S.
REGISTERS	POST OFFICE TYPE (400Ω).
RELAYS	POST OFFICE TYPE 3000 (120Ω).
CB	30-100 pF TRIMMER (BALANCE)

Fig. 5.—Detailed circuit diagram of the electronic random selector.

number of research workers into the subject do not think that wave-motion such as is known to-day can act as a carrier of information involving extra-sensory perception.

6. Conclusions

Psychical research requires a method of producing a random series. Three methods have been shown that attempt to do this; there are many others.

The electronic selector appears able to overcome the difficulties encountered in the other methods, but this can only be shown by a complete mathematical analysis of the tables that have been compiled.[5]

7. Acknowledgments

The author wishes to thank Dr. Bell and Dr. Wassermann for their very helpful criticism and for permission to present this paper.

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THE MANCHESTER UNIVERSITY HIGH-SPEED DIGITAL COMPUTER*

by

D. B. G. Edwards, M.Sc.†

Read before the North-Western Section of the Institution in Manchester on January 7th, 1954.

SUMMARY

The paper deals briefly with the simple principles and the various essentials of any digital computer. It then deals specifically with the Manchester Machine and shows how its mode of operation is moulded around the cathode-ray tube storage system. The provision of a large capacity "memory" by means of magnetic recording on a rotating drum is discussed and also the methods of communication with the machine. Mention is made of maintenance techniques which have been used to keep the machine operative for mathematical work since July 1951.

1. Introduction

Computing machines of this type find their use in the solution of mathematical problems where time is the chief barrier. They revel in problems normally considered tedious and where repetition is at a premium. Thus they would never be used on problems which would only take a few minutes to solve by ordinary means of calculation. Unfortunately, setting the machine a problem to solve involves rather more than the brief statement which could be sufficient for a human being to act upon. The problem has first to be split up into a series of simple steps, each one of which the machine can obey. Each of these steps corresponds to an instruction in the order code of the machine. These instructions and the numbers on which they operate have to be coded in a form which the machine can interpret, before they can be supplied to the machine. A problem drawn out in this manner is termed a "programme."

When the machine receives a "programme" and is operating on it, human intervention has to be reduced to a minimum because of the large time factor that it would introduce. Thus the whole programme has initially to be loaded into some form of "memory," to which access for the purposes of either "reading" out information or "writing" information back in can subsequently be made at high speed (i.e., at a speed far superior to a human being providing the same function). In most machines the "memory" can be divided into two important parts:—

(*a*) The main store where all the data is initially stored for later reference and hence has to be of large capacity.

(*b*) The subsidiary stores of which there may be many; the most important are:—

- (i) The control store which, with associated circuitry, orders the various operations of the machine to occur in the desired sequence.
- (ii) The accumulator store which, together with the various computing circuitry, performs all the arithmetic operations.

When the machine has fulfilled the dictates of the "programme," means of extracting the appropriate answers to the computation have also to be provided. This output mechanism, together with the input mechanism which performs the initial loading of data, provides the two-way communication system between the machine and the outside world.

Specific detail of the Manchester Machine‡ is now given bearing in mind the generalities that have already been discussed.

2. Representation of Numbers and Instructions Within the Machine

The machine works in a serial manner: digits of a number occur on a single wire and become available in temporal sequence. The least

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† Electrical Engineering Laboratories, Manchester University.

U.D.C. No. 621.389 : 518.5.

‡ T. Kilburn, G. C. Tootill, D. B. G. Edwards and B. W. Pollard, "Digital computers at Manchester University." *Proc. Instn Elect. Engrs*, **100,** Part II, 1953, p. 487.

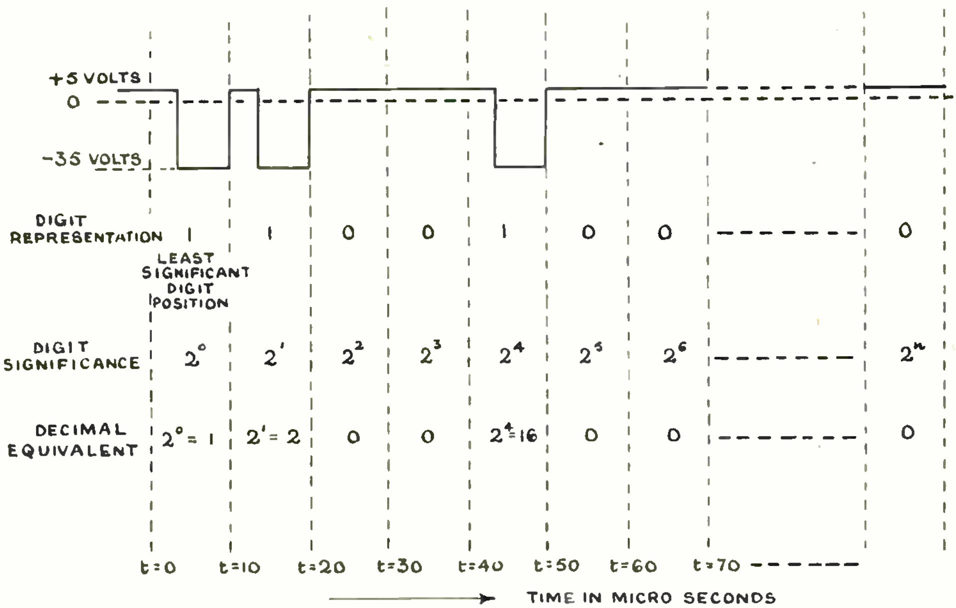


Fig. 1.—Pulse representation of a number on the binary scale.

significant digit of a number always occurs first in time so that during computation the "carry" digit can be propagated to the more significant digits.

The binary system of numbers is used since it requires only two digits "0" or "1" to be specified and thus the system can be represented simply and reliably by electronic devices. The time period for each digit of a number (digit period) is 10 μsec, 0 is represented by no pulse during this time and 1 by a pulse negative-going for approximately 7 μsec. The remaining 3 μsec time interval is used as a switching period. Fig. 1 shows the pulse representation of the binary number 11001 which is equivalent to the decimal number 19. A number within the machine normally occupies 40 binary digits, and the most significant digit is used to signify whether the number is positive or negative, i.e., 0 in this position indicates a positive number and 1 a negative number.

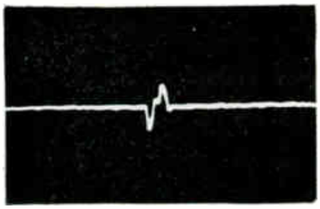
Instructions consist of two parts, one an address which specifies a storage location in the main store and the other a "function" which specifies what operation is to be performed on the number which is located by the address portion. Electrically, instructions appear identical in form to numbers; they are treated differently by the machine because they occur at different periods of time during the machine operation. When the machine receives an instruction certain gates are opened and others shut so that the number, whose address the instruction has selected, will be routed along a specific channel and perhaps through a computing circuit. The instructions are 20 digits long, nine digits specify any one of 512 address locations in the main store and a further six digits specify one of a maximum of 64 different operations. The remaining five digits can be considered unnecessary at this stage.

3. "Memory" or Storage

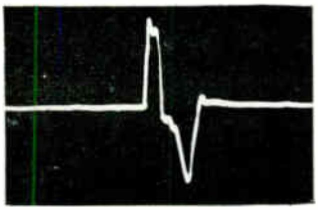
This function is carried out by the cathode-ray tube storage system which was pioneered at Manchester* and is now used in various machines both in this country and abroad.

Information is stored in the form of charge patterns on the screen of a cathode-ray tube. A

* F. C. Williams and T. Kilburn. "A storage system for use with binary digital computers," *Proc. Instn Elect. Engrs*, 96, Part III, March, 1949, p. 81; and, F. C. Williams, T. Kilburn, C. N. W. Litting, D. B. G. Edwards and G. R. Hoffman, "Recent advances in cathode-ray tube storage." *Proc. Instn Elect. Engrs*, **100**, Part II, 1953, p. 523.



(a)



(b)

Fig. 2.
(a) Amplifier pulse for a "0" digit.
(b) Amplifier pulse for a "1" digit.

certain charge distribution is used to represent the digit 0 and another to represent the digit 1. These charge patterns are established by the electron beam and when a storage location is inspected by the beam the charge pattern is changed. This change is capacitively coupled to a pick-up plate which is fastened to the tube face. After suitable amplification the pulse is gated to determine which charge pattern existed prior to inspection and it is then possible to use this information to restore the charge pattern to its original state. This latter process is called regeneration. The amplifier outputs for 0 and 1 are shown in Figs. 2a and 2b respectively, and Fig. 3 gives a schematic diagram of the storage system, showing the regenerative connection, read output and write input points.

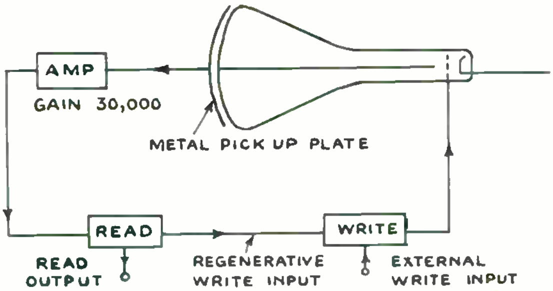


Fig. 3.—The cathode-ray tube store.

If a number of digits were stored at various locations on the cathode-ray tube face and then the electron beam was switched off, all the charge patterns would leak away in the order of seconds, due to leakage over the screen surface. In order to maintain the stored pattern the information is read merely for the purpose of re-establishing the charge patterns. This process of regeneration has to take place at a rate which permits only very slight deterioration of the charge so that no information can be lost.

The electron beam can be made to trace out a line of 20 distinct storage areas by the application of an appropriate waveform to the X plates of the cathode-ray tube and, by adjustment of the potential applied to the Y plates, many separate lines can be formed. In all, on one cathode-ray tube it is possible to store 64 lines of 20 digits. These are arranged in two columns of 32 lines placed side by side to form a raster of 40×32 digits.

The time taken to scan one line of 20 digits is 240 μsec, this allowing a 40-μsec switching period. Successive 240-μsec intervals, termed beats, are allocated alternately to the regeneration of the store which occurs sequentially (scan beats), and to obtaining access to the store for computation purposes (action beats).

The main store is provided by eight such cathode-ray tubes so that the first six digits of the instruction address specify one of 64 lines on a tube and the remaining three digits specify one of the eight tubes.

The subsidiary stores are also provided by cathode-ray tubes but as these are of much smaller storage capacity, one tube for each subsidiary store is more than adequate. The cathode-ray tubes used are 6 in. in diameter with electrostatic deflection and focusing. They operate at 1 kV with a focus of the order of a ¼-mm spot. The low value of the e.h.t. is used to minimize the effect of screen imperfections but also provides good deflector plate sensitivity.

4. A Simple Machine and its Mode of Operation

A schematic diagram of the simple machine is shown in Fig. 4, which indicates how the flow of numbers and instructions takes place. To avoid complexity no gating is indicated and only the routes, the numbers and instructions taken are shown.

When the machine is not operative, the main store is regenerating the contents of each address

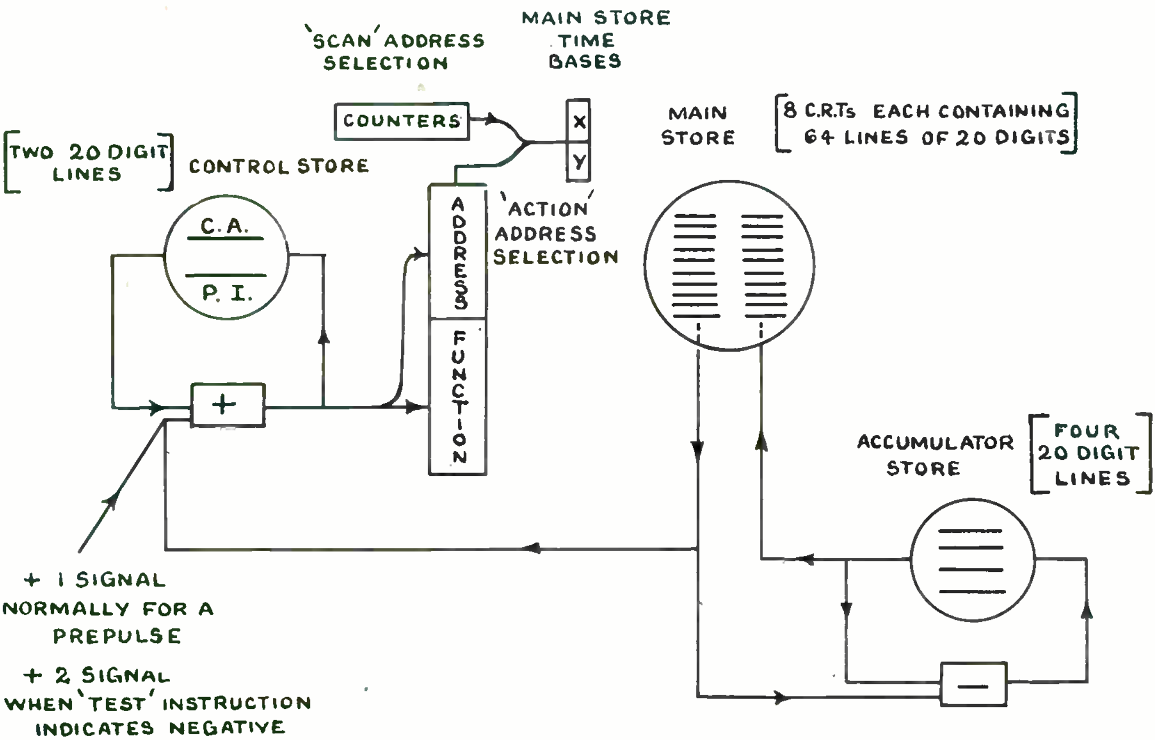


Fig. 4.—A schematic of the simple machine.

location in sequence as selected by a counter system (scan beat selection mechanism). When the machine is operative and action beats exist, then, during these periods, the store address is selected by a separate (action beat) selection mechanism.

Assume initially that the main store has all the necessary data stored in it and that the control and accumulator stores are both empty. The throw of a switch will give a "prepulse" which initiates the machine operation. The first beat to occur is always a scan beat S_1, during which time one is added to the contents of the control address (C.A.) line of the control store. The serial adder output, namely one, is then written on the (C.A.) line as well as setting the action address selection mechanism in this case to address 1. In S_1 the main store regenerates the contents of the store address indicated by the scan selection mechanism. The following beat is an action beat A_1 and address one in the main store is selected so that its contents are read out. This information is the present instruction (P.I.) and is temporarily stored on the second or P.I. line of the control store.

During the next beat S_2, regeneration occurs in the main store under the control of the scan selection. At the same time the P.I. is read out of the control on to both the address and function selection mechanisms. The address selects the line of the main store to be read out in the next action beat, and the function determines which gates are to be opened in the paths the number will attempt to flow along and thus will determine what operation is to take place.

Normally two action beats A_2 and A_3 then occur sequentially so that, for example, the contents of the address "n" selected during the S_2 beat and the contents of the address (n+1) are read out of the main store. This 40-digit number could then be subtracted from the contents of the accumulator store if this operation was needed. Alternatively, for a different function code a 40-digit number from the accumulator could be written back into successive address locations of the main store. An accumulator store of total capacity 80 digits has been provided so that the complete answer to a 40×40 digit multiplication can be recorded.

The end of the A_3 beat concludes the sequence of beats for instruction one but if further instructions are to be obeyed, a prepulse is given and the next beat, a scan beat, becomes the S_1 beat of the next instruction. During this beat one is again added to the contents of the C.A. which will this time be recording one so that instruction two will be selected. The beat sequence then repeats itself and instruction two will be obeyed.

This procedure allows the machine to obey instructions in a sequential manner but often it is necessary to act upon a certain set of instructions many times, i.e., in some iterative process. An instruction has thus been provided which modifies the control address (C.A.) during the A_2 beat, and it is referred to as a control transfer instruction. Since the C.A. line only contains 20 digits there is no need for an A_3 beat to occur; so that for this particular function the S_1 beat of the next instruction follows the A_2 beat. This is thus a four-beat or 20-digit operation as compared with an accumulator operation which normally occupies five beats (40-digit operation).

Consider the set of instructions listed in Fig. 5. Suppose the machine starts at instruction one and obeys the others in sequence. When it reaches the control transfer instruction this could reset the C.A. so that the next instruction to be obeyed would be instruction 3 again. This means the machine would obey instructions 3 to n+3 inclusive over and over again. To enable the machine to get out of this loop some form of discriminating power must be given to it. This occurs in the form of a "Test Instruction" which tests the sign of a number in the accumulator. When this number is positive, one is added to control at the start of the next operation as normally, but when the number goes negative two is then added instead, so that the control transfer instruction is then omitted (see Fig. 5). By arranging to subtract one from some known starting number every time the loop of instructions are obeyed, the number of times the machine operates on this instruction loop can be predetermined at any desired value.

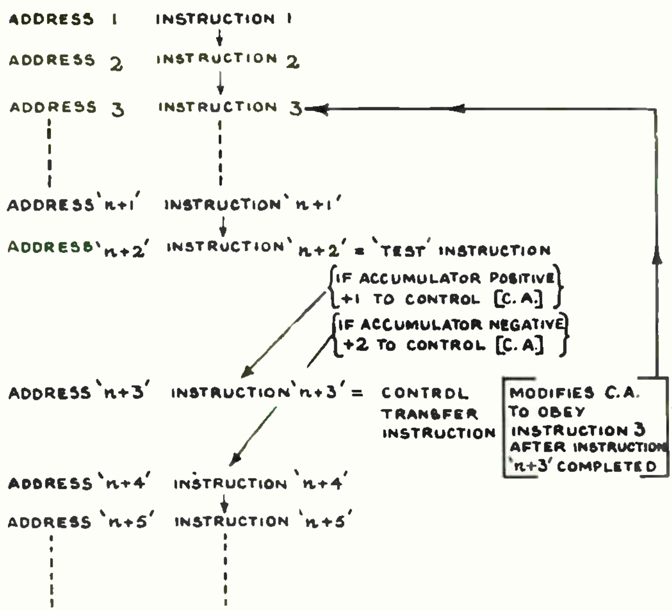


Fig. 5.—The operation of control transfer and test instructions.

5. Arithmetic Ability

In the simple machine which has just been described the only computing facilities indicated were those of subtraction. In the final machine the computing facilities include:—

(*a*) Addition.

(*b*) Various logical operations, for example: the "and" (&) operation which on receipt of the two input numbers only allows a "1" output to occur when both input digits are "1"; the "not equivalent to" (≠) operation which only allows a "1" output when the input digits are of unequal value, i.e., one input digit a "0" and the other a "1."

(*c*) The ability to reverse the significance of the less and more significant halves of the accumulator. This facility is of use when numbers exceeding 40 digits have to be used in the machine.

(*d*) The ability to find the position of the most significant digit of a number and represent it in binary form. This instruction is of use to test whether the capacity of the accumulator is in danger of being exceeded at any time.

(*e*) The ability to generate a 20-digit random number.

(*f*) Multiplication of two numbers, the product either being added or subtracted from the contents of the accumulator depending on the instruction.

These facilities have been provided for computation with numbers, but instructions may be sent from the main store to the accumulator where they will be treated as numbers. This means that instructions can be modified and thus new instructions generated by the machine itself. This process, however, is often inconvenient and is wasteful in time and storage space.

Thus another subsidiary store termed the B-tube has been provided which has a capacity of eight 20-digit lines. It has a subtractor associated with it and as well as modifying instructions can be used for 20-digit arithmetic.

Three digits of an instruction are now assigned to specify any one of the eight B-lines so that an instruction now reads:—

nine address digits 6 specify one line out of 64 3 specify one tube out of 8	3 b. digits specify one of 8 B lines	6 function digits specify one of 64 operations

During A_1 the present instruction is read out of the main store and recorded unchanged on the P.I. line of control. A note has been made in this period, however, which B line was specified and that line has been selected so that, during S_2 when the instruction passes through the control adder on its way to set the address and function selection mechanisms, the contents of this B line are added to it. This means that the instruction will have been modified before it is obeyed. This B tube becomes of particular use when calculated results have to be sent to successive addresses in the main store. The same instruction can be used over and over again with the address portion being "B modified" each time, by a number altering sequentially. Instructions are provided for sending such numbers to the different B lines and also for modifying the numbers in the B lines in a limited manner. The first B line is normally storing zero so that when this line is specified the instruction is obeyed unmodified.

Four beat operations take 960 μsec to obey and include all the control and B tube instructions which, of course, are solely concerned with 20-digit numbers. Five beat operations are concerned with 40-digit accumulator operation and take 1·2 msec to complete. Multiplication is one exception, however, and takes 2·16 msec to complete its operation. The other exception is the instruction which produces a 20-digit random number, this takes 5·8 msec.

It is of interest to note that other facilities such as division, square rooting, taking reciprocals, etc., have not been provided. In any computing machine it is essential that over a range of problems the machine should not be spending a large portion of its time performing one particular operation, i.e., there should be a balance of the speed of the various operations against the frequency of their use, in order that the machine can make the best use of the time available. Small programmes termed subroutines can determine the reciprocal of a number in 95 msec for example or square roots in 105 msec and these speeds when compared with their average frequency of use are more than adequate. Moreover, it is neither economic nor desirable to provide further circuitry which is seldom used and whose equivalent can be obtained by programming.

6. A Larger Capacity Main Store

The 10,240-digit main store provided by the eight cathode-ray tubes is quite inadequate for the majority of problems. It has been estimated that a figure of approximately 500,000 digits would be very useful and that if any more digits could be provided they would be very welcome additions. It would neither be economic nor desirable to provide this total storage by cathode-ray tubes.

The existing eight cathode-ray tube stores provide very useful working space however; what is needed is a large capacity store from which this working space or part of it can be replenished from time to time.

This ancillary storage is provided by magnetic recording on a rotating drum* whose time of revolution corresponds to the period which it takes to scan the raster on a cathode-ray tube twice. The drum is synchronized to run at this speed from the crystal oscillator which controls the operation of the whole machine. The use of this method, rather than controlling the machine with waveforms from the drum, means that at

* F. C. Williams, T. Kilburn and G. E. Thomas, "Universal high-speed digital computers: a magnetic store." *Proc. Instn Elect. Engrs*, 99, Part II, 1952, p. 94.

any time two or more drums can be run at the same time to provide an increase in storage capacity. Furthermore, the use of two drums would guard against the time when one of the drums fails for mechanical reasons.

A typical drum is 10 in. in diameter and 12 in. high. The magnetic recording medium, in this case nickel, is coated to a depth of 0·0005 in. on its peripheral surface. Two hundred and fifty-six recording heads, of which about 150 have been installed, can be mounted one above the other in eight separate columns of 32 which are spaced around the drum. Thus at the moment 150 peripheral tracks are available and on each 2,560 digits can be stored, i.e., the contents of the two cathode-ray tubes.

Two heads, one for reading and one for writing purposes, are mounted on each track. The heads are constructed to be clamped in a single holding piece and are only separated by a few thousandths of an inch. Due to this separation, reading and writing processes occur at slightly different times, the actual time difference being given by the speed at which the drum rotates. Reading occurs slightly before writing in time and this means that an inherent delay in the method of recording can be overcome.

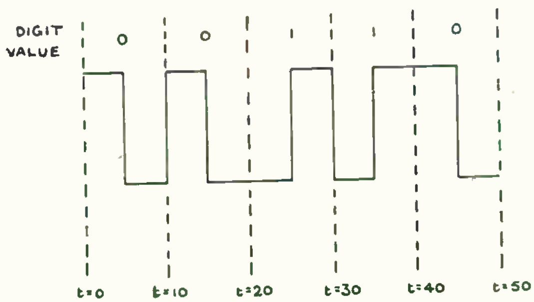


Fig. 6.—Ideal current waveform in the writing head.

To record a digit on the drum, current flow in the recording head occurs in one direction for 5 μsec and then reverses for the remaining 5 μsec of the digit period. The current waveform in the head is shown in Fig. 6 for the digit pattern 00110, where it can be seen that digits 0 and 1 are distinguished by the direction of current which occurs in the first 5 μsec of the digit period. Digits can be considered to exist on the drum in

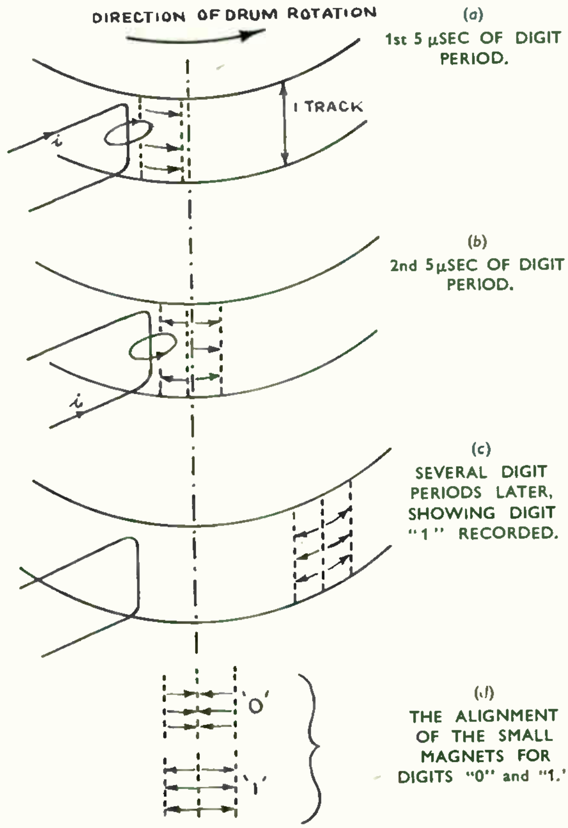


Fig. 7.—Recording on the magnetic drum.

the form of little magnets which are aligned first in one direction and then the other. The recording of a digit 1 is shown in Fig. 7 (a), (b) (c) and the alignment of the small magnets corresponding to a 0 and a 1 recorded on the drum are shown in Fig. 7(d). A high level of current is needed to record on the drum so that some form of power amplifier is needed. It is not economical to provide one for each recording head so a single power amplifier and relay switching of the connections to the heads is used. This means that before a writing operation can take place there must be a 30-msec delay to allow time for the relay switching.

On the reading side, when these small magnets pass the reading head, a small voltage is induced which after amplification is "strobed" at a particular instant in time. This process defines which direction of magnetization occurs first in the digit period and thus identifies the digits 0

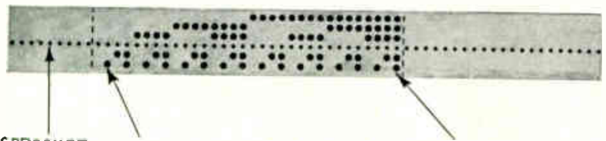


Fig. 8.
A portion of teleprinter 5-hole tape. (Between the dotted lines there are 32 five-digit characters corresponding to the decimal digits 0 to 31 inclusive.)

and 1. Each reading head has a separate preamplifier, the choice of track desired being made by switching on the appropriate preamplifier so that selection of the head for a reading operation can be made more quickly than for a writing operation.

Provision has been made to transfer information automatically between the two types of store, i.e., under the control of an instruction in the machine. Transfer can occur between a specified track and a stated pair of cathode-ray tubes or if more convenient between half a track and one cathode-ray tube.

The minimum transfer block is the content of one cathode-ray tube, i.e., 1,280 digits; this takes the same time, however, as the transfer of two such blocks of data. It would not be economical in time to transfer smaller amounts of information since there is the possibility that the information required might have just passed the reading head. In this case a waiting period of almost one revolution time would be introduced before access to this information could be obtained. A reading transfer, i.e., from the drum to the cathode-ray tube, takes 34 msec and a writing transfer, i.e., from the cathode-ray tube to the drum, 63 msec because of the relay selection.

7. Input and Output Facilities

It is necessary that a human operator should be able to supply the machine with data and that the machine should be capable of communicating with the operator when the calculation is complete. The organs providing these facilities are generally referred to as Input/Output. These mechanisms too can be controlled by the machine by the use of the appropriate instructions in the order code.

Input occurs from normal 5-hole teleprinter tape which has a maximum of five information holes across the tape and also a sprocket hole for driving or timing purposes (see Fig. 8). Each group of five digits specified at each sprocket hole position is called a character. For ease of working, instead of writing down the binary configuration each time, a letter or symbol on the printer has been assigned to each of the 32 possible five-digit configurations.

The actual tape reader is of a photo-electric type and can read tape at a maximum rate of 200 characters per second and still retain the facility of being able to stop on any character if necessary.

Output can occur in several ways:—

(*a*) On a tape punch which perforates the tape by normal mechanical means and whose maximum speed is 15 characters per second.

(*b*) On a teleprinter which prints the equivalent symbol or letter for the various five-digit characters at a rate of seven characters per second.

(*c*) On a Bull printer. A subsidiary store is associated with this printer, which is first filled with the data that has to be printed out. Then, having given the instruction for this type of output to occur, the machine can continue with further calculations. This printer, however, then prints the equivalent of 64 characters at one attempt and these groups of 64 characters occur at the rate of two per second until the contents of the subsidiary store have all been printed on paper. In effect the printer is identical to 64 teleprinters operating in parallel.

8. Machine Maintenance

The machine which has been described is of considerable size and contains in all some 4,500 valves and approximately 16,500 components (i.e. resistors and capacitors). The valve total is comprised of 2,400 diodes type EA50, 300 double triodes type 12AT7, 200 miniature pentodes type EF91, and 1,600 pentodes of either type EF50 or type EF55.

Since the circuitry used in this machine is of a relatively simple type, the main problem of maintenance is to locate a particular fault when it occurs. This problem has been simplified by the use of "Test Programmes," a process which uses the machine to find its own faults. For example, a test programme could order the machine to carry out all its possible operations in a sequential manner and check the results obtained after each operation against known answers. If a fault occurs it can be arranged that the machine stops working and indicates at what stage in the programme it failed. When this occurs the approximate location of the fault has been obtained. Then more specific test programmes have to be used to check thoroughly the faulty part of the machine. In this manner by locating the fault first in a general way and then in a more detailed way, a fault can in the best case be indicated to one of three valves, but normally to a chassis containing eight valves, the fault is then finally located by use of an oscilloscope.

This technique of test programmes is a very powerful one, particularly where the fault is of an intermittent nature, but unfortunately they can only be used to test about 73 per cent. of the machine. The remaining 27 per cent. forms the nucleus of the machine where all the fundamental waveforms are generated and this has to be tested by normal techniques. A fault in this section means that the machine will not obey the simplest instruction so the fault is generally easy to locate.

The machine is normally on for 24 hours each day and of this time three hours are allocated to maintenance of the machine. Faults will not necessarily occur in this period so that the time is occupied by "preventive maintenance" the purpose of which is to predetect all potential faults. If the system worked perfectly it should be possible to limit faults to the three hours' maintenance period and have no faults in the 21 hours' operative time, when the machine is being used for mathematical work.

Two main preventive procedures could be adopted. First, the machine could be given a thorough and periodic electronic check. This process if thorough could be very time wasting, so that it is limited to a check of all the fundamental waveforms in the machine, when their d.c. levels and amplitudes are noted. Various waveforms are checked each day so that in a week all the important waveforms have been checked.

The second procedure is that of "marginal checking," the idea being that by varying the operating conditions of the circuit, any circuit with an incipient fault can be made to fail, while those circuits free from such faults and thus more tolerant of this marginal check will still continue to operate satisfactorily. The process is normally limited in this machine to the lowering of the filament voltage by 5 per cent. The figure of 5 per cent. is used because it is the maximum tolerance allowed by the valve manufacturer on the filament voltages of miniature valves. The circuit tolerance is such that the h.t. voltages, too, can safely be varied by ± 5 per cent. at least. These variations of voltage supplies are carried out slowly when the machine is running on some of its test programmes. When a fault occurs under these conditions it is then traced in the manner already described.

Using these maintenance techniques a total of 861 valves have been replaced in the period July 1953 to March 1954. This means that the valve life in the machine is approximately 34,000 hours. In the same period 24 cathode-ray tubes used for storage purposes have also been replaced. Since only 13 cathode-ray tubes are used in the machine, their life is approximately 3,500 hours. Over half of the valve and cathode-ray tube failures were due to low emission. No specific detail can be given of component failures except that they were relatively few in number.

In this period of nine months' operation, the machine was not available for mathematical work for two months. However, in the remaining seven months of operating time the machine was kept functioning for over 80 per cent. of the time by using the maintenance techniques already described.

9. Conclusion

In this machine, for example, two numbers are added together as they flow out of their particular locations, in this case from the main store and the accumulator store, i.e., the least significant digits of the 40-digit numbers are added first and then the subsequent digits in order of significance. The machine assumes that the numbers have been arranged with the binary points (the equivalent of the decimal point in this number system) under one another. The task of shifting the numbers about until this is so is the responsibility of the mathematician. This type of machine is called a "fixed point" machine, as opposed to a "floating point" machine which shifts the two numbers automatically before computation takes place. In the latter type of machine indices are included with each number to specify its magnitude and the difference of two indices will indicate the relative shift which has to take place before these numbers are in the correct positions to be computed.

The mathematical experience gained from the present machine would indicate that the latter type of machine is more desirable for scientific calculation and, furthermore, that an increase in speed would also be of advantage. A machine of this nature has been almost completed in prototype form. It adds 30-digit numbers, whose magnitudes are specified by 10-digit indices, in the prescribed manner in 180 μsec and multiplies them in 360 μsec. Though this new development tends to make the present machine obsolete to some extent it does not mean that it will be of no further use. Indeed, mathematicians are only too keen to put their problems on any machine and at Manchester they will be very fortunate in having a choice of which machine to use.

Although this new machine uses miniature valves, pentodes type 6CH6, 6F12, 6F33, diodes type 6AL5 and germanium crystal diodes type CG4C, it is still of considerable size and uses the order of 20 kW of power. The problems of space and cooling are still of prime importance as they were with the other machine and no real advance has been made in these directions. However, present developments in the field of solid-state physics of transistors, magnetic and ferroelectric materials would indicate that future machines will certainly be more compact and economical. The chief deterrents to the use of these elements in this field at the present time are limited frequency response, expense, and availability.

10. Acknowledgments

The work described in this paper is part of a research programme on digital computers being carried out at Manchester University under the general direction of Professor F. C. Williams and Dr. T. Kilburn. Acknowledgment is also made to Messrs. Ferranti, Ltd., who constructed the present machine, and the computer research teams at Manchester University and Messrs. Ferranti, Ltd., for their considerable share in the design and development of this machine.

INDUSTRIAL APPLICATIONS OF ELECTRONIC COMPUTERS

The above paper by Mr. D. B. G. Edwards will be referred to during the forthcoming Convention. Contributors to the discussion on the series of papers outlined on page 238 might, therefore, consider the above contribution in making observations.

FAULT INCIDENCE IN MOBILE V.H.F. EQUIPMENT*

by

G. Raine (*Associate*)†

Read before the North-Eastern Section in Newcastle upon Tyne on January 13th, 1954.

SUMMARY

The result of an investigation into the analysis of past technical records is discussed, with a view to applying the information so obtained to future problems of maintenance. Methods of analytical approach are suggested, and the purpose of some of these methods is described.

1. Introduction

Fault incidence, which can be defined as the rate at which faults develop in any apparatus, is of great importance in a large maintenance organization, and it is the author's belief that the analysis of past technical records can provide valuable information for the prediction of future fault incidence.

A brief statement of the type of technical record necessary for such an analysis may be appropriate, and it can be stated with certainty that some form of job card is a necessity. Such a card should provide:—

(*a*) Positive identification of the installation and/or unit to which the sequentially-numbered job card refers.

(*b*) A brief technical description of the cause of the fault, and the action taken to cure it.

(*c*) The entry of time spent on the job, and also of any travelling time.

(*d*) Space for the listing, and costing, of materials requisitioned.

Such a job card provides all the information required for the analysis of fault incidence, but it is issued in the order of intake of faulty units, and not in order of customers. Consequently, it is simpler to refer to it in conjunction with record books which contain:—

(*e*) A "case history" of each installation—the Installation Record Book, which is grouped in order of customers, with installations following in numerical order of callsign.

(*f*) A complementary "case history" of each unit of equipment—the Set Record Book, which is sorted in numerical order of receipt of these units.

It is sometimes argued that the installation and set records are not worth their cost, but, as stated above, it can be shown that the cost is legitimate. For instance:—

(1) The "case history" is of great value to maintenance technicians in fault diagnosis. This is particularly so where early failure has occurred, for such occurrences are immediately apparent, and steps can then be taken to see that the fault is not inherent.

(2) Similarly, recurrent and basic defects are revealed in equipment, and the manufacturer can be advised in order to avoid them in future production. This is no reflection on manufacturers as subsequent analysis will testify, but no tests yet devised can compare with practical working conditions.

Other reasons can be quoted, but for all cases it is essential that the records be kept right up to date.

Interest in the possibilities of an analysis was aroused recently, when it was necessary to examine technical records in order to achieve a comparison between two periods of maintenance. Accordingly, a representative section of the technical records relating to one customer whose mobiles are in regular daily service was examined.

2. Basic Analysis

The examination of this representative section of the records related to forty mobiles in regular service, and all information so obtained was extracted for a period of 24 months. The table

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†Communications Branch, Home Office.

U.D.C. No. 621.396.61.029.62.

derived from this is presented below, and is the basic data upon which all subsequent assumptions are based. The choice of sample was at random, and this should be borne in mind by those able to identify the equipment.

The figures given in Table 1 refer to the *Faults Found* by maintenance technicians during work on faulty units brought into the depot for repair. Deterioration of valves or other components frequently necessitates their replace-

Table 1

Analysis of Faults Found

Month		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals	
Valves:																											
EF91	Emission	9	9	3	2	10	14	10	19	14	10	3	1	10	6	8	6	20	6	12	9	13	12	23	9	238	
	Electrode short-circuit	3	2	—	—	—	2	1	2	—	—	—	—	—	—	—	—	3	1	1	3	1	—	—	—	19	
	Heater open-circuit	—	1	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—	1	—	—	—	1	1	—	5	
	Microphonic	5	3	4	—	4	3	6	5	3	4	2	1	5	4	1	1	6	4	12	2	3	2	2	6	88	
	Soft	—	1	—	—	—	—	—	—	—	1	—	—	—	—	—	1	1	—	1	—	1	1	—	—	7	357
EF92	Emission	2	1	1	—	1	3	5	3	5	2	3	1	3	2	1	2	4	2	—	3	2	4	3	4	57	
	Electrode short-circuit	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	1	—	4	
	Heater open-circuit	1	—	—	—	—	—	—	—	—	—	1	1	1	—	—	1	—	—	1	2	—	3	—	1	12	
	Microphonic	—	—	—	—	—	—	1	—	—	1	—	—	2	—	1	—	—	—	2	—	—	2	—	—	9	
	Soft	—	1	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	3	85
EB91	Emission	—	—	—	—	1	—	1	—	2	—	—	—	—	—	2	1	—	—	—	—	2	3	—	1	13	
	Electrode short-circuit	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	
	Heater open-circuit	1	1	—	—	—	1	—	—	—	—	—	—	1	—	—	—	3	—	—	2	—	—	—	1	10	
	Microphonic	—	—	1	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	
	Soft	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	25
6V6	Emission	—	2	1	—	3	2	1	—	1	—	2	—	—	2	—	1	3	—	—	—	—	—	1	1	20	
	Electrode short-circuit	—	—	1	—	—	1	1	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	1	5	
	Heater open-circuit	1	—	1	—	2	—	2	1	—	2	—	2	—	1	2	2	—	1	2	—	3	1	1	1	25	
	Microphonic	—	—	1	—	—	1	1	2	1	—	—	—	1	1	—	1	1	—	4	—	—	2	—	—	16	
	Soft	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	66
QVO4-7	Emission	1	—	2	1	3	2	3	6	1	3	2	2	3	—	1	2	2	—	5	3	1	3	2	2	50	
	Electrode short-circuit	1	—	—	—	—	—	—	—	1	—	—	—	—	1	—	—	1	—	1	—	—	—	—	—	5	
	Heater open-circuit	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	
	Microphonic	—	—	1	1	1	—	1	1	—	—	—	—	—	—	—	1	—	—	—	—	—	2	—	—	8	
	Soft	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	63
Totals		26	21	16	4	25	29	33	40	29	23	13	9	26	17	17	19	45	15	41	24	26	36	34	28		596
Components:																											
Capacitors		3	5	6	3	3	2	8	4	8	6	5	4	6	4	7	4	6	2	4	3	3	3	8	9	116	
Resistors		2	3	7	2	2	2	3	5	4	4	3	4	4	3	6	2	6	1	2	3	2	2	4	6	82	
Coils and I.F. transformers		1	1	—	1	2	2	1	—	3	1	—	—	1	—	2	—	1	—	1	—	—	2	1	2	22	
Generator brushes (prs.)		1	1	1	1	—	2	—	3	4	—	2	—	2	1	1	1	1	2	4	2	2	2	7	9	49	
Generators		1	—	1	—	—	—	—	2	2	—	1	—	1	—	—	1	1	—	—	—	1	1	2	—	14	
A.F. transformers		—	—	—	—	—	1	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	
Crystals		2	—	—	—	1	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4	
Totals		10	10	15	7	8	9	12	14	22	12	11	8	14	8	16	8	15	5	11	8	8	10	22	26		289
Control Circuits:																											
Relays		—	1	1	1	—	—	2	2	3	2	—	1	—	—	1	—	—	1	2	1	—	—	1	1	20	
Controllers and control cables		3	2	1	1	1	—	1	3	1	—	—	1	4	—	4	1	1	1	3	—	—	3	1	1	33	53
Handsets		4	6	9	5	7	4	8	6	6	4	13	10	9	10	12	12	5	2	11	5	7	3	3	5	166	166
Wiring		2	2	1	5	4	2	4	6	10	7	2	8	3	7	8	3	7	8	12	10	12	4	3	10	150	150

Table 2

Analysis of Reported Faults and Man-hours

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Totals
Reported Faults	23	23	24	17	28	13	21	41	37	26	25	28	27	27	33	28	29	20	39	29	27	30	26	30	651
Man-hours	59	47	44	22	61	28	58	67	85	56	42	40	43	38	56	51	54	37	88	68	62	77	60	81	1324

ment in order to restore the equipment to an acceptable standard of efficiency in addition to the clearance of the original fault which brought the equipment to the depot: the *Reported Fault*. Consequently, *Reported Faults*, which equal the intake of faulty units and govern the number of job cards issued, are less than the *Faults Found*, which govern the mortality rate of all components. This difference must be clearly understood, for it is sometimes desirable to analyse one with respect to the other.

3. Analysis of Maintenance per Reported Fault

The Reported Fault is the actual failure experienced by the customer, and the rate at which these occur is important from his point of view. The primary purpose of a maintenance organization should be to reduce this rate to a minimum, and, in the author's opinion, it should think in terms of reported faults when seeking an assessment of component mortality. Moreover, it is always desirable that the maintenance technician should think in these terms even at the expense of increased man-hours for it is an insurance against the increase in reported faults, and an assurance of a satisfied customer. The method of this analysis can be shown by the presentation of the simple case. By considering the grand totals of Tables 1 and 2 as the general average, it can then be assumed that:—

(*a*) Each mobile will probably develop 8·14 reported faults per year, of which:

(*b*) One in every 1·09 reported faults will include a valve replacement.

(*c*) One in every 2·25 reported faults will include a component replacement.

(*d*) One in every 4·34 reported faults will require attention to the wiring.

(*e*) One in every 3·92 reported faults will require repairs to a handset.

(*f*) One in every 12·28 reported faults will require repairs to the controls.

Considerable expansion of this form would be necessary to be of any real use, but it could then provide a basis for the estimation of stores requirements as well.

4. Comparative Analysis by Percentage

This analytical method was devised in order to obtain a rational comparison between differing valve types used in variable quantities. It consists of assessing total annual mortality as a percentage of the quantity in use, and produces a figure which is the average mortality rate per valve, where 100 per cent. means one failure per valve per year.

The present paper arose from a controversy regarding the EF91 type of valve, in which it was suspected that too much reliance was placed on mortality figures alone. Reference to valve totals in Table 1 will show this point, for if one was influenced by these figures, as could easily follow from the examination of stores ledgers, the EF91 type looks rather poor. The use of the same figures in a percentage analysis provides a more rational picture as is shown in the following table.

Table 3

Percentage Analysis of Valve Mortality

Valve Type	Annual Mortality	Number in Service	Annual Percentage Mortality
			%
EF91	178·5	440	40·57
EF92	42·5	120	35·42
EB91	12·5	80	15·62
6V6	33·0	120	27·50
QVO4-7	31·5	80	39·37

The interesting feature of this analytical approach is the attention drawn to the remarkably good behaviour of these valves in service, for experience, which is mainly cognizant of total mortality, gives one the impression that valves are being used at a much higher rate than this. It is satisfying, therefore, to be made aware that the life expectancy of the EF91 valve is about two and a half years: the meaning of 40·57 per cent. per annum. This conclusion was so interesting that the percentage mortality figures of Table 3 were subdivided into the groups of valve failure listed in Table 1 and this further table is presented overleaf.

Emission faults account for the greater part of the mortality as was anticipated, but microphony and electrode faults are much lower than expected, for it must be remembered that mobile equipment is under review: equipment subject to constant vibration throughout its

Table 4

Detailed Percentage Analysis of Valve Mortality

Valve Type	Percentage Mortality	Emission Faults	Heater o/c	Electrode s/c	Microphonic	Soft
EF91	40·57	27·05	0·57	2·16	10·00	0·79
EF92	35·42	23·75	5·00	1·67	3·75	1·25
EB91	15·62	8·12	6·25	—	1·25	—
6V6	27·50	8·33	10·42	2·08	6·66	—
QVO4-7	39·37	31·25	—	3·12	5·00	—

working life. Such conditions cannot fail to aggravate such tendencies, and it speaks well for the manufacturers that rejection from these causes is so small. Again, the failure of 6V6 heaters is lower than expected, for the working temperature of these valves is high, and it was anticipated that this might contribute to just such a fault. It is also noteworthy that the heater failures in the EF92 and EB91 types is closely related to their proximity to the 6V6.

5. Graphical Analysis

Two factors determined the examination of this approach: the suitability of the data in Table 1 for graphical presentation; and the hope of revealing an anticipated rise of fault incidence with age of the equipment. For this purpose, a trial sample of five graphs of the monthly totals of Valve, Component, Wiring, Handset and Control faults was prepared. The five graphs are divided into two sections for clarity. The first section includes the three relating to faults within the actual wireless equipment, the second those relating to faults external to this equipment. The sections are presented in Figs. 1 and 2 respectively. In Fig. 1, the wide variations in monthly incidence are most striking, and illustrate the danger of using average figures for the assessment of staff requirements, but this point is more forcibly made in Fig. 3 by the graph of man-hours.

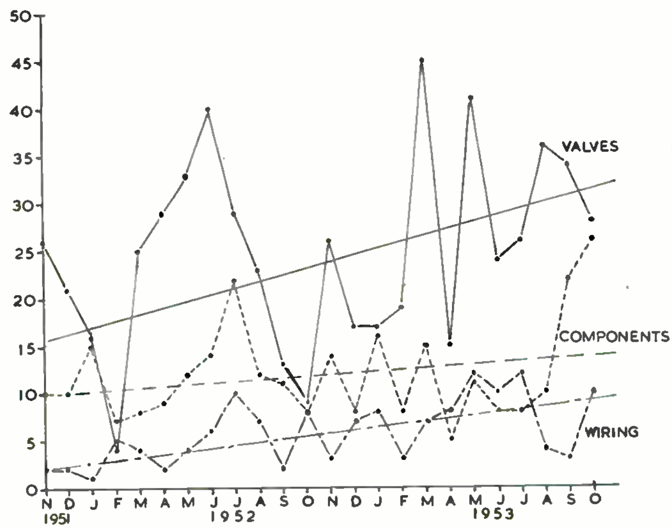

Fig. 1.—Graphs of internal fault incidence, showing rising incidence with age.

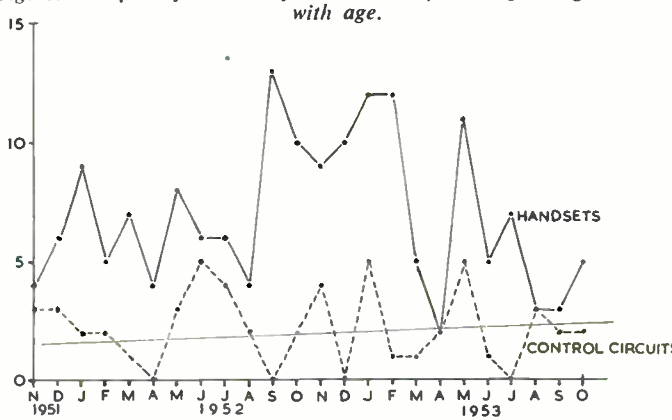

Fig. 2.—Graphs of external fault incidence, showing reduced rise with age.

Examination of the graphs of Fig. 1 proved the presence of the anticipated mean rise of fault incidence with age: this has been calculated approximately for each graph, and drawn in to stress the point.

Similar examination of Fig. 2 proves a slight rise in the graph for Controls, but there is no such rise in the graph of Handsets. The reason for this is not quite clear. The "hump" in the centre of the handset graph is due to the quality of the six-core cable then being used for replacement, and the only explanation which can be offered for the absence of rise is as follows. The handset is the one piece of equipment constantly handled by the operator, and its main failure is in the flexible cable to it, in the form of broken leads. These faults occur quite regularly, and the average is three cable repairs to one cable replacement. It should be seen, therefore, that these cables are being regularly changed, hence the fault incidence will ebb and flow rather than exhibit a mean rise.

To return to the evidence of mean rise of fault incidence with age, a further graph was prepared, in which the data from Table 2 were used. This is presented in Fig. 3, which compares reported faults with the man-hours required to service them, and the mean rise in each graph has been calculated approximately and drawn in. A most interesting graph results, for the mean rise in man-hours is further rising in relation to the mean rise in reported faults. From a two to one ratio at the start, it has risen to more than two and a half to one by the end of the twenty-four months. A higher expenditure of man-hours is anticipated as deteriorating equipment has to be restored to an acceptable standard of efficiency, but it is now shown that in addition to the anticipated mean rise of fault incidence with age, the position is aggravated by this further increase in man-hours per fault, and a further avenue of approach is opened up.

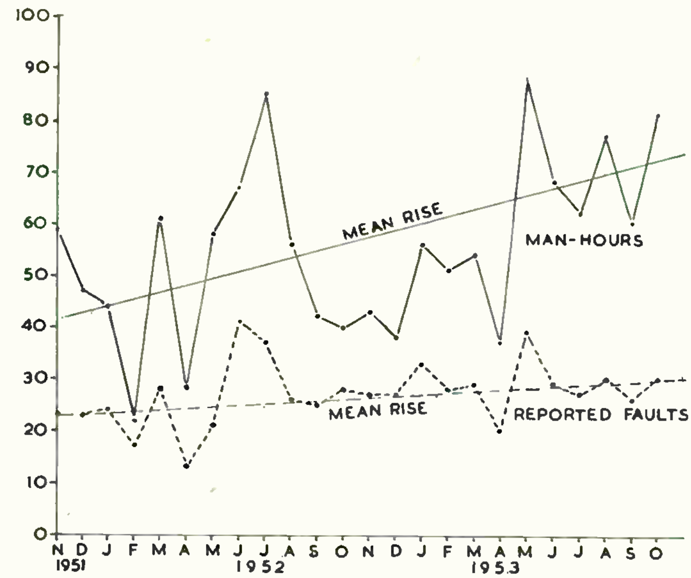

Fig. 3.—Comparison of man-hours with reported faults, showing further rise in man-hours per reported fault.

6. Prediction of Economic Limit

The estimation of the economic life of wireless equipment and the prediction of the time when it will no longer be possible to maintain it due to maintenance costs exceeding income governs the whole policy of a maintenance organization. It is of great importance that it should be estimated as accurately as possible, for the annual depreciation on present equipment as well as the large capital outlay necessary for replacement of the equipment must be related to this economic limit.

To return to Fig. 3, and considering man-hours as the maintenance cost they represent, the mean rise offers a basis for the prediction of a major charge against the organization. Similarly, since the material costs are shown on the job card, the mean rise in the graph can also be calculated. Here then are two of the major factors governing the increase in maintenance costs available for reasonable prediction.

In Fig. 4, the mean rise in labour costs (man-hours) and the mean rise in materials costs (as calculated) have been graphically compared with years of service. On this figure, the income level has been inserted, and a joint graph of combined labour and materials costs (total costs) also exhibited. The position of the gauge points of each graph is due to the fact that the survey began with the end of the first eighteen months of service.

If the "curves" of rising costs are assumed to remain linear, their projection will carry the "curve" of total costs beyond the income level at a predictable time in the future, and the point at which this occurs will obviously be the "economic limit." In this assumption, several

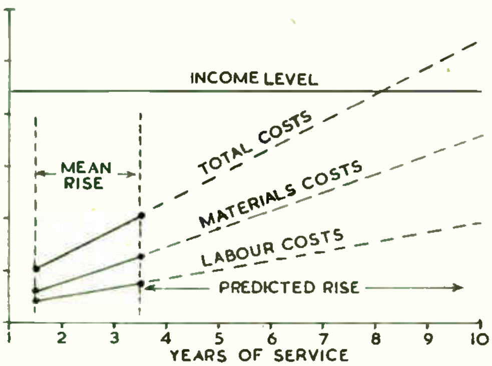

Fig. 4.—Analysis of economic limit by predicted rise in costs.

factors—notably the known trend of generator faults to increase rapidly after about four years of use—which have not been considered suggest that the rise will probably be exponential. Obviously, such factors would have to be taken into account in a serious investigation, but even a simple analysis of the style proposed can determine the economic limit with sufficient accuracy to be of considerable value in future planning. The factors used in such an analysis will vary according to the policy of an organization, consequently a more detailed treatment influenced by personal experience is unnecessary.

7. Conclusion and Acknowledgment

The information in Tables 1 and 2 was extracted with the primary purpose of refuting the adverse criticism of the EF91 type of valve which is mentioned in Section 4, and this analysis by percentage started the train of thought which has resulted in this paper.

It is suggested that the form of Section 2, Basic Analysis, presents remarkably fertile ground for the imagination, and it is recommended as such to others.

The ideas contained in the paper have been treated in very general outline, but the time available for reading the paper made such a course inevitable if even the few suggestions made were to be developed.

It must be stressed that the valves named in the paper represent their type, and the use of a classification peculiar to one manufacturer is merely for convenience.

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