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THE SECOND CLERK MAXWELL MEMORIAL LECTURE*

by

Sir John Cockcroft, K.C.B., C.B.E., F.R.S.†

Delivered on July 8th, 1954, in the Clarendon Laboratory Lecture Theatre, University of Oxford.

The Institution has met a second time to honour the memory of James Clerk Maxwell, the originator of the Electromagnetic Theory of Radiation which dominates the work of this Institution.

Clerk Maxwell was also the founder of the Cambridge School of Experimental Physics and the Cavendish Laboratory, and it is an honour and pleasure for me, a student and teacher in this great Laboratory to pay a tribute to his memory on this occasion. I was Secretary to the Centenary Commemoration of Maxwell held in Cambridge in 1931. During one of the notable addresses given on that occasion, Max Planck said "There are in every science certain exceptional individuals who appear divinely blest and radiate an influence far beyond the borders of their land, and thus directly inspire and expedite the research of the whole world. Amongst these is to be counted James Clerk Maxwell."

The history of Clerk Maxwell's life was described by Professor Howe in the Inaugural Lecture.‡ Much of his earlier life was spent at his father's country estate at Glenlair, in Galloway, and records of this early life survive in the sketchbook of a cousin, Jemina Wedderburn, which is now in the possession of the Wedderburn-Maxwell family.

His first scientific paper, written at the age of 14 in the Edinburgh Academy, was read to the Royal Society of Edinburgh in 1846. After three years at Edinburgh University, the young Clerk Maxwell moved to Cambridge, where he was soon recognised in Trinity College as a scholar of great genius. During this period, at the age of 24, he worked on the theory of colour, and one of the most attractive pictures of Maxwell portrays him with his colour top, which he used to mix primary colours in different proportions to determine the proportions used to produce secondary colours. You do not need to be reminded that the theory of colour is still a live subject and one of great importance in the future of television.

Maxwell's work has played a part in the development of modern colour photography. It was at his Royal Institution Lecture on Colour that he first demonstrated colour photography by the additive process. He photographed a particular subject three times, using three different filters, and he then used the negatives in projectors to give a superimposed picture in natural colour. This is, of course, the basis of the present Dufay system of colour photography.

Maxwell began the study of electricity in 1854. At this time the theory of electricity and magnetism was dominated by the German mathematicians, in particular Gauss, who thought and worked in terms of the potential of electrical charges and magnetic poles and their action at a distance. They made many interesting mathematical discoveries, but these contributed little to our physical understanding.

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† Director, Atomic Energy Research Establishment, Harwell, Berkshire.

U.D.C. No. 061.3 (425.7): 535.13: 92 Clerk Maxwell.

‡ *J. Brit. I.R.E.*, 11, December, 1951, p. 545.

Contemporary with these mathematicians lived Michael Faraday, the discoverer of Electromagnetic Induction. Faraday was no mathematician, but thought in physical concepts. He introduced the idea of lines of electric and magnetic force radiating from electric and magnetic poles. He considered these lines of force to be in a state of tension, and this produced the physical attraction between opposite electrical charges. Clerk Maxwell's combined physical insight and mathematical genius took Faraday's physical concept, translated it into mathematical terms and produced thereby revolutionary advances. He began by interpreting Faraday's lines of force in physical terms and showed that they must lead to basically the same results as the theory based on action at a distance. He went on from there to consider the properties of the space between in a paper published in 1855 on " Physical Lines of Force." He now made use of a mechanical model of the lines of force. (See Fig. 1) The lines of magnetic force were represented by cylinders rotating round the lines as axes, rotating faster as the field strength increased. Since two rough cylinders could not rotate in the same direction, he introduced idling spheres between the cylinders so that they would rotate in opposite direction to the cylinders. With daring intuition he supposed these spheres to represent particles of electricity and their motion an electric current. With this model, when the magnetic field is constant, the cylinders rotate at the same speed and there is no motion of the spheres—there is thus no electric current. But if one cylinder increases in rotational speed corresponding to a changing magnetic field, the sphere will move. The changing magnetic field produces an electric force—which was Faraday's discovery.

But the really interesting new point was that if the spheres are made to move by an external force when the cylinders are at rest, they in turn must rotate. Thus the starting of an electric current should on the model produce a magnetic field.

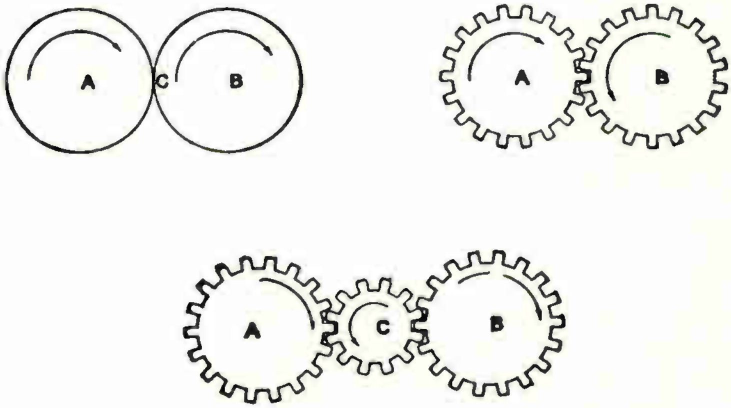


Fig. 1.—Maxwell's mechanical model of the lines of force.

This was Maxwell's great discovery—a discovery which led straight to the Electromagnetic Theory of Radiation. In his next paper, " The Dynamics of the Electric Field," he threw away the model and formulated electromagnetic theory in the now classical Maxwell Equations.

In its simplest form—the language of Vectors, Faraday's discovery—the rate of change of the magnetic field produces an electric force round a circuit which is written :

$$\text{Curl } E = \frac{1}{c} \cdot \frac{\delta H}{\delta t}$$

where c is the ratio of the electromagnetic and electrostatic units of electricity.

Maxwell's complementary discovery that a changing electric field produces a magnetic field whose magneto-motive force is proportional to the rate of change of electric field—the so-called displacement current—is written

$$\text{Curl } H = \frac{1}{c} \cdot \frac{\delta E}{\delta t}$$

From this follows the well-known wave equation

$$\nabla^2 . E = \frac{1}{c^2} \cdot \frac{\delta^2 E}{\delta t^2}$$

An immediate consequence of this equation was that electric and magnetic disturbances are propagated as transverse waves of electric and magnetic forces with a velocity which should be equal to the ratio of the electromagnetic and electrostatic units of electricity. Maxwell measured the ratio of the units by balancing the electromagnetic attraction of two coils with the electrostatic attraction of two discs. In a letter he wrote to Michael Faraday in 1861 he told Faraday that he had determined the velocity of propagation of transverse vibrations by measurement of the ratio of the units and found it to be 193,088 miles per second. This compared with Fizeau's experimental determination of 193,118 miles per second. The two figures agreed to within one part in 6,000, though both were found to be in error by about three per cent. Maxwell soon found this out but was not perturbed, since he knew that the velocity of light was not accurately known.

Many determinations have since been made of the velocity of electromagnetic waves in vacuo based on measurement of the velocity of radio waves in the atmosphere. The recommended value for this velocity is at present 299,793·1 km./sec., which is 17·1 km./sec. higher than the value widely recommended before the war for this fundamental physical constant and about 2 per cent. below Maxwell's value. It is interesting to notice that post-war radar science is enabling a new order of accuracy to be obtained in the experimental measurement of this important constant of classical (and indeed modern) physics.

Maxwell's results were embodied 12 years later, in 1873, in his famous treatise on Electricity and Magnetism, which in my student days was still the Bible of Electromagnetic Theory. Meantime the German mathematicians, Weber, Riemann, Lorenz, Neumann, had modified the potential theory of electricity to make the forces between electrical charges depend on their relative velocity and had also assumed that they did not act instantaneously but after a time depending on distance. In Maxwell's Presidential Address to the British Association in 1870, he referred appreciatively to these theories, but said " The theory of electricity which I prefer denies action at a distance and attributes electrical action to tensions and pressure in an all-pervading medium, these stresses being the same with those familiar to engineers and the medium being identical with that in which light is supposed to be propagated." Both theories had independently arrived at the same numerical result, which gives the velocity of light in terms of electric quantities. Because of rival theories, Maxwell's theory attracted little notice almost to the end of his life, and in Germany, according to Max Planck, it was regarded rather as an interesting curiosity. Only Ludwig Boltzmann studied the theory and verified Maxwell's prediction that the refractive index of light in passing from one medium to another should depend on the square root of the dielectric constant. Boltzmann also tried to make mechanical models to illustrate Maxwell's theory, and once came to Cambridge, after Maxwell's death, to search for the models he felt sure Maxwell had constructed. Even in Maxwell's newly-founded Cavendish Laboratory very little experimental work was carried out to follow up the important predictions of the theory and indeed Sir Richard Glazebrook has told how optical problems were still discussed in the Laboratory in terms of some form of Elastic Solid Theory. Maxwell's contemporaries in Britain did not accept the theory for years and Kelvin seems never to have believed it to the end of his life.

Oliver Lodge was one of the few who were inspired by Maxwell's theory to try to produce electromagnetic waves. He has told how in 1878 he met F. G. Fitzgerald at Dublin and discussed plans for producing and detecting them. In 1883, Fitzgerald calculated on Maxwell's principles the energy lost by radiation from an alternating circular current and showed that it should be proportional to the square of the current and the fourth power of the frequency—he derived in fact the radiation resistance of the circuit. Fitzgerald also read a paper to the British Association " On a method of producing electro-magnetic disturbances of comparatively short-wave length "—wave lengths as short as 10 metres. He did this by utilizing the alternating currents produced when a condenser is discharged through a small resistance. The missing step in the proof of Maxwell's theory was now the detection of the electromagnetic radiation. Fitzgerald, in a letter to J. J. Thomson, congratulating him on his election to the Cavendish Professorship in 1884, told about a receiver he was trying whose period of oscillation was equal to that of the current and which should have " resounded to the vibration " and thereby integrated the energy of a large number of vibrations. This was the idea of resonance.

Fitzgerald did not succeed, but success was achieved by the German physicist Hertz, who was a pupil of Helmholtz, one of the few Continental physicists who supported Maxwell's theory. Hertz showed that the electric waves could be detected by using a wire loop terminated by two spheres very close together (Fig. 2, D, E.). The electromotive force induced by the radiation made a spark between the two spheres, the spark produced in a fraction of the period of the radiation. Hertz used these sparks as a detector and could measure the strength of the radiation by measuring the maximum length of the spark. He showed that electric waves were reflected in the same way as light waves and they could be focused like light, and also showed that they could be made to exhibit interference effects from which the wave length could be determined.

J. J. Thomson in later years described his experience in using this method in the Cavendish Laboratory. He remarked how the younger physicists, with their efficient detectors, would find it hard to realize how difficult these experiments were. In the 1880's he had to observe how the tiny sparks, only a fraction of a millimetre long, waxed or waned when the detector was moved from one position to another, and this proved arduous and harassing.

Oliver Lodge, by 1889, had invented the coherer method of detecting electrical radiations, and this was followed by the iron filing coherer invented by Bramley. This was demonstrated by Oliver Lodge in Oxford in 1894 at the British Association and telegraphic messages were actually transmitted. The age of radio had dawned.

In Cambridge, Rutherford came from New Zealand, and using his own detector of highly magnetized steel needles which were demagnetized by the high-frequency current of the signal, was able to observe signals at a distance of one and half miles from the Cavendish Laboratory. His transmitter consisted of two large metal plates side by side and with two short metal rods protruding from them and ending in polished brass knobs about half an inch apart (Fig. 2, A, B, C.). These were excited by an induction coil so that sparks passed between the knobs and an oscillation was produced.

At the Observatory, one and a half miles away, was Rutherford's receiver, two metal rods in line, each two feet long, having as their receiving ends a coil of fine wire wound round the bundle of fine magnetised steel wires. When the signal came the needles lost the magnetism and this was shown by the deflection of a mirror with a little magnet behind it. This was in 1896. J. J. Thomson, the Director of the Laboratory, was so impressed that he enquired in the City about its commercial development, and Kelvin advised that it was worth spending £100,000, but not more.

In the same year Marconi came over to England with the beginnings of a practical system for wireless telegraphy. Thereafter the development passed from the hand of the physicists to the engineers and a new breed of engineer—the radio engineer—was born.

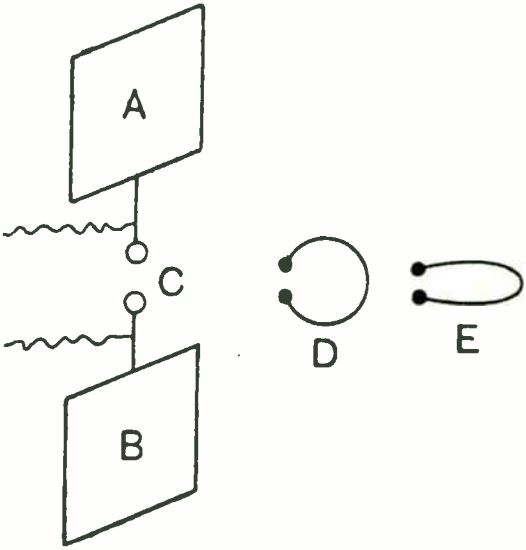


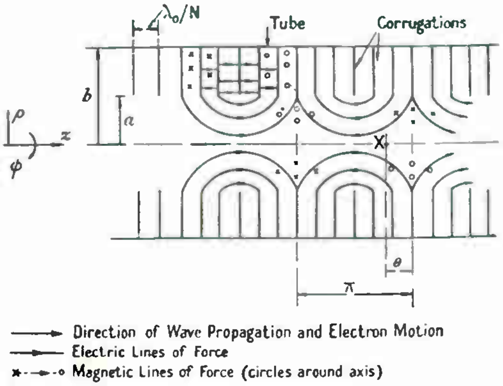
Fig. 2.—Diagrammatic representation of Rutherford's transmitter and Hertz' detector.

Maxwell's successor in the Cavendish Laboratory, Lord Rayleigh, applied his electromagnetic theory to the transmission of electric waves down hollow cylinders. He showed that transverse waves could be transmitted and that there was a lower limit to the frequency which could be transmitted depending on the transverse dimensions of the hollow cylinders. Rayleigh's work lay almost forgotten until the experiments carried out by Southwell and Barrow at the Bell Telephone Laboratory in the 1930's showed their practical importance for transmission of microwave power. For this purpose wave guide transmission has great advantages over transmission by parallel wires, since in the latter case there are greater energy losses in the surface of the conductors and also energy losses in supporting dielectrics. With the advent of large microwave power during the war, the use of wave guides for transmitting power from the magnetron to the antennae became standard practice. The construction of high gain antennae by using slotted wave guides to provide an array of radiating sources also became of great importance.

A post-war application of wave guides has been the electron linear accelerator. The 14-million volt electron linear accelerator which has been built at Harwell by Mullard Ltd. feeds pulses of 10-cm. power from a 2-megawatt magnetron down a rectangular wave guide into a circular wave guide in which a travelling wave is propagated 500 times a second. Diaphragms are introduced to make the velocity of the wave increase as it progresses. The direction of the electronic and magnetic fields in the wave guide are shown in Fig. 3. Electrons are injected into the wave guide at such a time that they surf-ride in front of the crest of the electric wave and are accelerated by the axial field of the wave. They thus acquire a final energy of 14 million volts. The electron current in the pulse is 30 milliamperes, so that the beam power is 420 kilowatts. A remarkably high proportion of the microwave power is thus converted into electron energy. The electrons can then be used to generate X-rays by impinging on a heavy target. We have therefore a very powerful source of radiation. Further developments now envisaged will increase the microwave power supply to 6 megawatts and the radiation will be correspondingly more intense.

Another enthusiastic supporter and follower of Maxwell was that scientific recluse Oliver Heaviside, who is well known to radio engineers not only for his contributions to electromagnetic theory, but also for his prediction of the existence of an ionized layer in the upper atmosphere to explain long-distance propagation of radiowaves. In his Electromagnetic Theory he showed his appreciation of Maxwell in these words :—"Even Cambridge mathematicians deserve justice. I cannot join in any general attack on them. I regret exceedingly not to have had a Cambridge education myself. It is to Cambridge mathematicians that we are indebted for most of the mathematical and physical work done in this country. Are not Thomson and Tait, Maxwell and Rayleigh, Cambridge mathematicians? We must take the good with the bad."

Oliver Heaviside generalized Maxwell's work and in particular developed powerful and elegant operational methods for the solution of practical electrical problems which have been of great value to engineers and physicists in later years.



Fog. 3.—Diagrammatical view of fields in the corrugated tube of a linear accelerator for the case where v = c.

Heaviside applied Maxwell's equation to develop the formula for skin effect in electrical conductors, showing that alternating currents do not penetrate far into a conductor. This is, of course, a major factor in determining the high frequency resistance of conductors.

He also gave for the first time the formula for the mechanical force on an electric charge which is moving in a magnetic field, namely : Force = charge × vector product of velocity and magnetic field.

Following on this came Larmor's discovery in 1896 of the rate of loss of energy by radiation from a charge having an acceleration $\ddot{x}$:—

$$W = \frac{2}{3} \cdot \frac{e^2}{c^3} (\ddot{x})^2$$

and the calculation by Abraham in 1898 of the electrical and magnetic field from an oscillating electrical dipole. Of particular importance to radio transmission are the radiation components of the electric and magnetic fields which, multiplied together, give the flux of energy in a radiation field: $(1/4\pi)(E.H)$. These developments by the immediate followers of Maxwell may be said to have rounded off Classical Electromagnetic Theory. Already, however, a new world of physics was opening through the activities of experimental physicists.

In Cambridge, in 1897, Townsend measured the electrical charge on droplets charged by the newly-discovered Roentgen rays and arrived at a value of 10^{-19} coulombs. The Cavendish Professor, J. J. Thomson, measured the ratio of the charge to mass of the carrier of electricity, and by 1899 had a clear vision of the electron as a particle of much smaller mass than ordinary atoms.

The interaction of the electron with the electromagnetic field was soon incorporated into Electromagnetic Theory—principally by H. A. Lorentz—and theoretical physics entered into a new phase.

One application of the new theory was to show how the velocity of transmission of electromagnetic waves was influenced by the induced vibration of the electrons which in general retard the phase of the wave. An important application of this is to the bending of radio waves and their reflection from the ionosphere which has made long-range wireless transmission possible.

Another application was to the scattering of light waves due to the electrical vibrations induced in dust particles. Lord Rayleigh showed that the scattering from a light beam is proportional to the fourth power of the frequency. This explained the greater transmission of red light in fog. It is responsible for attenuation of radiation of very short radio waves in fog and rain—particularly below 3 cm. wave length. It is also becoming of considerable practical importance in the scattering of radio waves from the troposphere. The turbulence of the medium can be thought of as leading to large-scale scattering centres having dimensions comparable with the new wave length.

By using directional transmitters and receiving antennae, it has already been shown possible to operate teleprinter circuits via troposphere scattering at long ranges, whilst very recent developments suggest that it may even be possible to operate microwave television links over long distances.

At higher frequencies—the frequencies characteristic of vibrations of electrons in atoms—electromagnetic theory has been modified by the introduction of the quantum theory. But there has been an orderly transition from classical theory to quantum theory and at all times the classical theory of Maxwell has been a guide to the extension to sub-atomic phenomena.

I should not close my account of Maxwell's work and influence on physics without referring to his great achievement in the Kinetic Theory of Gases. The middle years of Maxwell's life had seen the foundation of this theory in which the pressure and the heat were attributed to the irregular motion of streams of molecules colliding with each other and the walls of the containing vessel. Maxwell studied by powerful mathematical methods the velocity of individual particles, laying in so doing, the foundation of the science of Statistical Mechanics. He discovered by these methods the famous Maxwellian law of distribution of velocity of molecules in a gas, a law which is identical with the Gaussian distribution of errors.

It is of interest to recall that we employ Maxwell's theory—the kinetic theory—in calculating the sensitivity of so many of our electronic instruments. The limit of sensitivity is decided in these cases by the noise level. There is an irreducible minimum of noise, as is well known, associated with any resistor ; this is the thermal or Johnson noise, which arises from the random thermal motions of the electrons in the resistor. Maxwell's theory gives the well-known formula

$$\overline{V}^2 = 4kTR\mathrm{d}f,$$

where k is Boltzmann's constant, T the absolute temperature, R the value of the resistance concerned, and only the noise-voltage components within a frequency band of width $\mathrm{d}f$ are considered.

Effectively, the same methods can be applied when dealing with the newest electronic component—the transistor. This is particularly important, for example, when considering the design of a transistor amplifier, since the optimum signal-noise ratio is often the main criterion of performance.

An amusing side line of Maxwell's kinetic theory was his invention of the Maxwell Demon. He imagined a gas contained in two compartments separated by a small channel by the side of which sat a " finite being " who opened a trap door to let fast molecules through and closed it when slower molecules came along. In this way the faster molecules would accumulate in one vessel and the slower ones in the other. In this way the second law of thermodynamics would be defeated. This was suggested in a postcard sent to Tait in 1867. The appellation of Demon was conferred by William Thomson, later Lord Kelvin, for there is a subsequent postcard to Tait:

Concerning Demons

1. Who gave them this name? Thomson.
2. What were they by nature? Very small but lively beings, incapable of doing work but able to open and shut holes which were without friction or inertia.
3. What was their chief end? To show that the second law of thermodynamics has only a statistical certainty.

I fear that even the ingenuity of our electronic engineers will not allow them to produce a Demon!

I must finally, in duty bound, pay my tribute to Maxwell's work in founding the School of Experimental Physics in the Cavendish Laboratory in 1871. In his Inaugural Lecture he laid stress on "the experimental method which should first make the senses of the experimentor familiar with the phenomena and then find which of its features are capable of measurement. The history of science shows that even during that phase of her progress in which she devotes herself to improving the accuracy of the numerical measurement of quantities with which she has long been familiar, she is preparing the material for the subjugation of new regions which would have remained unknown if she had been contented with the method of her earlier processes."

This emphasis on the importance of new experimental techniques has been abundantly justified in the later development of science and particularly in the Cavendish Laboratory in my own experience in the late 1920's.

Maxwell also referred in this lecture to the important interaction of mathematics and experimental work. "This combined knowledge is of a more solid, available and enduring kind than that possessed by the mere mathematician or the mere experimentor. New ideas can arise only by wrenching the mind away from the symbols to the objects and from the objects back to the symbols."

He also deplored the growth of a "narrow professional spirit" amongst scientists, and suggested that it was the duty of scientists to preserve their acquaintance with literary and historical studies. So the "undue specialization in Science" with which we are often charged to-day is no new thing.

In this way Maxwell laid down the policy of the Laboratory and this has been followed in a remarkable way ever since by its successive Directors.

Maxwell was evidently a man of great versatility. A Cambridge undergraduate contemporary wrote: "Maxwell as usual showed himself acquainted with every subject on which the conversation turned. I never met a man like him. I do believe there is no subject in which he cannot talk, and talk well too, displaying always the most curious and out-of-the-way information."

He had evidently a great sense of humour, though at Aberdeen he wrote: "No jokes of any kind are understood here. I have not made one for two months and if I feel one coming I should bite my tongue."

He had a great gift for verse writing on every possible occasion. In commentary on Tyndall's address as President of the British Association in 1874, he wrote:

In the very beginnings of science,
the parsons, who managed things then,
Being handy with hammer and chisel, made
gods in the likeness of men;
Till Commerce arose, and at length
some men of exceptional power
Supplanted both demons and gods by
the atoms, which last to this hour.

* * * * *

From nothing comes nothing, they told
us, nought happens by chance, but by fate;
There is nothing but atoms and void,
all else is mere whims out of date!
Then why should a man curry favour
with beings who cannot exist,
To compass some petty promotion in
nebulous kingdoms of mist?

* * * * *

In the world of Science, Maxwell has an enduring reputation. Max Planck said of him:

"It was his task to build and complete the classical theory and in so doing he achieved greatness unequalled. His name stands magnificent on the portal of classical physics and we can say this of him: by his birth James Clerk Maxwell belongs to Edinburgh, by his personality he belongs to Cambridge, by his work he belongs to the whole world."

Your Institution has done well to commemorate his memory.

The British Institution of Radio Engineers

BENEVOLENT FUND

ANNUAL GENERAL MEETING OF SUBSCRIBERS

NOTICE IS HEREBY GIVEN that in accordance with the Rules, the Annual General Meeting of Subscribers to the Institution's Benevolent Fund will be held on WEDNESDAY, OCTOBER 27th, 1954, at 6.45 p.m., at the London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London, W.C.1.

AGENDA

(1) To receive the Income and Expenditure Account and the Balance Sheet of the Benevolent Fund of the British Institution of Radio Engineers for the year ended March 31st, 1954.

(2) To receive the Annual Report of the Trustees.

(3) To elect the Trustees for the year 1954-55.

Rules 5 and 6 state:—

> 5. The Trustees of the Fund shall consist of not more than five and not less than three members of the Institution who have been elected at an Annual General Meeting of subscribers to the Benevolent Fund.
>
> 6. The Trustees shall be elected at an Annual General Meeting by all members who have subscribed to the Fund during the preceding twelve months, ending March 31st in each year, and the Trustees shall hold office until their successors are appointed.

The present Trustees are:—

The President of the Institution.
The Chairman of the General Council.
E. J. Emery (Member).
A. H. Whiteley, M.B.E., (Companion).
G. A. Taylor (Member), (*Honorary Treasurer*).

(4) To elect Honorary Solicitors and Honorary Accountant to the Benevolent Fund.

The Trustees recommend the appointment of:—

Braund & Hill, 6, Gray's Inn Square, London, W.C.1, as Honorary Solicitors.

R. H. Jenkins, F.C A., 42, Bedford Avenue, London, W.C.1, as Honorary Accountant.

(5) Any other business .

By order of the Trustees,
(*Signed*) G. D. CLIFFORD,
(*Honorary Secretary*).

Brit.I.R.E. BENEVOLENT FUND

ANNUAL REPORT OF THE TRUSTEES

In examining the accounts attached to this Report the donations to the Benevolent Fund are of first importance, for the total sum reflects the interest shown by the membership of the Institution in the Fund's activities. It is always, therefore, the first consideration of the Trustees to extend thanks to all who have given their financial support.

A total of 606 members of the Institution contributed to the Fund during the year ended 31st March, 1954, and this compares with 770 members who subscribed in 1953 and 784 who subscribed in 1952. In addition to the contributions of members, Electric and Musical Industries Ltd., and Whiteley Electrical Radio Co. Ltd., again made donations, whilst for the third consecutive year the Committee of the Radio Industries Club of Manchester also gave generously to the Benevolent Fund from the proceeds of their Annual Ball.

A quarter of the total income is now secured as a result of the policy of investment and overall there is a small rise in total revenue received for the year, due to the increase in interest from investments. The main income of the Fund, however, must always be the contributions made by members of the Institution, and it is a great disappointment to the Trustees to report that for the first time since its inception twenty-two years ago, there has been a decrease in donations. Hitherto the Fund has gained increasing support from all grades of members as shown in the following record for the last ten years.

1945	£236	1950	£523
1946	£284	1951	£574
1947	£366	1952	£641
1948	£504	1953	£653
1949	£503	1954	£613

The Trustees do, therefore, make an urgent appeal to every member of the Institution to support the Fund to avoid any possibility of having to sell securities in order to meet any urgent calls that may be made upon the Fund.

It is felt that there cannot be a more satisfactory method of ensuring revenue than to urge once more the advantage of members completing a Deed of Covenant in favour of the Fund. Many members have now adopted this method of a regular, even if small, annual contribution. Not only does this meet the difficulty of the subscriber who intends to donate but forgets to do so, but it has the further very real advantage of enabling the Trustees to recover income tax since, of course, the Fund is recognised by the Inland Revenue as a charity.

The only condition is that the subscriber pays income tax at the full rate on some part of his income. With each annual payment, the subscriber is required to sign a certificate of deduction of income tax; this certificate, known as Form R. 185, is prepared by the Institution, and is sent ready for signature either with the usual reminder, or upon receipt of the subscription.

Signing the Deed does not involve the subscriber in the payment of any additional income tax. The death of the subscriber renders the agreement null and void, and no claim is made against the donor's estate.

A subscription paid under Deed of Covenant is considered to be the net amount remaining after deduction of tax, thus subscribers can, without any extra cost to themselves, greatly increase their donation to the Fund. The following table shows the benefits derived by the Fund when the standard rate of income tax is 9s. in the £.

Annual subscription.			*Income tax recovered by the Fund.*			*Making a total subscription for the year.*		
£	s.	d.	£	s.	d.	£	s.	d.
1	1	0		17	2	1	18	2
2	2	0	1	14	4	3	16	4
5	5	0	4	5	11	9	10	11
10	10	0	8	11	10	19	1	10
21	0	0	17	3	8	38	3	8

In the above examples the subscription actually paid to the Fund by the subscriber is the amount stated in the first column, and this is the net sum which should be inserted in the Deed of Covenant.

Expenditure.—The last Annual Report referred to the purchase of a Reed's School bursary which will enable one child to enter the school and when that child leaves the bursary lapses. The cost

THE BRITISH INSTITUTION OF RADIO ENGINEERS
BENEVOLENT FUND
INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH, 1954

1953 £		£	s.	d.
182	Grants	148	15	10
250	Part Purchase of Bursary at Reeds School	200	0	0
—	Uniforms Reeds School	41	10	0
7	Postage and Stationery	9	16	3
10	Sundry Expenses	5	3	11
342	Balance being Surplus for the year carried to Reserve Account	414	11	5
£791		£819	17	5

1953 £		£	s.	d.
653	Subscriptions and Donations	613	8	11
138	Interest Received (Gross)	206	8	6
£791		£819	17	5

BALANCE SHEET AS AT 31st MARCH, 1954

£		£	s.	d.	£	s.	d.
	RESERVE ACCOUNT						
	Balance, 1st April, 1953	4,342	15	2			
	Add Surplus for Year	414	11	5			
4,343					4,757	6	7
	CURRENT LIABILITIES						
—	Due to General Fund	27	7	1			
400	Sundry Creditor		10	6			
26	Bank Overdraft	—	—	—			
					27	17	7
£4,769					£4,785	4	2

Signed { W. E. MILLER } *Trustees*
G. A. MARRIOTT }
G. A. TAYLOR (*Hon. Treasurer*).
G. D. CLIFFORD (*Hon. Secretary*).

£		£	s.	d.	£	s.	d.
	FIXED ASSETS						
	Investments at cost:						
	£100 3% Savings Bonds 1960/70 ..	100	0	0			
	£100 3% Savings Bonds 1965/75 ..	93	17	3			
	£100 3½% War Loan	104	0	0			
	£600 British Transport 4% Guaranteed Stock 1972/77	597	1	10			
	£3,827 13s. 2d. 4% Consolidated Stock	3,364	6	11			
	£500 5½% Cumulative Preference Shares in Jays & Campbells (Holdings) Limited..	354	2	0			
4,416					4,613	8	0
	(*Market Value as at 31st March*, 1954 £4,951 18s. 4d.)						
	CURRENT ASSETS						
298	Due from General Fund	—	—	—			
55	Income Tax Repayment Claim	157	15	5			
—	Cash at Bank	14	0	9			
					171	16	2
£4,769					£4,785	4	2

I have audited the above written Balance Sheet dated 31st March, 1954, in respect of the Benevolent Fund.

I have received all the information and explanations I have required and in my opinion the Balance Sheet represents the true and accurate state of the Benevolent Fund.

18th August, 1954.
42, Bedford Avenue, London, W.C.1.

R. H. JENKINS, F.C.A., A.S.A.A.,
Honorary Auditor.

of a bursary is now £450: when it is remembered that the cost of maintaining and educating a child is estimated at £210 a year, and that most children remain there for at least five years, it will be seen that it is an excellent idea for the Fund to purchase such bursaries.

Appreciating the small revenue of the Fund, the authorities of Reed's School have been most co-operative in permitting these bursaries to be purchased by stages. The Accounts show that a payment of £150 has been made to complete the purchase of the first bursary and a further payment of £50 was made towards the purchase of a second bursary.

Grants.—The Trustees continued to grant assistance to a number of cases which have been mentioned in previous reports. There has been an additional case of a member of the Institution who, because of a lengthy illness before and subsequent to an operation, had been unable to take any employment for 18 months. A grant was made immediately to enable the member to meet accrued expenses and help is still being given.

One of the cases quoted in the 1952 Annual Report was that of a member who had contracted tuberculosis and who has now had his third operation. The Trustees wish to express their indebtedness to the Electrical Industries Benevolent Association who, on learning of this case, immediately offered to share equally the grant which is still being made from the Institution's Fund. If it had not been for this generous action by the E.I.B.A., the sum expended on grants would have been considerably increased during the year under review.

Members' dependents.—Children of deceased members who were placed in Reed's School by the Trustees are making good progress and in particular, mention must be made of a boy who was admitted to Reed's School five years ago. The boy passed his General Certificate of Education this year and has now left the school for specialized education in his chosen career of architecture. He has received a county education grant and the Trustees have also made a grant towards the boy's maintenance.

In September, 1953, Reed's School accepted another nominee of the Institution—a girl of 11 years, who is the child of a deceased member.

From these notes it will be obvious that the Trustees are very appreciative of the work of Reed's School. It is hoped that the revenue from the Benevolent Fund will enable the Trustees to increase the grants made to Reed's School, apart from the purchase of bursaries, thereby expressing tangible appreciation for the help given by the School in past years when the Trustees could not make very large contributions.

It is known that several members are making direct grants to the School and the Trustees of the Benevolent Fund would be very pleased to send to any interested member particulars of the work of the Boys' and Girls' Schools.

The Royal Wanstead School.—Reed's School is, of course, only able to undertake the care of fatherless children who are at least 11 years of age and who are considered fitted for a secondary grammar school education. In the past, the Trustees have been faced with the difficulty of finding independent boarding schools of charitable foundation able to provide suitable education for the younger child who might subsequently be admitted to Reed's School.

One of the schools catering for children from infancy to the age of 11 years is the Royal Wanstead School which has both primary and secondary schools for girls and boys. Since 1827 Royal Wanstead School has boarded, clothed and educated many thousands of fatherless or motherless children. Mainly as a result of the war the number of children has greatly increased, and the schools now have over 400 boarders.

It is felt that all subscribers will approve of the Trustees' decision to make regular grants to the Royal Wanstead School.

General.—It is the experience of the Trustees that very often the most deserving cases are the most reluctant to apply for help. Local Section Committees and, indeed every member, can do most useful work by always advising the Secretary of any case they know which appears to deserve the help of the Trustees.

Finally the Trustees express their thanks to the Honorary Auditor who has for some years given freely of his advice and help, particularly in the matter of building up the investment assets of the Fund.

APPLICATION OF ELECTRONIC COMPUTERS TO CLERICAL WORK*

by

T. R. Thompson, M.A., B.Sc.†

A paper presented during the Industrial Electronics Convention held in Oxford in July, 1954.

SUMMARY

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.

1. The Nature of Clerical Work and the Suitability of Automatic Calculators

1.1. *The Study of Clerical Techniques*

Most people have some experience of clerical work and the art of keeping clerical records in one form or another does, in fact, go back to early times. In spite of this little or no systematic study of this art was made before the turn of the century. This may have been because, with few exceptions, offices tended to be very small and clerical wages were low so that there was little to be gained by such study.

An American, W. H. Leffingwell, is generally regarded as the pioneer of scientific office management.[1] As an office manager and later as a consultant, he endeavoured from about 1910 to apply to the office the principles of scientific management expounded by F. W. Taylor. In this country the impetus to study the techniques seems to have gathered momentum through the necessity of rationalizing clerical procedures in order effectively to introduce machines into offices; the Office Machinery Users' Association came into existence in 1915 and the Office Management Association, which has perhaps done most in this country to develop the technique of office management, in 1932. Only therefore in the last twenty years has serious attention been given by office managers to the rationalization of office work in its widest sense.

1.2. *The Basic Concepts of Clerical Procedures*

For those unfamiliar with the techniques which are now being more widely applied, it is necessary to explain in some detail the fundamentals of clerical procedures. They are necessarily concerned with information of one kind or another. The basic operations carried out are:—[2]

- (*a*) making initial records of information,
- (*b*) abstracting particular items from a collection of information,
- (*c*) doing arithmetic,
- (*d*) comparing different items of information,
- (*e*) sorting information into a given order,
- (*f*) recording information in a required form,
- (*g*) filing information for future reference, and
- (*h*) communicating information.

The incidence of these fundamental operations in different procedures varies widely, particularly in regard to the amount of arithmetic that is involved. A surprisingly small proportion of the work consists of doing arithmetic, but on the other hand a large proportion of it is concerned with information expressed in numerical form. Because the proportion of arithmetical operations is relatively small this does not mean that an automatic calculator is not a suitable machine for doing it; the greatest value of these calculators, even for mathematical work, is not in carrying out arithmetical operations but in the efficient organization and general manipulation of numbers, that is, in carrying out the last of the basic operations of clerical work—presenting numbers at the time and place that they are required to be used.

A clerical job is, in essence, a procedure carried out on given numerical information—"the data"—to produce the information required—"the results"—and an automatic calculator is thus capable of doing it—theoretically at least. The fact that the procedure carried out may depend on the nature of the data or of intermediate results only makes a calculator more suitable, as another important characteristic

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U.D.C. No. 518.5: 621.37/8: 657.4.

of automatic calculators is their ability to vary the procedure according to circumstances.

1.3. *The Scope for Automatic Calculators in Clerical Work*

Whether or not it is practical or economical to use automatic calculators to do clerical work remains to be considered. There is certainly plenty of scope for economy in clerical effort, for the 1950 Census of Population showed that there are some 2,300,000 people employed in clerical work of various kinds, so that the cost involved in doing clerical work on this counting must therefore be well over a thousand million pounds per annum. Despite the widespread introduction of mechanical aids into the office over the last thirty years or more, the number of clerks is steadily increasing. This seems to be due to the growing complexity of social and industrial organization which has led those responsible for managing affairs to ask for more and more information in order to know what is happening. Whereas in the nineteenth century Management was content to see the overall effect of their policies by reference to the overall accounts of an organization, prepared some time after the end of an operating period, the tendency nowadays is to ask for more and more detail about the factors which have led to the variation in the total figures. This information is required as soon as possible after any event, or even before the event in the form of a budget.

By traditional methods, this leads to the preparation of a great deal of numerical information for Management to peruse. So voluminous do these records become that Management is sometimes at a loss to find time to read them to decide on the necessary action. In the armed services "provisioning" statements are prepared regularly showing the quantity of different items of stores held; these are scrutinized by officers who decide from them the requisition policy to be followed. With an automatic calculator such voluminous statements need not be prepared, for, so long as the criteria on which action may be required can be prescribed in advance, the calculator can be instructed to examine the information as it is prepared and to record it only when a specific action is required. Again, the calculator can, when required, vary or supplement the information recorded. By such means Management can obtain an increasing measure of control by looking at fewer figures.

1.4. *Typical Clerical Procedures*

The clerical procedures carried out in different organizations vary widely in extent and nature according to the nature of the activity carried on, the size of the organization, and the demand by the Management for information. Banks, Insurance Companies, Government and Municipal Offices all need records peculiar to themselves, yet others of their records have much in common with those of large industrial concerns. A rough idea of the nature of these records can be gathered from the following list of records commonly kept by such concerns.[3] A more detailed understanding of how these records are used may be gathered by reference to various publications to which references are given.

(*a*) Records of cash received, paid, and held.[2, 4]
(*b*) Records relating to employees and their remuneration.[2, 4, 5]
(*c*) Records of goods and services obtained from suppliers, amounts paid and owing to them.[2, 4, 5]
(*d*) Records of materials held in stock and consumed for various purposes.[4, 5, 6]
(*e*) Records of goods (and services) ordered by customers and despatched to them, of amounts owing and paid by them, and analyses of sales under commodities and types of customer.[2, 4, 5]
(*f*) Records of factory production plans, progress, and achievement, together with materials, labour, etc., employed.[7, 8]
(*g*) Estimates of the cost of manufacturing individual items, and budgets of costs and sales.[8, 9]
(*h*) Records of rent paid, received, or due, and of associated matters.[10]
(*i*) Records of insurance covers, of premiums paid and due, and of claims made.
(*j*) Financial accounts and similar records required by law.[10]
(*k*) Records of holders of stocks and shares in the concern, of transfers made, and of dividends paid,[10, 11]

1.5. *Inter-relationship of Procedures*

It is a moot point where a given procedure ends and another begins. With the expansion of businesses and consequent increase in the size of offices, there has been a tendency for different aspects of clerical work to be dealt with by specialist groups. For instance, in dealing with sales orders, there might be separate groups dealing with:—

(*a*) packing and despatching records,
(*b*) invoicing,
(*c*) sales ledgers,
(*d*) sales analysis.

Procedures therefore are often broken up into a series of smaller procedures which necessitate the passing of information from one group dealing with a particular aspect to a second dealing with another. This involves the recording, reading, and handling of intermediate numbers whose only function is to serve as data for a subsequent procedure. With highly mechanized systems using punched cards a considerable amount of labour is involved in passing cards from one machine to another, and sorting operations are often necessary between one stage of the procedure and another.

One may regard an automatic calculator as a single super-human clerk able to carry out a complete clerical procedure, reading data as he requires it, mentally carrying out the arithmetic and logical processes involved, and writing down only those results to be used by someone outside the office. This viewpoint is, however, an idealized one for the whole of the procedures of an office are inter-related directly or indirectly; to encompass them all in one gigantic job would make it quite unmanageable; nor would it be economic to build a calculator large enough for the purpose. Nevertheless the greater the scope of any single job the better, for once data has been taken into a calculator there need be no restriction on the processes to be carried out or on the results to be derived, provided the storage space is available for the numbers and the necessary programmes of instructions.

2. Characteristics of Clerical Procedures in relation to Automatic Calculators

2.1. *Calculations Occurring in Groups*

The result numbers produced during most clerical jobs fall into natural groups. For instance, in sales invoicing, the invoice for each customer can be regarded as containing a separate group of result numbers. Similarly, with the payroll, the payslip for any employee contains a group of result numbers.

Each group of result numbers is produced by a given set of calculations, using a related batch of data numbers. The fact that procedures can be divided in this way can be exploited with advantage when using an automatic calculator. Before any burst of calculations takes place the batch of data specifically required for it can be fed in and as soon as the calculations are finished the results relating to it can be recorded. The batch of data for the next burst of calculations can now be fed into the storage compartments of the calculator previously used for holding the first batch of data and the results as they are produced can be stored in the compartments used for holding the first group of results.

Not all the data is, of course, specific to a burst of calculations; some of it may be common to all or very many of the calculations and must therefore be fed in before the first set of calculations takes place and held throughout the job. Thus in sales invoicing the price of any commodity may be required as data in order to work out any one invoice, so a table of prices for all commodities must be fed in before starting on the first invoice.

Similarly some results may not be related to any particular set of calculations, but to all or to a large part of them. In sales invoicing totals of invoices for all customers in different areas and for the whole country may be required; to do this, running totals must be maintained by adding, as part of the procedure for any invoice, the total of that invoice to any required totals to date.

2.2. *Results Required*

The results required of any clerical procedure may be used for a variety of separate purposes and the form of statement most suitable for one purpose may not be suitable for another. Thus, if one is considering the preparation of sales invoices, one type of statement will be required for the customer to show him the goods supplied and their cost, but quite a different statement will be required by the sales manager to show the total quantity of each commodity sold to each type of customer. Each result must therefore be prepared in a form that suits its particular purpose and the different numbers that form the result must be set out on it in appropriate relation to one another. Some of the results may be needed only as data for a subsequent clerical job, either the same one in a subsequent week, as occurs in the carrying forward of the gross pay earned to date in the preparation of the payroll, or in quite a different job in the same week. For instance, a clerical procedure concerned with piece-work calculation may be required to produce:

(*a*) the piece-work wages for individual employees to be used for the payroll, and (*b*) the labour costs to be used in working out the costs of different factory processes.

Such results produced solely for the purpose of being used in another clerical job are called "carried forward" results, to distinguish them from "printed" results which must be produced in conventional form for use outside the office.

Because of this variety of results from any one procedure required for different purposes, whether carry forward or printed, an automatic calculator which is to produce these results must, to be effective, have more than one channel whereby it can record the results.

The volume of results produced in clerical procedures is, of course, very great in relation to the amount of calculation as compared with the volume of results for most types of mathematical or scientific jobs. Since the recording of results is essentially a mechanical operation of one sort or another, the speed of recording must be many times slower than the electronic operations within the machine, so that an automatic calculator to be effective for this kind of work, must have facilities whereby it can send out a group of result numbers at electronic speeds and then, while these results are being recorded at mechanical speeds, carry on with the calculations on the next batch of data and so not have to wait while the recording takes place.

2.3. *Data Used*

The data is usually of several kinds coming from different sources. For payroll, hours worked may come from the factory foreman, changes in rates of pay from the personnel department, and pay and tax-to-date from last week. Data which comes from another clerical job are termed "brought forward data". Some data, such as rates of pay and prices of commodities, remains constant over a considerable period and is therefore called "permanent data". Provision must, however, be made for revising it at any time; data giving such revisions is called "amendment data". Finally there is data which applies only to the current run and which originates outside the office, such as orders placed by a customer or hours worked by an employee. This type of data is called "current data". There may be brought forward or current data from more than one source, e.g. for payroll there may be piece-work wages from a factory labour control job, and total wages and tax-to-date from the payroll last week, or on stores control a goods-received docket from the goods-in-dock and requisitions from using departments.

It is not always convenient or even possible to intermingle the documents containing data from different sources. Because of this an automatic calculator, to be effective on clerical work, must have more than one channel whereby data may be fed into it.

The volume of data used in clerical procedures is even greater in relation to the amount of calculation than are the results. Again since the means of reading data must involve mechanical operations, the automatic calculator must have facilities whereby it can read a batch of data in advance of the time when the calculator is ready to start the calculations on the batch.

2.4. *The Calculations and Organization*

The calculations involved in carrying out a single step of a clerical procedure are usually very simple as compared with those met in mathematical work, but there is no difference in the elemental arithmetic operations required. The arithmetic facilities provided in general purpose calculators do equally well for clerical as for mathematical work. On the other hand there are usually greater complications in the organization of clerical procedures than in mathematical ones. This may seem surprising but the reason is not far to seek. Mathematical requirements must essentially be rational, but commercial requirements are not. They arise partly from Acts of Parliament and Ministry Orders, partly from commercial custom, sometimes from the whims of Directors and Managers, but most of all from the diversity of human needs and complexity of society. A payroll is a good example of this: P.A.Y.E. tax is normally calculated on the tax to date, but it may in certain cases have to be calculated for the current week alone; there are usually diverse factors to take into consideration in calculating sick pay; and there are numerous purposes for which it may be required to make deductions from the gross pay and equally numerous ways in which the amount deducted may have to be accounted for.

2.5. *Variations in Procedure and Exceptions*

Clerical work to be effective must provide for all variations in procedure that may be required and for all exceptions that may arise in the figures. The procedures consequently become correspondingly lengthy and complicated. Mathematical procedures can often be reduced to a relatively few iterative processes repeated many times a second. Clerical procedures lend themselves much less to this treatment, though iterative processes can often be used; dealing with one batch of data after another is itself an iterative process.

2.6. *The Speed of Producing Results*

There is one final requirement of clerical work which distinguishes it from mathematical work—the speed with which the results are often required: employees must have their pay on time; orders must be executed without delay; managers want to have their figures as soon as possible. Doing clerical work by automatic calculator means that, on the one hand, results can be produced faster than ever before but, on the other, the dependability required of the calculator must be very much greater than is necessary for mathematical work.

3. Circumstances in which Clerical Work can with advantage be done by Automatic Calculator

The calculator can only deal with procedures where it is possible to prescribe in advance all the possible circumstances that may be encountered. It does not necessarily mean that it must be possible to prescribe the exact procedure in every case; if particular exceptions are rare it will be sufficient if the procedure is simply to print out the circumstances and to leave the precise procedure to some scrutiny clerk.

It should be made clear that an automatic calculator is quite useless for carrying out small *ad hoc* calculations that may be required at short notice. It has sometimes been suggested that any clerk within an office might be able to feed a central automatic calculator with a calculation and get the answer back almost at once. This seems to be quite an impractical proposition and must almost certainly be an uneconomic one. Nor could it be economic to have the calculator carrying out occasional clerical procedures which are required from time to time but which are not repeated very often. It must be realised that to programme clerical procedures costs at least hundreds, and often thousands, of pounds. Therefore, unless the jobs cost hundreds or thousands of pounds over a period by traditional means, it is not worth while making a programme to do them by an automatic calculator. By the same token it is not worth while programming jobs which, by traditional methods, take say only an hour or two each week, for the calculator would take only a minute or two and it could hardly be worth while putting the job on to it.

It is where there is a large volume of work to be carried out, using the same procedure over and over again, that the automatic calculator comes into its own and it is naturally only in the larger organizations that this occurs. In time to come it may, of course, be possible to use a calculator to carry out the same procedure, as for instance the payroll, for a series of different concerns; but this is not likely to take place until calculators are more commonplace.

Briefly, it may be said that the automatic calculator is suitable for carrying out clerical procedures involving a sufficient number of different operations provided that:—

(i) the operations can be prescribed in a high percentage of cases;
(ii) all the possible exceptional circumstances that may occur may be laid down in advance;
(iii) there is a sufficient volume of data that can be assembled ready at any one time to justify putting on the calculator, and
(iv) the job is sufficiently repetitive to justify the preparation of the programme.

4. Fundamental Requirements of an Automatic Calculator and its Auxiliary Equipment

4.1. *Dependability*

The calculator must not be out of action for more than an hour or so during any working day and it must not break down often during operation, say on average not more than once a day. Only then will it be possible to work to a tight schedule.

4.2. *Store*

There must be a store to which access is possible in a time comparable with that of the arithmetic operations.

The store must be capable of holding at least:—

(*a*) The programme of orders for the main procedure;
(*b*) additional orders for subsidiary procedures or variations of the main procedure;
(*c*) common data numbers required throughout the whole or a substantial part of the job;
(*d*) numbers from all sources forming data for a single batch of calculations;
(*e*) intermediate numbers produced during the course of the calculations;
(*f*) numbers representing results for a single batch of calculations;

(*g*) numbers representing results for the job as a whole—running totals and the like.

There may be hundreds of items of each of these kinds so the total capacity of store required may run into thousands of compartments. Precisely how many there should be depends to some extent on the nature of the work to be carried out, and to a great extent on whether there is an auxiliary store of even greater capacity to which access can be obtained more slowly. A main (high speed) store of 2,000 or more compartments is very desirable, but with an auxiliary store it is possible, though not very convenient, to do with less. The greater the capacity of the store, both main and auxiliary, the lengthier are the procedures that can be carried out and, other things being equal, the more economically the work can be carried out. Once the data is in the machine the more results that can be produced from it the better, provided the extension of it does not involve taking in a disproportionate amount of additional data.

The particular method used for storing information is, of itself, immaterial so long as it meets the requirements. Above all it must be completely reliable, for in doing clerical jobs the programme and other information has to remain in the store for long periods at a time and it is essential that it should not be subject to corruption.

The second important requirement is that of accessibility. If full use is to be made of the electronic speeds of calculation it is important that there should not be too much delay in waiting for information to be got from the store. The average time of getting information from the main store should not be more than a fraction of a millisecond and the average time from the auxiliary store should not be more than a few milliseconds.

Finally, because the amount of storage capacity required in a calculator to do clerical work is so great, the equipment used for storage forms a high proportion of the total for the calculator and therefore must be as inexpensive as is possible consistent with the other requirements.

4.3. *Input*

It must be possible to put data into the calculator by a number of independent channels, each of which must be capable of reading data simultaneously with the others; they must also be able to read independently of the operations inside the calculator so that batches of data can be read in advance of the actual needs of the calculator. At least three channels are required. The speed of reading that is required naturally depends on the nature of the job; 25 "words" a second is a modest minimum but 200 words a second would sometimes be very useful.

The particular medium from which the data is read is not of itself important and it is a convenience for different channels to be able to read from different sorts of media. Punched tape, punched cards, magnetic tape, magnetic wire, and film may all be acceptable media in the right circumstances. Again reliability is paramount and it is desirable that there should be a means whereby, by means of some control total or other figure, a check can be made that the data taken into the calculator does correspond with that which was presented to it.

Most if not all jobs have some brought forward data and very often it is convenient to feed this into the calculator in a different order from that in which it was prepared in the previous job. It is desirable, therefore, that one channel at least should use a medium which is capable of being rearranged into the required order before it is fed in. Punched cards are, of course, a valuable medium of this sort.

Many jobs require a large permanent storage, as for example posting accounts to ledger records, keeping group pension records, and in fact any procedure which involves a large number of records relating to a large group of people. Quick access is required but may be difficult to obtain without pre-selection and sorting of information.

4.4. *Output*

Again, so that the calculator shall not have to wait while mechanical operations take place, it must be possible to send out the results from the calculator along a series of independent channels working independently of each other and of the calculations going on inside the calculator.

At least two channels are required; one of these must be a high speed printer capable of printing a line of information at a time. This is necessary because it is important to be able to scrutinize the results of the calculations made at the earliest possible moment. Because the operator is blind to what is happening inside the calculator, at least so long as it is still working, any system of recording which involves printing off subsequently to see results of calculations makes the job completely unreal from the operator's point of view. Experience gained of operating with and without a direct printer has shown how great is the added confidence given to the operator when he can see results being printed as they are produced.

The speed at which results can be printed is a very important factor. The minimum speed required is one or two lines (of 70 to 100 characters) a second; up to 20 lines a second would be very useful for some jobs.

There must also be an output channel suitable for recording carried forward results, preferably in binary form. Punched cards or magnetic tape or wire are all possibilities, but punched cards have the advantage that the information can be sorted into a required order before the brought forward data is fed in; a rate of recording of 15 words a second is usually necessary but 100 words a second is sometimes desirable.

It is also important that there should be an output channel which can record subsidiary printed results. During the course of most clerical jobs statements are required on forms which can be conveniently pre-printed. In addition there is likely to be information of a different character which requires to be printed from time to time throughout the job. It is not convenient to print this additional information directly on the pre-printed forms, and to have a separate printer working in parallel at infrequent intervals would not be economic. It is desirable, therefore, that there should be a method of recording information on some other medium which can be fed subsequently to a reading device attached to a printer. In payroll, for instance, payslips can be printed on pre-printed forms by the main printer, and subsidiary statements of totals, exceptions and the like, punched into cards which can be printed later by means of a cheaper sort of printer. It may be convenient to send out these subsidiary printed results along the same output channel as the carried forward results, e.g. by punching cards intermingled with carried forward cards, the two sorts of results being separated by sorter afterwards, the cards containing results to be printed being fed to a card reader linked with a teleprinter or an electric typewriter.

4.5. *Arithmetic Unit*

Fundamentally there are no arithmetical requirements for a calculator to do clerical work which are not provided by one designed to do mathematical work[12, 13]. Some of the more mathematical operations, such as, say, extracting square-roots, are not relevant to clerical work. On the other hand, because certain combinations of arithmetic operations occur quite often in clerical work (although not so much in mathematical work) it is of some advantage to be able to carry out the combination of operations in response to a single instruction. A particular example relates to the accumulation of running totals which occurs very frequently in clerical work; it is possible by a single operation to take a running total from its compartment of the store, augment it by a new contribution, and put the revised total back into the store to replace the old one.

The speed of arithmetic operations is not a paramount factor in machines to be used for clerical work since there is a smaller proportion of arithmetic operations than in mathematical work. There is, therefore, little to gain by introducing the extra complication of parallel circuits in order to do such operations as multiplication more quickly.

4.6. *Overall Concept of the Calculator*

The relationship between the fundamental parts of an automatic calculator intended for clerical work is depicted in Fig. 1. The operations carried out between the parts are of three main kinds:

1. Input operations, involving putting into the main store data from one of the input reading devices, or from the auxiliary store.
2. Arithmetic operations, involving also transfers from the main store to the arithmetic unit and back again.
3. Output operations, involving sending out information from the main store to the auxiliary store, the printer, and other recording equipment.

The control mechanisms required to effect these are similar to those described for other machines.[14] The programme of orders to be carried out is held in the main store and a control unit is caused to extract the orders one at a time in a specified sequence. Each order is interpreted in the control mechanism and thereby gives rise to changes in electrical voltage applied to a series of gates which permit the flow of information along the required path. At any point in the sequence of orders a "sequence-changing" order can be inserted in order to switch to an earlier or later point in the sequence.

4.7. *Preparing Current Data for feeding to the Calculator*

Since current data originates outside the office, it is normally prepared in a conventionally written form which cannot be fed automatically into the calculator. Under these circumstances, the first step on receiving it is to transcribe it into a form that can be read automatically, as for instance into punched tape, punched cards, or magnetic tape, and it must then be carefully checked. The cost of transcribing and checking the large volume of data needed to keep an automatic calculator fully occupied is, of course, considerable and, in addition, the very fact that the transcription has to take place introduces another possibility of error. It is therefore most desirable for the initial form of data to be one that can be read automatically.

Where it is economic to have a machine to make the record, the information can be recorded in the form of punched holes, say, as well as in conventional form. Sometimes it may be possible to take information over the telephone and punch it straight into a card. But these circumstances are in a minority and in the great majority of cases recording has to be written by someone in circumstances which do not permit anything but a very simple form of record to be used. This would apply to salesmen taking orders, to customers themselves, and to waiters in restaurants. The form of record required need not be one which can be sensed rapidly; the documents containing data must almost certainly be sorted and scrutinized after they have been received in the office and while the scrutiny is taking place they can conveniently be fed to a special machine which senses them and creates an intermediate record suitable for feeding to an automatic calculator.

Mark-sensing is an example of recording in this way, though it has only limited application.

5. Experience gained from operating LEO

The main features of LEO have recently been described[15] so no attempt will be made to give technical details here. The main arithmetic, storage, and control circuits of LEO have been operating effectively since the summer of 1951 but the high speed input and output arrangements were not satisfactorily completed till the end of 1953. In the meantime, however, it was possible to do mathematical work and to experiment with clerical work using slow speed input and output channels; in fact one job, a cost-accounting job, was done regularly every Friday from October 1951 onwards. The use of the calculator on mathematical work and on experimental clerical jobs enabled much invaluable and varied experience to be gained.

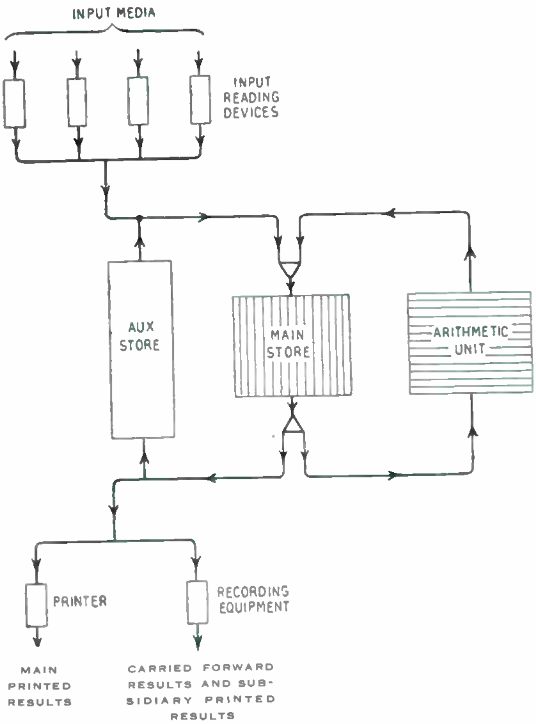

Fig. 1.—Basic layout of LEO (Lyons Electronic Office)

First ample assurance was given that the calculator could be relied upon to give accurate results. Errors did occur, of course, but almost invariably they were obvious ones. The errors most difficult to detect were those resulting in corruption of the results during the last stages, particularly those due to a mechanical fault in the recording mechanism. The number of errors other than patent ones was, in fact, far fewer than the errors occurring in clerical work which has been checked. For instance, for the first three weeks of the cost-accounting job referred to, the job was also done by ordinary clerical means and checked. Each of a number of differences was investigated and, in each of the three weeks, all were found to be due to errors in the ordinary clerical work. After the third week the office ceased to check work done by LEO and has not done so since.

The programmers gained experience too in devising the programmes so that the operations should as far as possible be self-checking and so that when an error was revealed by the operation of the programme, an indication was given as to what had gone wrong.

It was also found that much could be done to minimize wasted time when a fault occurred during the course of a long job. The programme was planned so that from time to time in the course of the job, records were made of intermediate totals, etc., and so that after a fault had been put right the calculator could be restarted from the point where the last intermediate totals had been recorded.

During this period the greatest experience of all was in developing fault-finding techniques. Initially the faults to be found were due to errors in design or construction or to defective components, e.g. dry joints and short circuits in components. There then came a stage when the calculator would always do its test programmes but failed occasionally during particular jobs. These faults were found to be due to the occurrence of special pulse patterns or the timing of certain waveforms and were due to weaknesses in design which had not made provision for these circumstances. To detect faults of this kind it was clearly necessary to improve on the test programmes which in the first place were based on those used for EDSAC. New test programmes were devised which incorporated the most stringent aspects of operational programmes and which used a variety of test numbers with pulse patterns that were known to be critical.

The next phase in fault-finding was one in which the predominant type of fault was due to a drift in the characteristics of components, particularly of valves. When the morning tests were made the calculator would appear to be in order, yet faults would start to occur during the day due to changes in components. The only way to overcome this was to ensure that when the morning tests were made there was a sufficient margin of operation. This was done by carrying out the tests with an alternating voltage injected into the circuits at any or all of a number of points. The magnitude of the voltage which can be applied before the tests fail is a good measure of the margin of operation that is enjoyed at any point in the circuits. A more detailed explanation of this system (and of the maintenance and operation of LEO generally) is to be published shortly.[16] Since this arrangement has been adopted faults due to a drift in characteristics of components have seldom occurred during operation and then only with circuits to which marginal testing had not been applied.

The types of fault which now cause most difficulty are:—

(*a*) Intermittent inter-electrode shorts in valves.

Any kind of intermittent fault is a difficult one to overcome because hours may be spent on testing without the fault occurring once and, unless one can deduce from the phenomena that occur which particular circuit gives rise to the fault, it is often very difficult to induce the fault to occur frequently. When the faulty circuit is suspected vibration of the chassis near the circuit usually shows where the faulty valve is.

(*b*) Mechanical faults in the input and output mechanisms.

The difficulty here is to get any warning that the wear and tear of mechanical parts is reaching the stage when it can endanger successful operation. When a breakdown does occur, it takes much longer to dismantle the faulty mechanism, put in a spare, and reassemble the unit than it does to cure an electronic fault, and it is difficult to have spares of every conceivable mechanical part of the equipment. For this reason, complete spare units of the input and output equipment are being introduced which can be switched into service instantly.

Catastrophic breakdowns of components inevitably occur but not more than once or twice a week during operation. When they do they are easily detected and replaced.

The experience of operation while the high speed input and output arrangements were being developed did thus enable the calculator to be brought to a degree of dependability which allowed clerical work to be done to a schedule.

Experience has been gained in designing forms on which current data can be entered in the first place by people with no special training and which are so designed that the operators who transcribe them can readily put in the necessary separation characters without pausing. The keyboard of the perforator used to punch the tape has been rearranged so that the operator can "touch-type" with the right hand leaving her left hand free to move the manuscript containing the data and her eyes to read it. A manual of training has been built up so that young girls not long out of school can be trained in a few weeks to attain a speed of 3 characters a second.

Very particular attention has been paid to checking. A tape checking device has been designed and built so that the tape perforated by the first operator can be used as a control to check another tape prepared by a second operator. A printed proof slip is produced highlighting any variations made by the second operator in correction of the first. This apparatus is shortly to be described.[17]

A great deal was learnt also about operating the calculator itself. Once a job is fully operational it is put on the calculator by one senior and one junior. The latter is concerned with loading the programme cards, and data tapes and cards, and with removing punched cards and printed result sheets according to a prescribed routine, and need have no knowledge of what the calculator is doing. Senior operators, selected from ordinary office personnel, are given an elementary introduction to programming but take no part in preparing programmes for jobs. The senior operator is provided with a manual about the job he is about to put on the calculator so that he knows precisely what goes on inside it, where the programme orders and the data and result numbers are stored, and what checks are provided; he knows too the specific indication for the failure of each different check. In these ways the senior operator can control operation with confidence despite the spate of results that is produced.

Introducing a calculator into the office does not end with the operational procedure. Office managers and others who are responsible for providing the data and for using the results must feel that they can safely make use of it. Office managers are used to making plans for a group of clerks to do jobs and waiting on them for the completed figures, but when an automatic calculator takes the place of the clerks they will not at first have the same confidence that the machine will do what has been planned for it. Steps have been taken to explain to all concerned how a job is done by LEO and what they can expect from it. Summaries with reconciliation accounts and exception slips give all information necessary to those who are responsible for the figures. When managers see that the machine really produces what has been planned they quickly accept it as a tool of the office. Even the auditors can be satisfied.

By the time the high speed input and output arrangements were complete, plans for operating were fully laid. For input there are three separate channels; two are for punched tape read by Ferranti tape readers and the other for punched cards read by a Hollerith card feed. It is also possible to switch one channel from tape to cards, to provide two input channels for cards and one for tape. There are two output channels, one linked to a modified Hollerith tabulator printing at 85 lines per minute and the other to a Hollerith gang punch. As had been planned, data is made available to the calculator in such a way that it can start calculations on the new batch as soon as those on the old are finished. In the meantime the results of the calculations on the old batch are concurrently being printed or punched. The tabulator is not in fact usually quite able to complete the printed results before the next set of results is ready. The waiting time of the calculator is, however, only a relatively small percentage of the calculating time and faster tabulators will be available in due course. The equipment is set out on an operational floor around a control desk. The layout of the equipment was planned on the basis of experience of experimental operation.

Once the high speed input and output equipment was in position it was immediately possible to start transferring clerical work on to the calculator. One of the first jobs was the payroll with all associated records for 1,700 employees. For the first few weeks the work was done in parallel by the Wages Office but, since the beginning of February, LEO has week by week been solely responsible for the job which has been and is being expanded progressively to cover more employees. Experience with this and other jobs confirms the belief that it is both practical and economic to do large scale clerical work by means of an automatic calculator, though naturally it is appreciated that there are many ways in which it may be possible to improve calculators to be used for this purpose.

A much closer understanding of the costs involved and the savings to be made has been gained than could possibly have been obtained without using a calculator in this way. We should not wish to be too precise in our estimates but, on the basis of jobs done so far, LEO working about 60 hours per week can be expected to do the work of up to 400 clerks. To keep it fed with current data may require 40 operators and checkers and there would need to be about 10 people to supervise and control the work and to operate the calculator. A team of three or four maintenance engineers is provided for a single shift, but if there were no development work to be done they would not very often be busy. One engineer can readily carry out the routine morning tests; the others are only called upon when a fault occurs. The cost of testing and replacing valves and components is around £1,500 per annum. Stationery and other costs are lower than for ordinary clerical work.

A modest estimate of the saving in running costs of clerical work might therefore be expected to reach £50,000 per annum. From this must come depreciation of the capital cost of the calculator, which is, of course, the main item of cost. Calculators with the facilities for speed, quick access storage, and multiple high speed input and output channels to meet the requirements specified, tend to cost at present of the order of £100,000. It is expected, however, that improvement in manufacturing techniques and simplification of design will quickly lead to a reduction in the cost.

Finally the cost of reorganizing the clerical work and preparing the programmes must not be forgotten. So far only 6 or 7 programmers have been used for both clerical and mathematical work. The cost of actually preparing a programme for a clerical job must be measured in hundreds of pounds, but in preparing a clerical job for LEO the greatest cost is in clarifying the requirements and in making the necessary rearrangements in the office proper.

6. Problems remaining to be solved

Although it has already been possible to demonstrate that clerical work can under certain circumstances be done effectively and economically by means of automatic calculators, this does not mean that the way is now clear for their general introduction into all large offices. A useful start has, however, been made and the main lines along which improvement is needed can now be stated. These are:—

(*a*) *A cheaper form of main store.* Since the cost of a main store with a capacity of some thousands of words and an access time of a fraction of a millisecond represents a large proportion of the cost of the whole machine, a means of providing the store cheaply is of the utmost importance; to reduce the cost by reducing the size of the store limits greatly the scope of job that can be carried out as a single entity and to do so by increasing the access time significantly diminishes the productivity of the whole machine.

(*b*) *More compact construction.* Present automatic electronic calculators with a quick access store of the size envisaged throughout this paper are, by comparison with other office machinery, very bulky. This has been so partly because of the amount of heat generated by valves and partly because of the present need for access to the components for servicing. Technical improvements are, however, tending to reduce the size, and once transistors with consistent characteristics can be manufactured cheaply and the design of circuits to use them has been more fully explored, much more compact calculators should be possible.

(*c*) *More dependable valves or their equivalent.* Valves have been shown to be the most unreliable element in calculators, particularly as regards inter-electrode shorts. A significant improvement in reliability during their effective life would greatly facilitate the maintenance and improve the dependability of calculators. Transistors may provide an answer to this problem.

(*d*) *Simpler and more reliable input and output mechanisms.* Whatever the difficulties in maintaining electronic equipment, the problem of keeping the mechanical parts of input and output equipment in full working order is greater. The simpler this equipment can be made the better. The Ferranti tape reader is a case in point: the mechanically operated parts are reduced to a minimum and their operation controlled by an electronic servo-system; as a result the dependability is of the highest order. It is to be hoped that other mechanical equipment will be designed to feed calculators and to record their results, making use of simple mechanisms under full electronic control.

(*e*) *Faster printers.* The direct printing of results is at present the most serious bottleneck. There are printers about to be marketed which are designed to print at the rate of 15 lines per second and if they prove to be reliable this bottleneck will have been removed.

(*f*) *A cheap method of long term storage.* Many clerical systems need to have a large volume of records. The most outstanding instance is afforded by the National Insurance records at Newcastle, where a record is kept possibly amounting to 200 bits of information per insurable person of the population. To hold the records for the whole country a store would need a capacity of the order of 10^{10} bits, though naturally it could conveniently be divided into more manageable sections by dividing the records alphabetically or otherwise. A study group of the Electronics Division of the National Physical Laboratory is at present engaged on this problem. Punched cards could conceivably be used, but in such quantities they would be cumbersome and access would be slow unless an expensive sorting and selection process were carried out each time they were used.

Reels of magnetic tape or photographic film are both possibilities. In some ways the use of film is more convenient, but it has the difficulty that it is not easy to amend the information on the record. On the other hand, the very ease of amending magnetic tape gives rise to possible dangers, for it is important that such a record should not be erased accidentally; should a mistake of any kind take place during the course of carrying out a procedure it is important that it should be possible to restore the status quo, which would not be possible if the only record of the original information had been accidentally replaced by other incorrect information.

(*g*) *A document reader.* Once large scale clerical procedures can be carried out automatically, the most expensive part of the job will be the preparation of the large volumes of data to be fed to the calculator. To reduce this cost substantially necessitates some form of document scanner.

This is another problem which is being considered by the N.P.L. in connection with the work at the Ministry of National Insurance. This problem may be simpler than the general case, as much of the data is recorded initially in the Local Offices of the Ministry and it may therefore be possible to install simple machines to record it in a form that can be read automatically.

The more general problem of sensing information written by hand is likely to prove more difficult owing to the great variations in the way people write numerals and other characters.

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NATIONAL RADIO SHOW 1954

This year's National Radio and Television Exhibition organized by the Radio Industry Council, was the 21st of the series, the first having been held in 1926. The total public attendance of 315,970 was the highest since 1949, and over 20,000 more than last year. The Show was held as in the previous three years, at Earls Court, London.

The official opening was performed by Sir Miles Thomas, D.F.C., Chairman of British Overseas Airways Corporation, on August 25th. He said: "It is indeed gratifying to learn that this progressive industry already employs about 125,000 people; that its annual output is worth at least £135,000,000; and that its direct exports, which as early as 1946 were valued at £7,800,000, have increased to £25,700,000 last year, and are still rising.

"Outside the entertainment sphere and the cultural and educational aspects, some of the latest developments in electronics are positively awe-inspiring. They are a powerful factor in our defence mechanism. Today, radio and radar are indispensable to civil and military aviation and to naval and merchant shipping. In B.O.A.C., as in other airlines, we are also keenly interested in the progress of a form of search radar that will enable the pilot not only to keep track of other aircraft in his vicinity, but also to receive an indication of areas of turbulence on or near his course. We hope to install such equipment in forthcoming types of airliners and thus improve still further the already high standards of air travel.

"In present day military aviation the rôle of electronics, of course, is of supreme importance, and the latest all-weather day and night fighters can truly be described as flying radar stations.

"In the meantime, in the general field of commercial activity, there is such a growing appreciation of the ways in which electronics can increase productivity that the radio industry has become an enterprise with stimulating prospects and high responsibilities. I wholly commend its exciting opportunities to young people who have a scientific frame of mind and are in search of a worthwhile career."

Review of the Show

The main point of interest both for the engineer and for the general public at this year's Show was the demonstration of television receivers working on one of the frequencies to be allotted to the Independent Television Authority. The television programmes on the closed circuit of the exhibition were on a Band I frequency (B.B.C. Sutton Coldfield, 61.75 Mc/s), but a Band III signal of 189.75 Mc/s from a special transmitter within the R.I.C. control room was superimposed on the internal network, so that receivers having facilities for reception on both Bands could be switched from one to the other. The modulating signal was a moving picture without entertainment value but it was quite adequate to demonstrate the programme switching capabilities of receivers.

The majority of manufacturers included receivers for the two Bands, while others made a feature of the ease with which adaptors can be incorporated when required. The most usual method of providing alternative programme tuning was by a 12 (or 13) position turret tuner (that is, for four or five channels in Band I and eight channels in Band III). The other method used a two-position band switch with two continuously variable controls, each tuning over one of the Bands; it was claimed that this tuning control would be of particular use in enabling the user to correct frequency drift.

Other developments in television were designed to improve the quality of the picture by providing more uniform focus and scanning over the area of the screen. More efficient synchronizing, particularly for fringe area reception was claimed for sets using "flywheel" circuits. There was a larger number of receivers with 17-in. cathode ray tubes than any other size and the proportion of smaller sized tubes had decreased since last year. A few sets with larger than 17-in. tubes were shown and one manufacturer presented a table projection model with a 20-in. diagonal screen.

Aerial manufacturers showed various television aerials for the reception of Band III transmissions. These included both simple and multiple element types but naturally the final combination of these with the Band I aerials will depend on the siting and polarization of the v.h.f. transmissions.

The efforts of the television side of the radio industry were not totally confined to manufacture of sets for the home market and several firms showed receivers for the continental standards of 625 lines as well as for the American 525-line standards. Pattern generators for use with these standards were shown by several makers.

The most interesting innovation in the field of sound radio was receivers for the B.B.C.'s v.h.f. f.m. broadcasting due to begin in certain areas next year. The general practice among designers was to add the v.h.f. band as an extra range, with continuously variable tuning. So far only a few manufacturers appeared to be contemplating adaptors for this purpose.

High fidelity reproduction will receive added impetus with the introduction of v.h.f. sound broadcasting and this no doubt stimulates the increasing attention paid to tape recorders, reference to which was made in the report of the last Show.

Applications of Electronics.—Last year's interest in electronics was maintained and in addition to some of the exhibits included then, a number of new applications were on view. Among the many possible uses for stroboscopes shown were their application to examination of machinery in operation and to research into fluid motion, the latter being demonstrated by the examination of a fountain of water.

Yet another application of ultrasonics was the exhibit demonstrating testing of motor car tyres. The tyre was immersed in a bath of water (which acts as a coupling agent) and the relative signal obtained by the multiple receiving transducers on the outer surface of the tyre from the single transmitter inside indicated the presence of faults in the tyre structure.

The melting of light metal without using a crucible by supporting the metal in a magnetic field produced by a high-frequency generator was a demonstration which attracted considerable interest. A standard industrial high-frequency generator was used with its output delivered to a coil of seven or eight turns having the top turn reversed. The magnetic field thus set up held the specimen in the centre of the coil while it was heated and melted. On switching off the h.f. current, the molten metal could fall into a mould below the coil.

Some of the basic principles of telemetering from guided missiles during flight were shown in a working diagrammatic exhibit by the Royal Aircraft Establishment of the Ministry of Supply. The particular type shown was a time-division multiplex f.m.-a.m. system.

Underwater television was again shown this year on the Royal Navy stand, while the Army had set up a relief model of a battle field which was televised by a small industrial television camera. This was supposedly in a helicopter from which the headquarters could gain an idea of the course of the battle.

The stands of all three Services showed a wide range of current equipment both for communications and for navigation, as well as for special purposes such as servo-mechanisms and analogue computers used in Army predictors.

Technical Training.—The Technical Training stand incorporated some of the suggestions contained in last year's review of the Show.* There was more information on the availability of courses of training, etc., and there was a fair display of the various details of manufacture which the trainee would meet in a three-year course. A useful feature was a small cinema which was part of the stand, where a film was shown outlining a typical training scheme with one of the larger manufacturers.

The stands of the three Services prominently featured training equipment in operation. In tackling problems of recruitment the Services showed a greater awareness of the "drawing power" of working displays as against the static type which was the main characteristic of the industry's Technical Training stand.

Elsewhere in the Show there were examples of "work in progress" but it would have been an advantage if the Technical Training stand could also have had such working exhibits including, perhaps, examples of the use of fault-finding equipment in actual servicing.

The Institution, in its rôle of a constituent member of the Radio Trades Examination Board, was represented on the sub-committee responsible for that part of the stand devoted to the radio and television servicing work for which the Board, in conjunction with the City and Guilds Institute, awards certificates.

Mention has previously been made in the Institution's *Journal*† of the man-power needs of the radio industry and the Radio Show is a unique opportunity to publicize the advantages open to the youth just leaving school. The Technical Training stand is a comparatively recent innovation—this being the third year in which this feature has been included in the Show. It gives a great deal of valuable support to the work of the technical training colleges and it is hoped that it will be a regular part of this Show, with improvement based on the experience of these first three years.

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* *J.Brit.I.R.E.*, 13, September 1953, page 445.

† "Man-power Problems," *J.Brit.I.R.E.*, 13, April 1953, page 181.

THE ALPHA GAUGE*

by

E. N. Shaw, B.Sc.(Hons.)†

A paper presented during the Industrial Electronics Convention held in Oxford in July, 1954.

SUMMARY

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.

1. Introduction

With the possible exception of gamma radiography, the chief industrial application of the by-products of atomic piles to process control has been in the continuous gauging of thin materials by non-contact methods. In many processes, such as paper and acetate film manufacture, this gauging could not be performed by any known means, and samples had to be taken from the strip at regular intervals to keep a check on the weight per unit area. This not only necessitated the wastage of a large quantity of time and material, but also in many cases, gave warning too late of an off-gauge run. Again, in the metal foil industry, although contact gauges of various designs were a partial solution, it was difficult to perform the gauging on the softer materials without damage and without error, and with increased speeds of production, troubles due to friction have presented insuperable problems. When radioactive isotopes emitting beta rays became available in quantity, considerable development was begun on the measuring instrument now generally known as the Beta Gauge. Initially, the only suitable radioactive material available was thallium 204, which with a half-life of 3 years and emitting beta rays of maximum energy 0·78 MeV permits gauging in the range from 4 mgm/cm^2 to 120 mgm/cm^2 with the required accuracy and response time (usually of the order of ± 1 per cent. at 1 second). More recently, strontium 90 and ruthenium 106 with maximum energies of 2·6 MeV and 3·5 MeV respectively, have increased the range to 1 gm/cm^2, and promethium 147 with a maximum energy of 0·23 MeV has lowered the range to approximately 2 mgm/cm^2. This still left a considerable section of industry, including the capacitor paper manufacturers for example, without an instrument to cover their own special requirements. It was for this specific range of materials, i.e. below 2 mgm/cm^2 that the Alpha Gauge was developed.

2. Beta Gauge Techniques

Before going into the details of the Alpha Gauge, it would probably be helpful to summarize the standard procedure adopted in Beta Gauge measurements. The beta rays emitted by radioactive material are not of uniform energy, but cover a spectrum with a defined maximum energy, and a peak in the region of approximately ⅓ of maximum energy. Such an energy distribution curve is shown in Fig. 1. If these beta rays are allowed to pass through an absorber a general process of scattering and slowing down occurs, the end effect of which is to reduce the beam intensity in a logarithmic manner. The distortion of the spectrum, however, is not large, as can be seen by comparing the dotted curve in Fig. 1 with the continuous curve. The second curve shows the energy spectrum of a beam of beta particles from the same source after it has passed through four half thicknesses of material. The half thickness is defined as that weight per unit area of material which will absorb 50 per cent. of the initial radiation. Thus the effect of an absorber is to modify the energy spectrum only slightly, but to decrease the number according to a definite law. Any detector therefore which is sensitive to the number of beta rays falling upon it can be used to give a measure of the thickness of absorber interposed between it and the source. Because of the necessity of detecting a large number of

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particles in the resolution time, and so avoiding prohibitive statistical fluctuations, ionization chambers have been universally adopted for detection. These are of the cylindrical or parallel plate type, and are invariably filled with a gas which absorbs only part of the residual energy of the beta particles. Due to the unchanging shape of the spectrum, the mean current per beta particle will remain constant and the total current will thus be proportional to the number of beta particles incident upon it. In practice, this current, which is of the order of 10^{-9} amperes, must be measured with an accuracy of the order of 1 to 0·1 per cent.

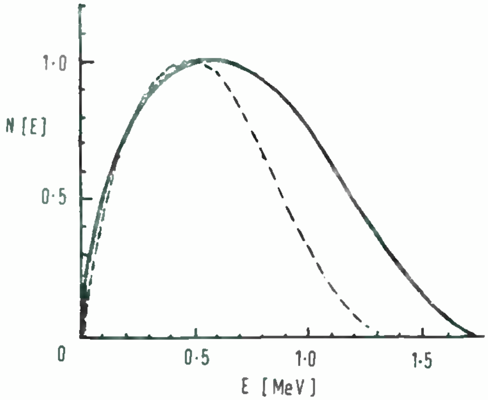


Fig. 1.—Spectrum of beta rays from phosphorus 32.

3. D.C. Amplification

Two main approaches have been made to this problem. Firstly, by the use of a vibrating reed electrometer, electronically backed off to provide an output which varies about a mean position with the absorber weight. The disadvantage of such a system is that the high resistor that is inevitably incorporated in such a circuit must not vary in value by an amount greater than the fraction of current that it is required to detect. This clearly presents a considerable problem. The alternative method is to back off the initial input current to the amplifier by means of an identical ionization chamber system working with opposite polarity. The main criterion for the amplifier which follows is then that the zero stability should be of a high order. Deflections from the zero position will still be affected by changes in the value of the high resistance, but these represent variations in the off gauge reading only.

The development of miniature electrometer tubes now commercially available has made the design of a d.c. amplifier which will fulfill these conditions relatively straightforward. A simplified circuit diagram for the amplifier on which the author's company have standardized is shown in Fig. 2. It consists of a Mullard M.E. 1401, feeding a two stage d.c. amplifier consisting of two double triodes to minimize the dependency on heater voltages with 100 per cent. voltage feedback from the cathode follower output to the input. It has been found that adjustment of the zero control is necessary at intervals of the order of one or two months only and that once warmed up (say 10 minutes), the drift over any 24 hours is undetectable when working at the same sensitivity as is required for normal beta gauge requirements. Certain additional features (not shown) have been incorporated; the power supply to the anode of the M.E. 1401 is provided with a long delay (1 minute), and the thermal delay which controls this is also caused to operate a further delay circuit to prevent violent kicks on the meter at its closure.

Zero setting of the amplifier is performed by disconnecting the chamber input from the electrometer grid. The response time of the amplifier is controlled by adjusting the degree of capacitive feedback between output and input. With feedback components R and C, a loop gain of A and the feedback ratio $1/p$, the response time is $RC/(pA + 1)$. That is, when the capacitor is directly across the resistor the natural time constant is RC and when the capacitor is coupled directly from grid to ground the value changes to approximately RC/A. A smooth potentiometer control allows the value to be varied continuously from 0·1 seconds to 10 seconds.

Some time has been spent on the description of the d.c. amplifier used, as it was subsequently incorporated in the alpha gauge design. The only troubles that have been encountered in industrial practice with this amplifier have been caused by the breakage of leads from the electrometer valve itself, particularly during transit. The electrometer valve and relay are mounted in a hermetically sealed can and the various components are rigidly clamped to a support. No microphony has been observed by this method of mounting, and troubles with pin breakage have been finally eliminated by encapsulating the lower portion of the M.E. 1401, together with the high resistor and fixed relay contacts in Araldite D. No information from the manufacturer is available yet on the resistivity

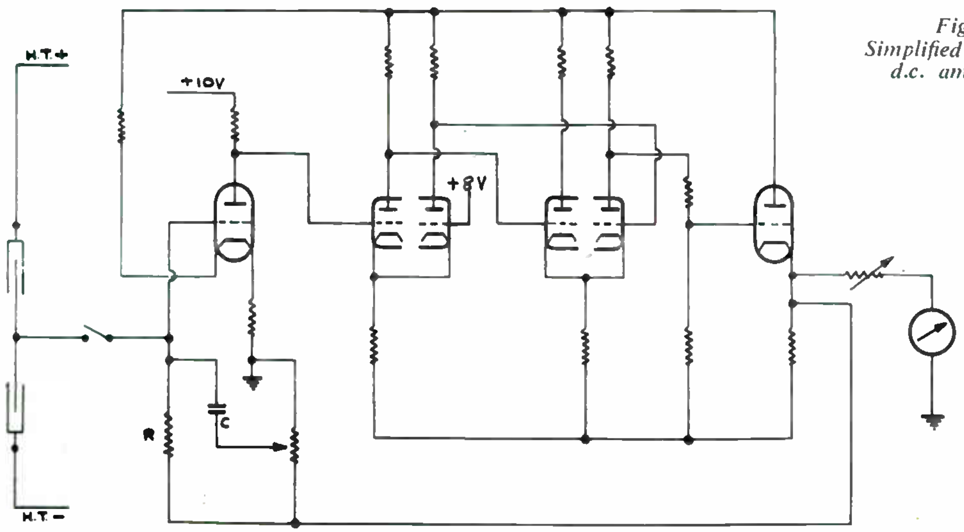


Fig. 2.
Simplified circuit of d.c. amplifier.

that can be obtained with this resin, but from a number of experiments performed by the author, it is apparent that by using a mixture of 10 parts of hardener to 100 parts of polymer, a resistivity of 10^{14} ohms per cm^3 can be achieved. It should be noted that in some cases, this value has been as low as 10^{12} ohms 24 hours after potting, but has increased steadily up to periods of 10 days. Other ratios of hardener to polymer give lower values of restivity, and all values appear to be only sightly affected by pre-heating and/or pre-pumping the hardener which is known to be hygroscopic.

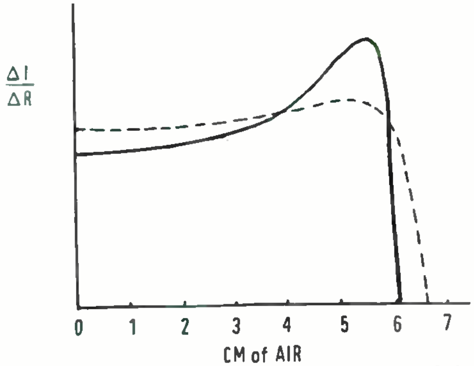
4. Theoretical Considerations

Reverting now to the main subject of this paper, it was decided to approach the problem of the measurement of thin films from a different angle by measuring the decrease in energy of alpha particles on passing through an absorber. A single alpha source of zero self absorption will give a line spectrum output; that is, all the alpha particles will be emitted with the same energy. Neglecting scattering then the alpha particles will be slowed down by the same amount on passing through an absorber. The deceleration can be expressed in terms of the ionizing power of the radiation along its path length. A curve of this ionizing power against range is shown in Fig. 3, and is normally referred to as the Bragg curve. It will be seen that the particles decelerate more rapidly the slower they are travelling, until their energy is below the ionizing energy of the detector. A detector, therefore, which measures the residual energy of the beam of alpha particles after passing through an absorber, will give a measure of the weight of the absorber. It is clear also from the shape of the curve that for very thin materials it is advantageous to increase the absorber weight by inserting additional absorbers to decrease the residual range of the alpha particles. A small change in absorber weight will then cause a greater relative change in the residual ionizing efficiency.

5. Experimental Model

In designing the instrument, radium was chosen as the source of alpha particles because of its long half life and its availability in standard foil form. Quite apart from safety precautions, such a source must be deposited in a durable form in order that the inevitable collection of dust can be removed without fear of harming the source.

Radium and its daughter products emit alpha particles, ranging in energy from 4·5 MeV to 7·68 MeV, and these, together with self-absorption in the source itself, will modify the Bragg curve shown in Fig. 3 to the dotted curve shown in the same figure. This will modify the sensitivity obtainable, but the general arguments apply. For the same reasons that apply to the beta gauge, an ionization chamber was chosen as the detector, but due to the necessity for a thin window facing the source, it was decided to carry out initial experiments with a non-sealed type. Some form of window is necessary in order to eliminate the effects of draught on the ionization current. The chamber was finally constructed of polythene, with a thin polythene window facing the source, and parallel to it, a brass collecting electrode. Subsequently it was found essential to have a coating of aquadag on both the inside and the outside of the polythene window, in order to eliminate the effect of static charge build up.



Fi. 3.—Ionizing power against range of alpha particles.

A large number of experiments was then performed to determine the optimum chamber depth. It was found that the optimum sensitivity occurred at approximately the same standing ionization current throughout the range, there being a small increase in the value for increasing absorber weight.

Using a source of 150 microcuries, and an absorber of 1 mgm/cm^2 weight changes of one per cent. could easily be detected against the statistical fluctuations. A series of experiments was then performed to determine the effect of temperature on such a system. It was reasoned that, providing the temperature in the chamber and in the air gap was the same, an ionization chamber would be made of such a length that not quite all of the residual range was detected. An increase in temperature would thus cause a decrease in the chamber current, but also a decrease in the absorber weight. It seemed reasonable that some measure of compensation could be obtained. As a result of many tests on the changes in output reading for various geometrical arrangements with various absorber weights, it was discovered that the minimum temperature sensitivity occurred at almost the same place as the maximum weight sensitivity.

It has been stated previously that for small weights the sensitivity is increased by increasing the total absorption and thus diminishing the residual range. It was found that this could best be achieved by increasing the distance between source and chamber and using the additional air gap as the additional absorber. Furthermore, the geometric term so introduced almost exactly compensated the change in optimum standing current obtained for different weights in the initial experiments.

6. Prototype Gauge

Following these experiments a detector head was built consisting of an ionization chamber with a 1 mgm/cm^2 window mounted over a 150 microcurie source. The two mountings were set at a fixed distance of ½ in. and provision made for the source to be movable below the level of the source assembly. In order to provide a lead through for the strip material under works' conditions, curved guides were provided on either side. Some difficulty was expected in feeding such thin material through a narrow gap, but subsequent experiments have shown that the method is perfectly practicable and the incidence of breakage of the web small. In order to bring the apparatus in line with the standard beta gauge design, the standing current in the ionization chamber was backed off by a similar ionization chamber fed from a similar source, but operating with opposite polarity. The amplifier previously referred to was used with a 10^{11} ohms feedback resistor. With this arrangement, a 1 mgm/cm^2 sample gave a sensitivity of 1 per cent. per mA output. The electronic zero drift with this value of feedback resistor incorporated is immeasurably small, and it is hoped in a final model to eliminate the zero set control completely. Initial setting up and occasional checkings can be carried out by covering the sources. From previous experience it has been found that electrical leakages across the chambers, and around the electrometer valve, are negligible.

7. Practical Experience

A brief outline has been given of the experiments that have been performed in the development of a gauge for the measurement of very thin materials. The essential difference in approach has been to recognise the difficulty of building ionization chambers with very thin windows which are hermetically sealed, and which are independent of ambient temperature and pressure. Furthermore, an attempt has been made to compensate for the changes in the temperature of the air between source and detector, the weight of which is comparable to the weight of the absorber being measured. In general, in the paper industry, the manufacturers can work to within a tolerance of approximately ±5 per cent., but in the acetate film industry considerably closer tolerances can be achieved. The aim has been to produce an instrument which although not necessarily retaining an exact calibration over months, would nevertheless be of value in giving an accurate determination of the weight over extended periods between checks. Thus, although not eliminating completely the necessity for taking weighed samples, the operator is provided with a measuring instrument which will give him a continuous record of the weight, with possibly a slow small drift which with experience, he can allow for. (Note that this drift will be as little as ½ per cent. of 1 mgm. paper over 12 hours, providing ambient conditions do not change abruptly). He is furthermore provided with an instrument which will give a reading of the corrections he has been making to the weight of his material, as he applies them.

In a series of trials at a paper mill making cigarette paper, the chief problem that was expected in operating under works conditions was in threading through the small gap that is essential to the operation of the gauge. In practice, this gave surprisingly little trouble, and although when first mounted on a paper machine, a few breaks were caused, small modifications to the leading edges of the head completely eliminated the incidence of tears, particularly when the gauge was removed from the measuring position during roll changes.

The results obtained during the works trial were initially confused by the small area of source being used, as the detailed variation across the web was considerable; in fact a movement of 6in. caused a change of 10 per cent. in weight in one case. In order to save the necessity for continuous checks of weight against reading by tearing out samples of the strip, a number of runs were performed at the edge of the paper machine, using a static sample. Initially, these results gave drifts of as much as 5 - 6 per cent. but these were later found due to the take-up or evaporation of moisture from the paper sample, and decreased to less than 1 per cent. on the substitution of a polythene sample.

During reasonably constant conditions in the works, and even during start up where there was a considerable change in humidity and temperature, the general drift rarely exceeded 1 per cent., but occasional variations of as much as 3 - 4 per cent. were observed, due probably to short term variations in the source gap temperature. (The drift of the electronic equipment was checked periodically, and found to be negligible).

As a result of these works trials, and as a result of consultations with the management of the mill at which these trials were performed, a gauge is being built with an extended window, 7in. long, surrounded by a saucer-like guide. This will be mounted in a head containing the electrometer tube and a fixed source-compensating chamber system. The compensating source will be provided, however, with a partial shutter, to give a fine control, on the backing-off current. The mounting of the measuring source will be micrometer controlled, the micrometer being calibrated in terms of absorber weight.

The Alpha Gauge will thus extend the range of radio-isotope instrumentation down to cover the finest materials, implying that nuclear techniques can now be used to monitor the weight per unit area of continuously produced strip over the entire production range—at of course, a price.

Points from the Discussion on this Paper will be found on page 433.

JOURNAL OF THE BRITISH INSTITUTION OF RADIO ENGINEERS

A GAMMA RAY THICKNESS GAUGE FOR HOT STEEL STRIPS AND TUBES *

by

G. Syke, Dipl. Ing. †

A paper presented during the Industrial Electronics Convention held in Oxford in July, 1954.

SUMMARY

A prototype gamma ray thickness gauge for hot mills rolling steel strip of 0·05 in. to 0·30 in. thickness is described, which uses a scintillation detector and provides distinct readings 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.

1. Introduction

A great variety of materials is produced for industrial and domestic use in the form of strips and sheets. Steel strip for motor car bodies, tinplate, aluminium strip for domestic utensils, aluminium foil for capacitors and for wrapping cigarettes, etc., paper, linoleum, chipboard, photographic film are but a few examples.

Close control of thickness or weight per unit area during the manufacturing process is of great importance. The motor car body manufacturer buys steel strip at a given price per ton. The number of car bodies he can make out of a ton is inversely proportional to mean strip thickness. The weight per unit area or the area per unit weight is thus an important economic factor.

In the manufacture of paper capacitors thickness of the paper and metal foil will greatly influence the capacitance, if the width and number of turns are fixed. Thickness of these strips is closely related to their weight per unit area, since density of the aluminium foil as well as of impregnated paper are fairly constant.

Mechanical contact gauges measure thickness in thousandths of an inch or in millimetres. In some applications they are quite satisfactory. If, however, the strip is soft and pliable, or at a high temperature, or moves at great speed, or the density is variable, mechanical contact gauges are not applicable and non-contact gauges are required.

Among the non-contact gauges developed in recent years radiation gauges play a prominent part.[1,2] A radiation gauge consists of a source of ionizing radiation—radio-active isotope or X-ray tube—and a detector responsive to ionizing radiation, with associated amplifier and indicator, recorder or controller. The strip or sheet to be gauged passes between source and detector. The ratio of transmitted to incident radiation is a measure of the weight per unit area of the interposed absorber ; the relationship between this measured ratio and w.p.u.a. of the absorber depends on the nature and penetrating power (energy spectrum) of the radiation, geometrical relationship of source, absorber and detector, composition (mean atomic number) of the absorber and characteristics of the detector. If these are constant or accurately predictable and controlled, then the incident/transmitted radiation ratio is only a function of absorber w.p.u.a.

Radiation gauges using *beta rays* of radioactive elements are now well established and widely used in industry on both sides of the Atlantic.[3,4] *X-ray gauges* are in fairly general use, mainly on some types of steel rolling mills in the U.S.A. and installations now also exist in this country.[5,6]

The *gamma ray transmission thickness gauge* is the youngest member of the family of radiation thickness gauges,[7] and there is now sufficient evidence to show that on hot steel mills producing narrow strip (e.g. for welded tubes) and for gauging the wall thickness of hot steel tubes the gamma gauge offers definite advantages.

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U.D.C. No. 621.387.46 : 621.771.

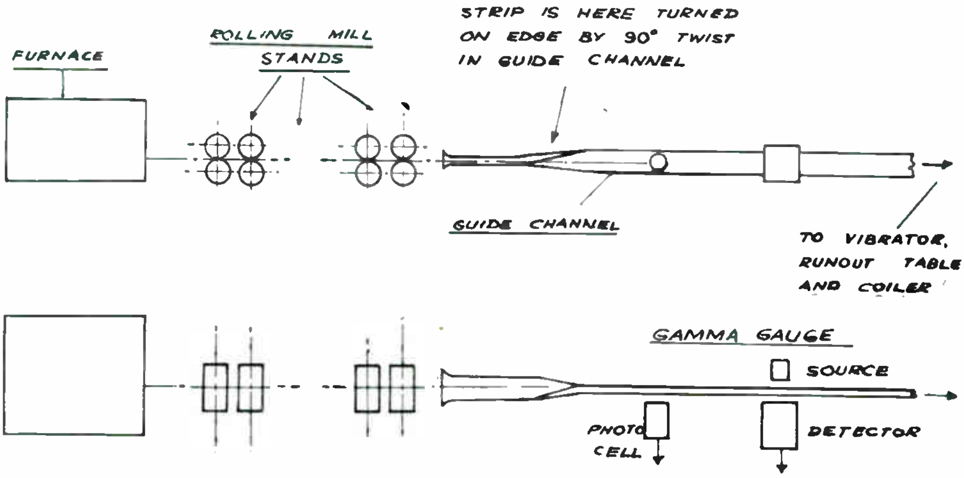

Fig. 1.—Gamma gauge on hot strip mill.

Steel thickness greater than some 0.050 in. or 1·25 mm is only penetrated by X- and gamma rays. The main *advantages* of a gamma source over X-ray generator are as follows :

(i) Much smaller size—a few cubic millimetres instead of many cubic decimetres.

(ii) No need for cooling, even at temperatures in the region of 1,000° C.

(iii) No need for source stabilization ; X-ray tube output is nearly proportional to the 3rd power of supply voltage whilst the gamma source is absolutely stable over short periods and the long-term decay characteristics are accurately known and predictable.

(iv) Much lower cost—a few pounds for a gamma source against hundreds of pounds for an X-ray generator.

(v) Less vulnerable—a radio-active source in a small steel shell is practically indestructible ; this can hardly be said of the X-ray generator comprising evacuated glass tube and oil-immersed e.h.t. transformer.

(vi) Requires no connections, whilst the X-ray generator needs power supply and cooling water.

The present *limitations* of the gamma gauge as compared with an X-ray gauge are as follows :

(i) Limited choice of energy spectra ; there are very few available isotopes of adequate life within the required energy range of 40 kV to, say, 400 kV.

(ii) Limited source strength ; the number of quanta per unit time contained in a narrow beam of gamma rays from the strongest low energy sources now available is much smaller than in a comparable X-ray beam. The maximum practicable source-detector distance is thus more restricted ; the implications of statistical random fluctuations due to the quantum nature of these radiations are also more serious when high speed of response is required.

In the case of the applications now to be described the advantages of the gamma rays greatly outweigh their limitations and the gamma gauge in these and similar instances fully meets production requirements.

2. Gamma Gauge for Hot Strip Mill

Figure 1 shows the diagrammatic arrangement of the gamma gauge on a hot strip rolling mill.

Ingots are preheated in a furnace and fed to the mill, which rolls them into strips of several hundred feet length. The objective is to produce strips which have the correct thickness throughout their length and width. To achieve this result various adjustments can be made on the mill and on the furnace.

If the operators know that the *mean thickness* of a strip is wrong, they can adjust the gap between the rolls of the last stand before feeding the next ingot into the mill. If the *longitudinal profile* of the strip is wrong—say the front half is too thick and the rear half too thin—the temperature distribution in the furnace can be altered so that the front half of subsequent ingots is made warmer and the rear half cooler ; raising the temperature makes the metal more pliable and the same roll setting will produce a greater reduction. If the *transverse profile* is wrong—that is, the cross-section of the strip forms a taper instead of being parallel—the operators can tilt one of the rolls to make top roll and bottom roll exactly parallel.

A thickness gauge installed on such mill should, therefore, give information concerning :

(*a*) mean thickness of each strip
(*b*) longitudinal profile
(*c*) transverse profile

Figure 2 shows the diagrammatic arrangement of the gamma gauge. When the leading edge of a strip reaches the photo-cell unit, the red radiation of the hot strip falls on the photo-cell and causes a relay to be energized. This puts the electronic measuring circuit in readiness and opens a shutter placed in the path of the gamma ray beam. Just after the leading edge of the strip reaches the measuring head a timer device initiates the charging of a capacitor. The pulses derived from the photomultiplier pass through head amplifier, discriminator, pulse shaping and diode pump circuits ; each registered pulse thus feeds a definite amount of charge into the integrating capacitor.

The voltage across this capacitor C1 (Fig. 3) at the end of a time interval t_1 is a measure of the mean strip thickness passed through the gamma ray beam during this interval. At the end of t_1 a definite fraction of the charge of C1 is transferred to a sharing capacitor C2. The integrating capacitor C1 is now momentarily shorted to discharge it, and the whole process is repeated during the second interval t_2. During t_2 the voltage Vc across C2 is electronically compared with a preset standard voltage Vs. If the mean thickness of the strip during t_1 was exactly right, then $Vc = Vs$. If, however, the strip is too heavy or too light, a signal $Vc - Vs$ is obtained, which is a measure of the thickness error. This error signal is fed through biased amplifier valves V1 to V4 to relays Ry1 to Ry4. All relays whose bias voltage is lower than $Vc - Vs$ will pull in, whilst those with a higher or more positive bias will remain off. The biased relays are connected through a uniselector to further relays on the lamp display board (Fig. 2) and cause one of the lamps in the first vertical row to light up and remain on.

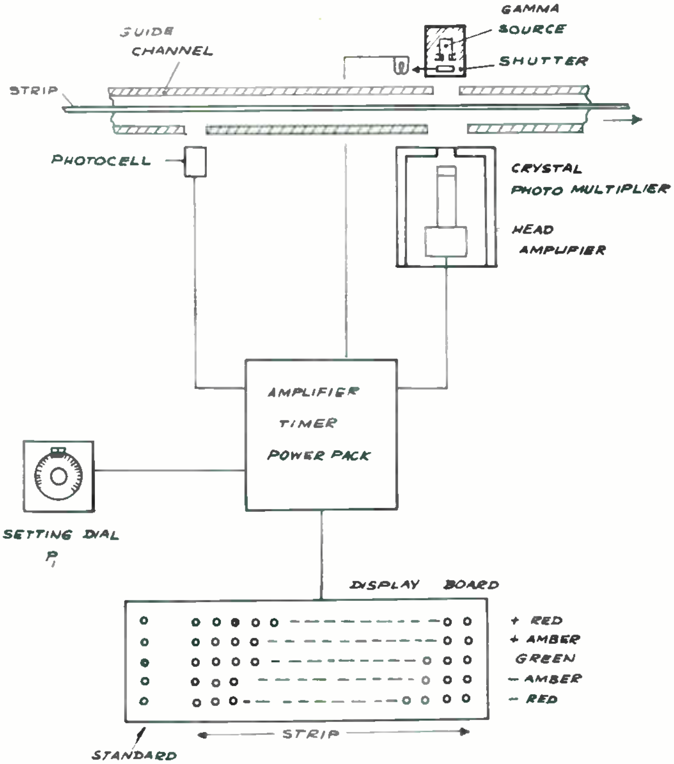

Fig. 2. Schematic diagram of the gauge.

If, for instance, it is intended to roll strip of 0·100 in. thickness, Vs is set by means of a potentiometer to a corresponding value ; this potentiometer (P1 in Figs. 2 and 3) is calibrated in terms of thickness. If the mean strip thickness during interval t_1 was between, say, 0·099 and 0·101 in., i.e. within ± 1 per cent, of the correct value, a central green light will come on. If the thickness error is between + 1 per

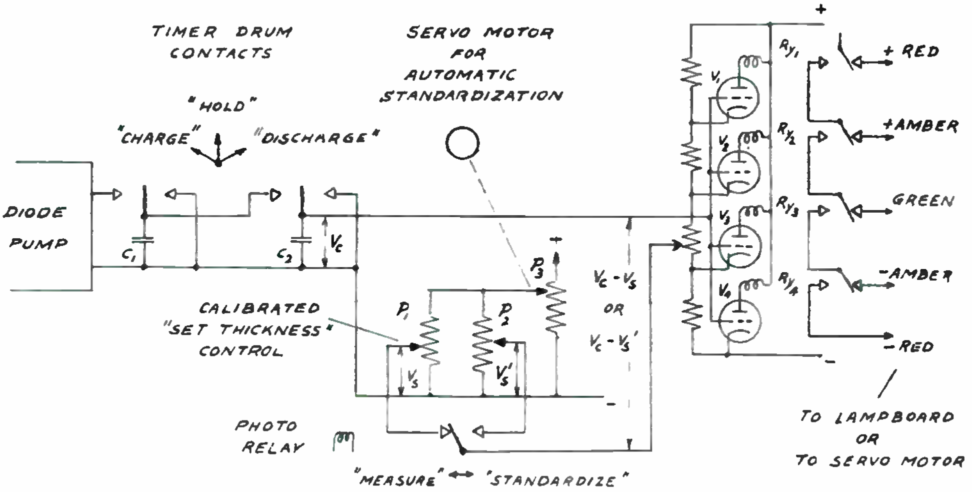

Fig. 3.—Simplified diagram of gamma gauge output circuit.

cent and + 3 per cent, an upper amber light (second from the top) comes on. If the error exceeds + 3 per cent., an uppermost red lamp lights up. The two lower lamps represent similar minus errors. The complete scheme is thus :

Upper red lamp—error exceeds + 3%.
Upper amber lamp—error is between + 1% and + 3%.
Central green lamp—error is within ± 1%.
Lower amber lamp—error is between — 1% and — 3%.
Lower red lamp—error exceeds — 3%.

The sensitivity is adjustable, but the example quoted— 2 per cent per lamp row—may be taken as typical.

At the end of interval t_1 a lamp in the first vertical row lights up : at the end of t_2 a lamp in the second row, and so on, until the entire strip has gone past the measuring head. By this time a picture of the longitudinal profile of the whole strip is displayed on the lamp board.

As the tail end of the strip leaves the photocell (Fig. 2) the photo-relay drops off and closes the source shutter. It also switches the instrument from " measure " to " standardize " (Fig. 3). The shutter consists of a steel specimen of standard thickness. During the standardizing interval, i.e. between consecutive strips—the voltage *Vc* is compared with a standard voltage *V's* corresponding to the thickness of the standard specimen. The error signal *Vc* — *V's* is fed to the same set of biased relays as during measurement, but these relays are now connected to a servomotor which alters the setting of potentiometer P3 whenever the error signal *Vc* — *V's* exceeds a critical value. If *Vc* — *V's* is positive the voltage across P1 and P2 is increased; if *Vc* — *V's* is negative it is decreased. Any drift or error in the absolute calibration of the instrument—e.g., due to thermal or mechanical distortion of the measuring head, source decay, change in photo-multiplier sensitivity, etc.—is thus automatically corrected and the instrument is fully self-checking. It is proposed to incorporate a safety device which will switch off the lamp board if the instrument develops a fault and balance is thus not restored within, say, 3 consecutive standardizing cycles. In this way the risk of mill operators being misled by incorrect instrument indications is practically eliminated.

During the standardizing process—i.e. whilst there is no strip passing through the measuring head—the profile of the last strip remains on the board ; it is cancelled when the leading edge of the next strip enters the measuring head.

Having given a general description of the mode of operation of the gamma gauge on a hot strip mill, the component parts will now be examined in more detail.

2.1. *Source*

The isotope used as a gamma source is thulium 170, which is obtainable from Harwell as a standard radiography source.[8] It consists of a small sintered pellet, totally enclosed in a

Birmabright (aluminium alloy) capsule. The decay scheme of thulium 170 is fairly complex; it will suffice to note that some of the disintegrations are accompanied by one 84-keV gamma quantum, and some internal conversion X-ray quanta of about 50 keV energy are also obtained. For convenience it is proposed to refer to both as gamma rays.

The thulium pellet is activated by neutron irradiation in the pile, and sources of 250 mC to 500 mC activity are usually obtainable. The half life is 127 days and the useful life in the instrument is about 4 to 6 months, i.e. 1 to 1·5 half lives.

Figure 4a shows the absorption curve obtained by placing steel sheets of varying thickness in a narrow beam of thulium gamma rays: the relative number of registered pulses per unit time—n—is plotted against strip thickness.

Figure 4b shows the attenuation curve. The change in relative counting rate—$100\, dn/n$—resulting from a small relative change in steel absorber thickness—$100\, dT/T$—is plotted against thickness T. If it is required to measure nominally 0·100 in. thick steel strip to an accuracy of ± 1 per cent, then the counting rate must be measured to ± 0·75 per cent accuracy. The attenuation curve thus shows how accurately the counting rate must be measured in order to find thickness to a specified accuracy.

2.2. *Shutter*

In front of the source is a solenoid operated shutter, containing a steel specimen of standard thickness. For a thickness range of 0·075 in. to 0·125 in. a standard specimen of 0·100 in. thickness is used; for measuring over the range of 0·125 in. to 0·175 in. the standard specimen is 0·150 in. and so on.

2.3. *Detector*

The detector consists of a sodium iodide crystal and photo-multiplier on shockproof mount inside a water-jacketed welded steel structure. A head amplifier is also incorporated in this unit. The electronic circuitry from head amplifier to diode pump is based on that developed by the Electronics Division of A.E.R.E. Harwell for Ratemeter 1037A.[9,10]

To get highest accuracy in the shortest possible integrating time it is necessary to work at high counting rate. The practical limit is set by the electronic circuitry and is at present about 6×10^4 pulses per second. With an integrating time of about 1·6 sec up to 10^5 pulses per cycle are obtained, subject to random fluctuations with a standard deviation of ± 0·3 per cent. From the attenuation curve (Fig. 4b) it can be seen that this corresponds to about ± 0·4 per cent of thickness at 0·100 in. and to about ± 0·3 per cent of thickness at 0·180 in.

Source and detector are embodied in one rigid welded steel structure, which can be raised or lowered to explore the width of the strip.

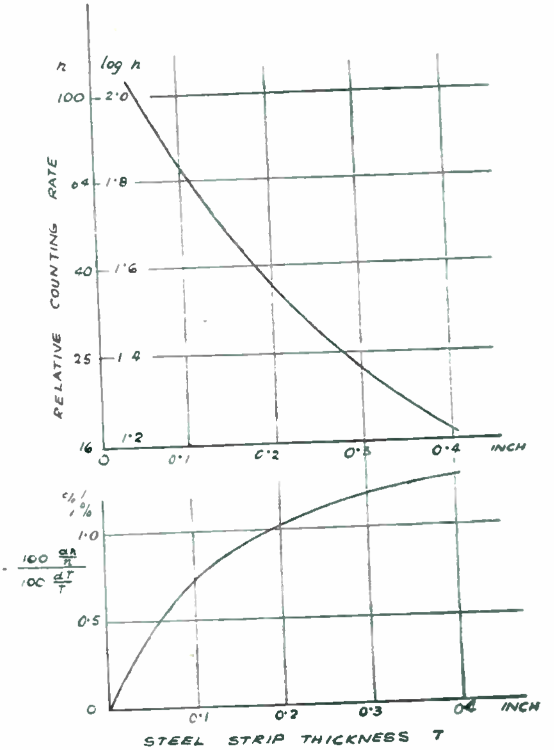

Fig. 4.—*(a) Absorption curve. (b) Attenuation curve.*

2.4. *Timer Unit*

The timer unit is a contact drum driven by a synchronous motor. The drum makes one revolution per integrating cycle and controls the following events in appropriate sequence:

(i) Start and terminate charging of C1.
(ii) Transfer charge from C1 to C2.
(iii) Discharge C1.
(iv) Move uniselector by 1 step.
(v) Energize lamp relay during measurement or operate servo motor during standardization.
(vi) Discharge C2.

2.5. *Photo-relay and Lampboard Display*

Whilst there is strip in the measuring gap the photo-relay keeps the shutter open and feeds the error signal to the lamp board ; during this period the voltage Vc is compared with a voltage Vs corresponding to the preset nominal strip thickness, selected on potentiometer P1.

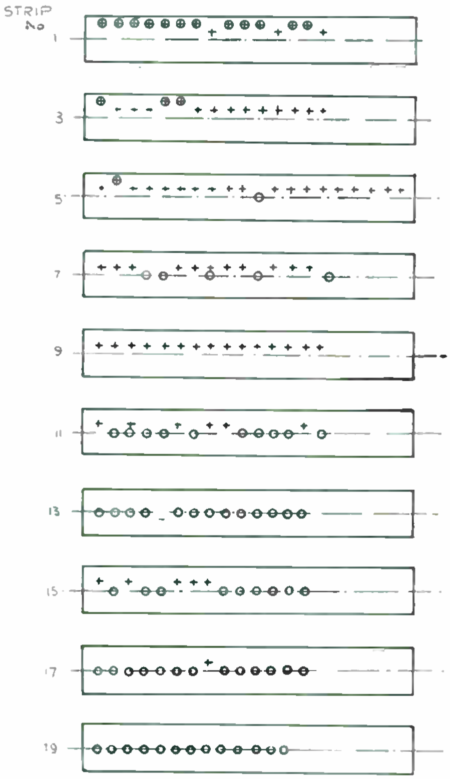

Fig. 5.—Display of rolling results.

Whilst there is *no* strip in the measuring gap the photo-relay closes the shutter and feeds the error signal to the servomotor of the automatic standardizing device ; during this period the voltage Vc is compared with a voltage Vs' corresponding to the thickness of the standard steel specimen in the shutter, preset on potentiometer P2.

When the photo-relay drops off (end of strip) it causes the uniselector to go to the " home " position ; when it pulls in (start of strip) it causes all lamp relays to drop off.

The lamp board (Fig. 2) consists of 23 or 48 vertical and 5 horizontal rows of lamps to display the longitudinal profile of the strip. A typical strip may be 600 ft. long. At a rolling speed of 1,200 ft/min this will pass through the mill in 30 seconds. At a timer drum setting of 1·6 seconds per cycle 18 lamps light up on the board, each lamp representing the mean thickness of a 32-ft. long section. The overall size of the 23-row lamp board is approximately 2½ ft. × 6 ft., and mains-voltage pygmy lamps are used. The board is mounted in a central situation high up on the wall, where it is well visible to all mill and furnace operators and to the foreman in his office.

Figure 5 shows a series of lamp board displays immediately after starting up the mill. It will be seen that the first few strips were too heavy—outside tolerance limits—and the mill was gradually adjusted to bring the strip over its entire length to the correct thickness.

3. Gamma Gauge for Tubes

Another typical application of the gamma gauge is the measurement of wall thickness of red hot steel tubes. Fig. 6 shows the general arrangement for tubes of about 2 in. to 6 in. bore and 0·1 in. to 0·6 in. wall thickness. Measuring while the tube is still hot offers several advantages ; the results are much sooner available than if one has to wait for the tube to cool and the amount of " off gauge " material is thus greatly reduced. In some processes it is possible to correct wall thickness in a second operation, and it is of practical importance to carry out the measurement with minimum loss of heat.

The source is mounted in the end of a steel rod and the tube, which is rotating in a cradle, is threaded over this. The detector unit is outside the tube and is again water cooled. An experimental set-up is shown in Fig. 7. By rotating the tube and pushing it forward at the same time, its wall thickness is explored along a spiral line. Source, detector and electronics (head amplifier to diode pump) incorporated in the tube wall thickness gauge are similar to those used in the strip thickness gauge, but the output is fed through an R–C ratemeter circuit to a strip chart recorder. Eccentricity of bore relative to outside diameter of the tube shows up as a wave on the recorder chart, and ± 2 per cent wall thickness variations due to eccentricity on ½ in. thick tube are well detectable at a scanning speed of 20 revolutions per minute.

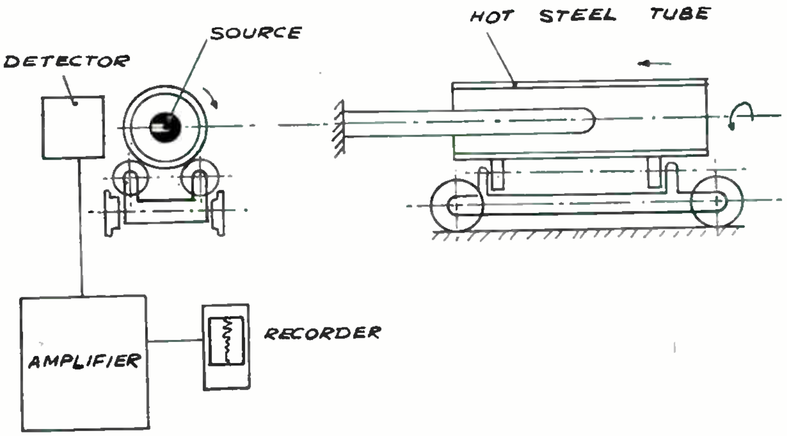

Fig. 6.

Gamma gauge for hot tubes.

4. Maintenance

The question of maintenance is a particularly important one on steel works installations. In the present equipment the measuring head has been made as simple and rugged as possible, since this works under most arduous conditions. Photo-multiplier and head amplifier are assembled as one unit on a single flange ; the whole unit can be exchanged in a few minutes. Shutter unit and photo-cell unit are constructed in similar fashion.

The main electronic unit is usually placed in a much more favourable situation and is well accessible for maintenance. Test meters and test switches are incorporated so that in case of a failure a works electrician without much electronics knowledge can—by carrying out a simple routine—rapidly identify the defective chassis or unit and replace it as a whole. Stocking the relevant spare units, in conjunction with the built-in fault tracing facilities, will largely eliminate the risk of prolonged stoppages due to instrument failure. By running regularly—say once a fortnight—through all test switch positions it is often possible to locate and replace valves, whose characteristics have changed, before they actually fail.

5. Acknowledgments

I should like to make an acknowledgment to Messrs. Stewarts & Lloyds, Ltd., whose help and encouragement was a decisive factor throughout the development of the gamma ray strip thickness gauge. All trials took place on one of their hot strip mills at Corby.

Our thanks are also due to various members of the Electronics Division of A.E.R.E., who were always most generous with their expert advice on details of circuitry.

In conclusion I should like to pay a tribute to my colleagues at the Baldwin Instrument Co., Ltd.—particularly Mr. S. J. Wright and Mr. C. Copping—for their share in bringing this development project to a successful conclusion.

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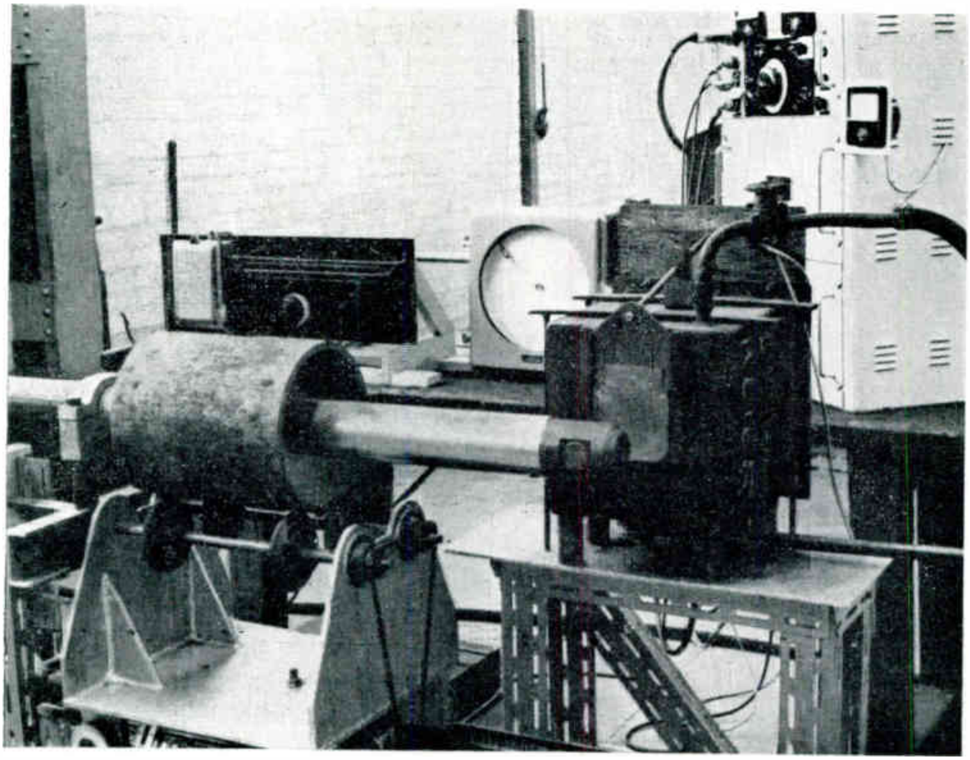

Fig. 7.—View of an experimental pipe measuring set-up.

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Points from the Discussion on this Paper will be found on page 433.

JOURNAL OF THE BRITISH INSTITUTION OF RADIO ENGINEERS

A COMBINED BETA AND DIELECTRIC GAUGE*

by

R. Y. Parry†

A paper presented during the Industrial Electronics Convention held in Oxford in July, 1954.

SUMMARY

Beta gauges are now being used very successfully in many industries and are noteworthy for their long term stability; however, they do not have a very fast response time. Dielectric gauges, on the other hand, have a very fast response time, but inherently for many applications do not possess an adequate long term stability. Therefore, by combining the two gauges in a single installation, an equipment is obtained which has long term stability and high speed response.

1. Introduction

The use of beta gauges in industry for the measurement of the mass of materials has now become widespread and the acceptance of this type of instrument is due to its unique facilities for many applications. However, it is not an instrument which responds to fast changes in mass and it is the need for an instrument with the stability and accuracy of a beta gauge, together with high speed response, which has led to its combination with a dielectric gauge. This instrument has a very fast response time but when used for the measurement of mass, has the disadvantage of being very sensitive to humidity and temperature changes, both of which are, under most industrial conditions, relatively slow changes.

By using the beta gauge as the overall measuring instrument and taking an a.c. signal from the dielectric gauge for rapid changes, a mass measuring equipment is obtained with most of the advantages of both instruments. Such equipments are now in full use in the cigarette industry.

2. Beta Gauge Principles

Beta gauges have been well covered in the technical journals and the description here will be limited to a statement of the principles and an outline of the practical equipment.

If a source of beta radiation is positioned facing a radiation detector at a convenient spacing, the amount of radiation falling on the detector will depend upon the geometrical factor and the amount of absorption between the two. If the geometry is fixed and constant, the amount of absorption becomes the controlling factor and the output from the radiation detector can be calibrated in terms of the amount of absorption. A diagram of a very simple type of gauge is shown in Fig. 1.

It is usual for an ionization chamber to be used as the radiation detector. The current from the chamber is passed through a resistor of the order of 10^{10} ohms and the resultant voltage applied to a d.c. valve voltmeter. High sensitivity is achieved by backing off the standing current or voltage, and very special precautions are taken to ensure the stability of the d.c. amplifying system.

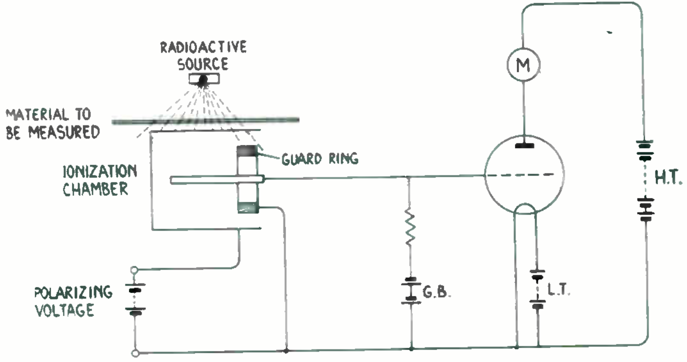

Fig. 1.—Simple thickness gauge.

The speed of response of a beta gauge is mainly limited by the need to smooth out the fluctuations in the ionization chamber current. These fluctuations are due, in the first place, to the random nature of radioactive emission and, secondly, due to the variation in ionizing ability

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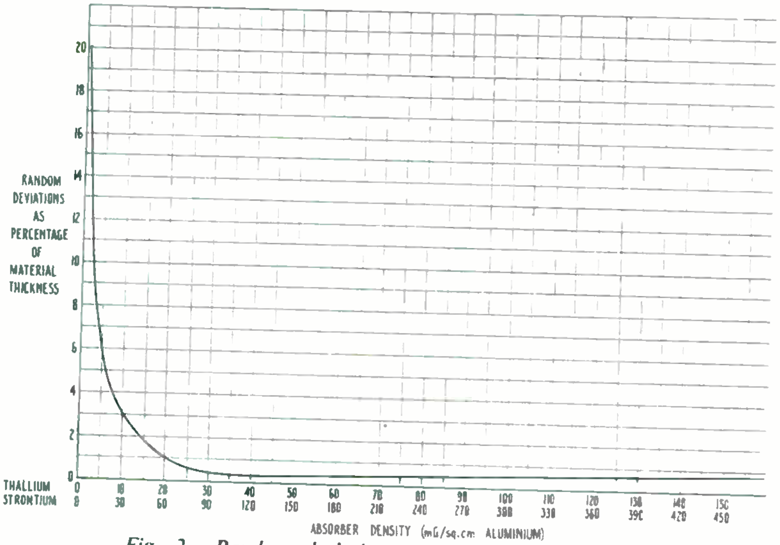

Fig. 2.—Random deviations as percentage of material thickness using 10 mC/s sources with N504 thickness gauge. (0·2 sec time constant.)

of differing energy particles. It must be remembered that a beta source emits particles having energies from near zero up to the maximum.

It may be thought that due to the very large quantity of particles emitted by a 10 millicuries source—$3{\cdot}7\times10^8$/sec.—the statistical variation will be small, but this is not necessarily so. With a 10 millicuries source, allowing for the geometrical factor and the presence of an absorber, the actual number of particles falling on the sensitive area of the ion chamber, may be one million or less with a statistical variation of 1000 or 0·1 per cent. for a one-second time of measurement.

If this amount of radiation generates 10 volts across the load resistor, the statistical variation of 0·1 per cent. will generate 10 millivolts. It must be remembered that the standing voltage is backed off and that the meter which indicates deviation from the mean mass may be fully deflected for an input as low as 100 mV. Under these conditions, with a one-second time of measurement, the meter pointer will be rapidly fluctuating over a distance equal to 10 per cent. of full scale deflection and the reading accuracy cannot be better than this.

Additional fluctuations due to uneven ion pair production in the chamber will have to be added to this figure.

Fortunately, conditions are not often as bad as this example, but Fig. 2 shows some actual figures of the maximum deviation experienced, expressed as a percentage of the thickness of the material being measured.

3. Practical Application

The equipment in use on cigarette making machines incorporates a pair of balanced ionization chambers and radioactive sources and the cigarette rod to be measured passes between one chamber and source, through a guide which is designed to collimate the radiation and eliminate positional errors; between the other chamber and source is fitted an absorber having equivalent mass to the cigarette rod. The polarizing voltages across the ionization chamber are of opposite polarity and the currents from the two chambers pass in parallel through the same load resistor, which is also the input resistor of the amplifying system.

When the cigarette rod is at its mean value of mass, the currents through the two chambers are equal but opposite in polarity and, therefore, the voltage across the load resistor is zero. If cigarette rod mass increases or decreases, the currents no longer balance and a voltage is generated across the load resistor, the polarity and amplitude of which is related to the change in mass.

The use of a second ionization chamber and source to generate a balancing current to back off that generated in the measuring chamber has many advantages, some of which are that changes in value of the load resistor or changes in amplifier gain are cancelled out at mean mass and have only a secondary effect at deviations from balance. In addition, if the two sources and chambers are placed near to each other, compensation is obtained for changes in temperature and/or humidity, in so far as they affect the air gap between the source and chamber.

Electronic instrument stability is ensured by using the well-known vibrating reed electrometer as the measuring instrument, an instrument which has considerably less zero drift than

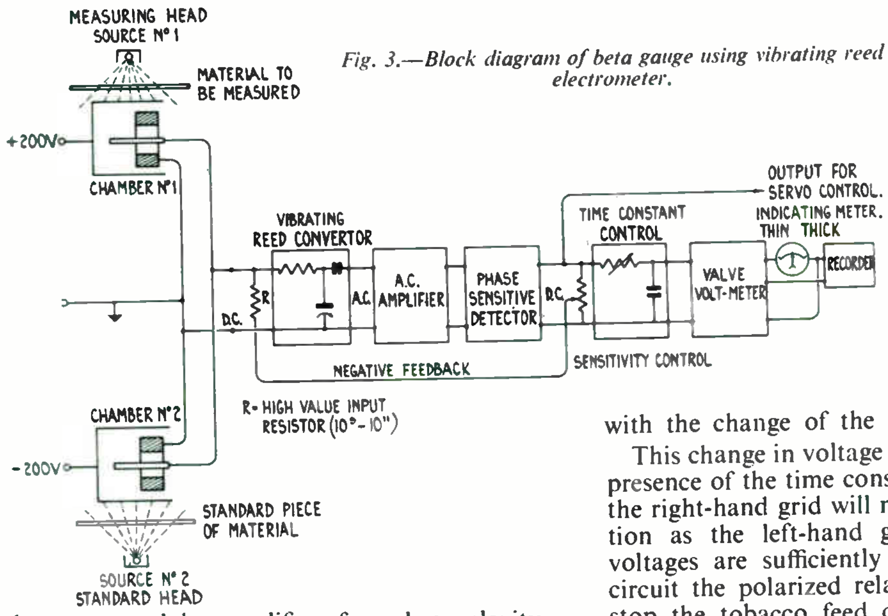

Fig. 3.—Block diagram of beta gauge using vibrating reed electrometer.

the more usual d.c. amplifier of equal complexity.

A block diagram of the beta gauge is shown in Fig. 3.

4. Automatic Control

The beta gauge is used to control the weight of the cigarette and the diagram of the circuit used to achieve this is shown in Fig. 4.

When the cigarette rod is at its mean value there is no output from the beta gauge. If the cigarette increases in mass, a positive voltage in respect to ground is obtained and if the cigarette mass decreases, then a negative output voltage is obtained.

The proportional control circuit is shown in Fig. 4 and the output from the beta gauge is applied to the left-hand grid of the balanced pair. A polarized relay is connected between the two cathodes and provision is made to balance the circuit and to adjust the relay sensitivity, both by means of variable resistors. The right-hand grid is normally earthed. When the output from the beta gauge changes from zero, the current through the left-hand valve will change and the polarized relay between the cathodes will be deflected. If the current change through the valve exceeds a preset limit, the polarized relay contacts will be closed and these will in turn energize slave relays which will start up a control motor to increase or decrease the tobacco feed, as necessary. At the same time, the right-hand grid voltage will be switched by means of slave relays to a more positive or more negative voltage in sympathy with the change of the left-hand grid.

This change in voltage will be slow, due to the presence of the time constant in this circuit, but the right-hand grid will move in the same direction as the left-hand grid until the cathode voltages are sufficiently near balance to open circuit the polarized relay contacts, which will stop the tobacco feed control motor and the right-hand grid will start to return to zero. By now, the tobacco feed should have altered and the peak variation on the left-hand grid should have passed and this grid should now be slowly returning to its normal voltage; however, if the tobacco feed change is slower than the return to normal on the right-hand grid, the cathodes may again become unbalanced, the control motor will be restarted and the right-hand grid will

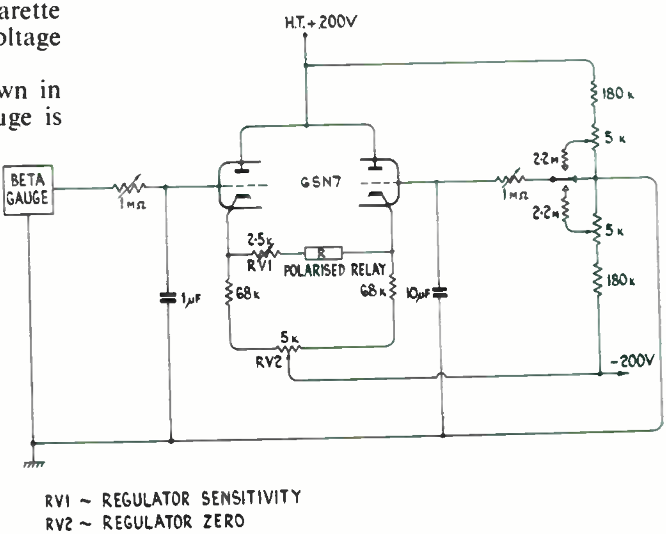

Fig. 4.—Regulator circuit.

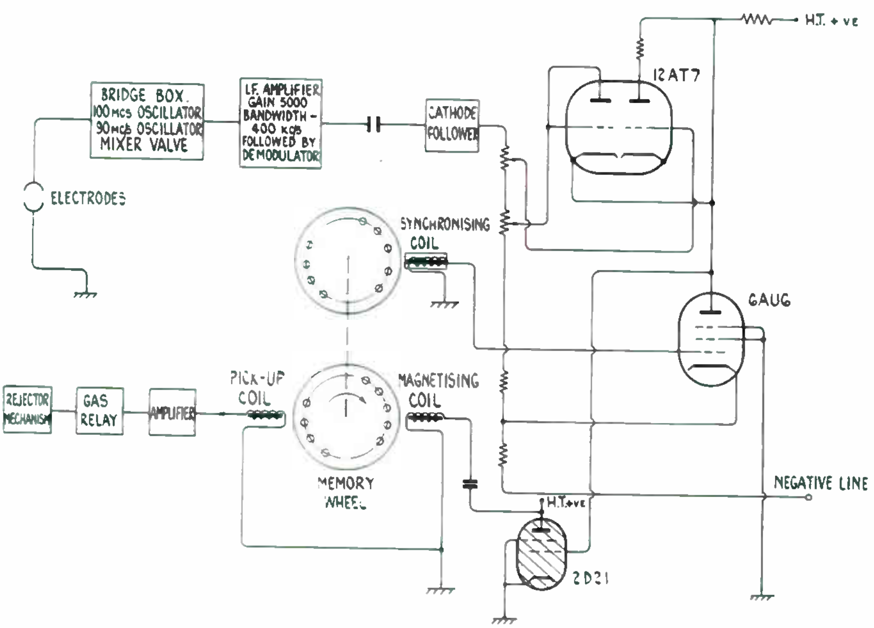

Fig. 5.—Block diagram of dielectric gauge and rejector.

again be switched to the feed-back voltage line. The resultant voltage on this grid will be a combination of the voltage applied and that remaining in the grid capacitor. This cycle will be repeated until the cigarette rod mass is at its mean value.

If the correction has been excessive, the left-hand grid voltage will pass through zero and will now be of the opposite polarity to the right-hand grid. The polarized relay will take note of this and will switch on the control motor in the opposite direction and apply a reversed polarity voltage to the right-hand grid, again repeating the cycle until balance is restored.

It will be seen that the voltage applied to the left-hand grid of the pair will vary directly in sympathy with changes in the mass of the cigarette rod, within, of course, reasonable limits. The time taken for the right-hand grid to equal the voltage of the left-hand grid will depend upon the amplitude of the left-hand grid voltage. During the whole time that the right-hand grid is seeking the left-hand grid, the control motor will be operating and, therefore, the time for which the tobacco feed speed regulating motor is switched on is proportional to the magnitude of the error in cigarette mass which has to be corrected.

5. Dielectric Gauge

The beta gauge measures and controls the slow changes in the mass of a cigarette rod, while the facilities supplied by the dielectric gauge are:—

(1) The detection and rejection of out-of-limit individual cigarettes.

(2) The automatic disengagement of the rejector and regulator mechanisms when the machine is inoperative or not running correctly. This function is referred to as automatic lockout.

The dielectric gauge is, as its name indicates, an instrument which measures the change in the dielectric between a parallel plate capacitor which forms one arm of an alternating current bridge. For many applications it is completely successful, but when measuring a complex material like shredded tobacco, which has strands of material at all angles and a variable moisture content, it has many limitations.

Measurements have been made at various

frequencies and it has been found that the most satisfactory frequency for tobacco is around 100 Mc/s. At this frequency there are two major difficulties remaining, temperature and humidity changes, both of which, in general, change slowly. If the frequency response of the system is adjusted so that these slow changes are not accepted, the gauge will no longer give any indication of slow changes in the mass being measured, but will respond to short term changes. Therefore, when used with a beta gauge, which has the opposite characteristics, a satisfactory composite instrument will be obtained.

It will be appreciated that under these conditions, the dielectric gauge is not capable of detecting slow changes, and therefore, cannot be used as an instrument on its own.

The dielectric gauge uses the beta gauge cigarette rod guide bars as the plates of the measuring capacitor in the bridge circuit which works at 100 Mc/s. The bridge elements, the 100-Mc/s oscillator, a 90-Mc/s oscillator and a mixer, are all built into a small unit, using sub-miniature components, which is mounted on the ionization chamber to reduce lead lengths. Special precautions are taken to ensure oscillator stability, including the stabilization of all power supplies. The output voltage from the mixer is at 10 Mc/s and is passed via a co-axial cable to an i.f. unit, mounted in the main instrument case, together with the rest of the installation. After rectification, the signal is a.c. coupled to a cathode follower and is then used to operate an electro-magnetic mechanism which rejects out-of-limit cigarettes.

6. Automatic Rejection

The dielectric gauge is measuring the mass of the cigarette rod whilst it is still in continuous form and obviously individual cigarettes cannot be rejected until they have been cut. This cutting operation occurs 1/10th of a second after measurement and the rejector mechanism operates 1·6 seconds after cutting. It is, therefore, necessary to delay reject information to the rejector mechanism for 1·7 seconds and at the same time to ensure that the rejector operates only when the cigarette is correctly positioned. By this is meant that the rejector must not operate between or partially between, cigarettes.

These functions are performed by a memory wheel and a synchronizing wheel, both of which are driven from the cutting mechanism.

The synchronizing wheel is a disc of brass containing soft iron inserts. These inserts pass through an electro-magnetic pick-up coil and generate a voltage pulse for each cutting action, that is for each cigarette.

The memory wheel is of similar construction, but the soft iron inserts are magnetized by passing a current pulse through a magnetizing coil. This current pulse is a product of the synchronizing voltage and the voltage resulting from out-of-limit cigarette rod mass. A pick-up coil displaced around the periphery of the wheel by a distance equal to 1·7 seconds, collects reject information and passes it, through an amplifier, to the rejector.

A simplified circuit diagram of this section is shown in Fig. 5 and the operation is as follows:

A tap on the cathode follower following the dielectric gauge is adjusted for zero voltage with respect to ground when the cigarette rod is at its mean mass. Point-to-point increases or decreases in mass will thus cause positive or negative changes in the voltage at the tap. Positive variations will be passed through a diode to the anode of the gate valve and negative variations will be reversed in polarity by the triode and applied to the same anode. This anode is connected to the grid of the thyratron but the circuit parameters are such that the increase in voltage from the dielectric gauge is not, on its own, sufficient to trigger the thyratron.

The voltage pulses from the synchronizing wheel, previously described, are applied to the grid of the gate valve but again the resultant increase in anode voltage is, on its own, insufficient to trigger the thyratron and it is only when a signal on the anode coincides with a signal on the grid, that the anode voltage rises sufficiently to cause the thyratron to conduct, which passes a current through the magnetizing coil and this magnetizes an insert which in due course activates the rejector mechanism.

Potentiometers are used to permit the voltages from the cathode follower to be adjusted to the required limits and a permanent magnet is used to erase the memory wheel reject information once it has been used.

7. Automatic Lock-out

The final facility available is the automatic "lock-out" which disengages all forms of automatic control under abnormal conditions, such as are caused during the starting up or

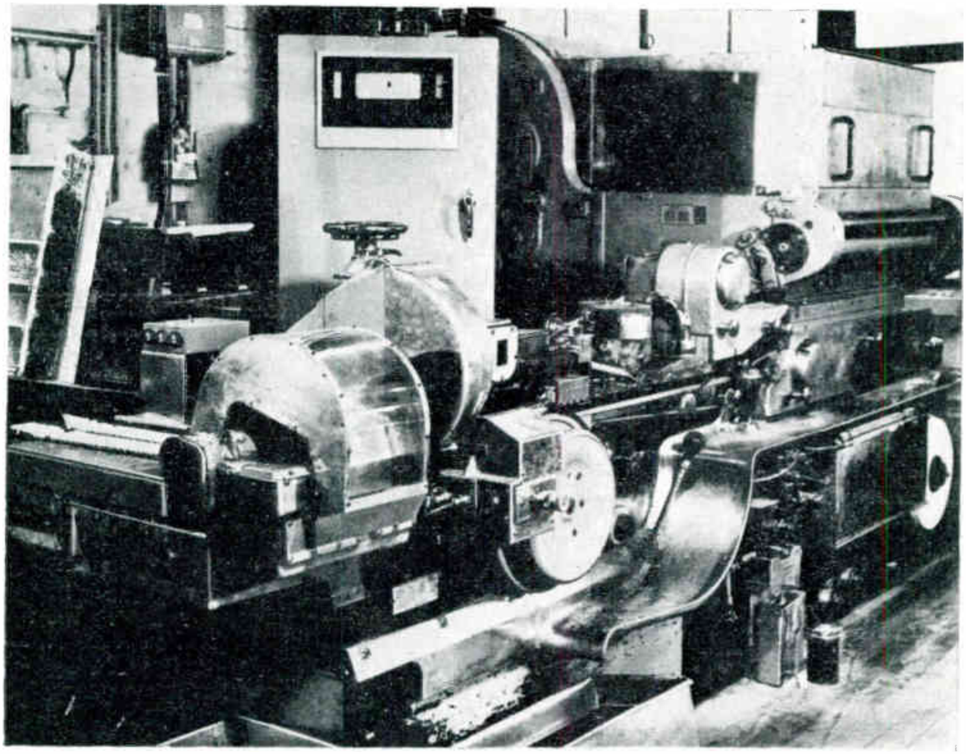

Fig. 6.—General view of cigarette weighing and cutting equipment. The electronic circuits are contained in the cabinet at the rear.

stopping the machine, or when a break occurs in the cigarette rod.

It has been pointed out that the dielectric gauge is functioning on short term changes only and it can readily be appreciated that with an uneven material such as cigarette rod passing the measuring head, there will always be a certain amount of "noise" and that the frequency of this noise will be related to the speed of the rod through the measuring head.

The noise voltage is taken from the cathode follower subsequent to the dielectric gauge and is amplified, shaped and then applied through a diode pump to a simple ratemeter circuit, consisting of a capacitor shunted with a resistor. The voltage across this network depends upon the frequency of the applied pulses and it is so arranged that when this voltage reaches a certain level, a valve is switched on and energizes a relay which starts the regulator and rejector mechanisms. When the cigarette rod is stationary or is travelling slowly, so that the ratemeter voltage is low, the valve is inoperative, the relay contacts are open and the regulator and rejector circuits inoperative. An electronic time delay is fitted to prevent premature operation of regulator and rejector during the warming up period.

8. Conclusion

It will be seen that the combination of a beta gauge and a dielectric gauge, retains the good points of both instruments and that the facilities obtained from such a combination are probably impossible of achievement by either individual equipment. Fig. 6 shows a complete gauge installed on a cigarette making machine.

9. Acknowledgments

This paper is published by permission of the Directors of the Industrial Machinery Company, Ltd., E. K. Cole, Ltd., and Ekco Electronics, Ltd., and thanks are due to my colleagues for assistance in its preparation.

DISCUSSION ON NUCLEONIC THICKNESS GAUGES*

C. S. Selinger (*Associate Member*): Can Mr. Shaw describe how he differentiates on his Alpha Gauge between variations in paper weight and moisture content.

E. N. Shaw (*in reply*): Where in the discussions I have mentioned thickness, the term weight per unit area should have been used implying that the effects of water and paper are identical. This is generally true, particularly with thin papers, but it is possible that the two will give different effects, for example, if the paper is of a very open structure, and looks rather like a net, then the holes will be completely transparent to the alpha rays, whereas the fibres may stop the alpha rays entirely. In this case, the output reading is a function of the shadow area rather than weight, and the introduction of moisture may make either no change or very dramatic changes if the moisture is held in the interstices. This is, of course, an extreme case, and is unlikely to occur in practice. In general, then, the significant criterion is the weight per unit area with the proviso that small changes in calibration must be expected with different types of paper structure.

B. C. Fleming-Williams (*Member*): I notice in the papers on Beta and Alpha gauges a resistance of 10^{10} and 10^{11} ohms. Can the authors get reasonable reliability under working conditions?

E. N. Shaw (*in reply*): In practice, we totally enclose all the high resistance units in a potting compound so that the only leads in contact with the atmosphere are low impedance. This is so with the Beta Gauge, but with the Alpha Gauge where the chamber is not sealed, one has to rely on long path lengths across polythene. It is possible under these conditions that with sudden drops of temperature under saturated humidity conditions, condensation will occur over significant points, but we have found that in practice this happens only very rarely, and almost never when the mill is running. Furthermore, with a guard ring between collector and polarizing electrode and a balanced chamber system, any leaks are to earth only, which will alter the sensitivity admittedly, but will not alter the calibration.

G. Syke (*in reply*) High resistors of 10^9 to 10^{12} ohms have certain performance characteristics which need to be taken into account when using them. I have found that such resistors of reliable make, when treated and sealed with reasonable care, have a long term stability of a few per cent. per month to a few per cent. per year, but their short term stability after having corrected for temperature coefficient is very high.

The long term stability of calibration of the Beta Gauge should not be based on that of the input resistor, but on some other reference standards. We generally use two such standards:

(*a*) zero, i.e., no absorber in the measuring gap,

(*b*) infinity, i.e., radiation cut off completely by closing the source.

Two ends of the calibration scale are thus fixed: the intermediate calibration scale depends on the energy spectrum of the source, which is constant throughout its life.

Replying to suggestions by **Mr. W. Nock** for the use of scintillation counters and a balancing capacitance gauge, **Mr. R. Y. Parry** pointed out that it was the increase in sensitivity achieved by backing off the standing current in the measuring chamber that caused trouble due to random variations. In obtaining the same deviation sensitivity from a scintillation counter, random variation would again become the limiting factor. One of the main troubles affecting the long term stability of dielectric gauges was the moisture content of the material being measured and obviously, it would not be always possible to simulate identical positions in both capacitors in a balanced system. In addition, it was extremely difficult over a long term to relate accurately the sum of the mass of the material being measured, plus the moisture content, in terms of true mass.†

P. S. Brackenbury: Am I right in assuming that the results obtained by the gamma ray thickness gauge are independent of temperature; in other words the thickness result that you get from it is not the thickness at the time of measuring the strip, but at the time when it becomes cold.

G. Syke (*in reply*): The readings obtained on the thickness gauge depend on how it was initially calibrated. The surface area of steel strip changes with temperature, but its mass remains constant. Hence the change in mass per unit area appropriate to average rolling temperature is allowed for in the calibration and the instrument therefore indicates the strip thickness when cold.

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* Points from the discussion at Session 3 of the Industrial Electronics Convention referring to the papers by Shaw, Syke and Parry published on pages 414 to 432.

† See, for instance J. A. Van Den Akker and K. W. Hardacker, *T.A.P.P.I.*, 35, July 1952, pp. 138-148.

CONTRIBUTION:

SPATIAL POWER DISTRIBUTION DIAGRAMS FOR AERIALS WITH VERTICAL RADIATION*

by

Paul Adorian (*Member*)†

SUMMARY

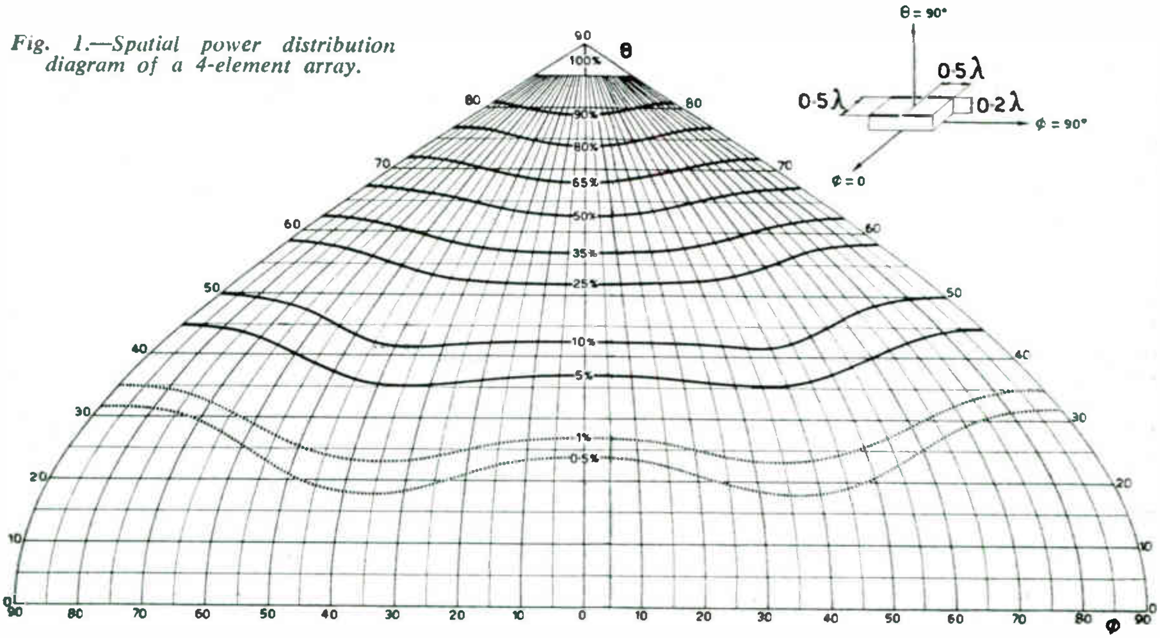
Spatial power distribution diagrams are given for 4-element and 16-element arrays radiating in a predominantly vertical direction. The arrays are primarily intended for tropical broadcasting.

1. Introduction.

A paper by Mr. A. H. Dickinson and the present author, read before the Institution in 1951, dealt with high frequency broadcast transmission with vertical radiation.[1] In this paper the three-dimensional polar diagrams of some suitable aerials were given including the polar diagram of a 16-element array.

Subsequently, when the International Radio Consultative Committee (C.C.I.R.) met in London in 1953 the above paper was discussed, and, on the suggestion of the present author (who was the British delegate in connection with Tropical Broadcasting), the C.C.I.R. Directorate were asked to prepare spatial power distribution diagrams for aerials with predominantly vertical radiation for including in the C.C.I.R. Antenna Diagrams Handbook.[2] The reason for this request was that the polar diagrams as shown graphically and the three-dimensional models in Ref. 1 are somewhat clumsy in practical use and it was thought that by the inclusion of the polar diagrams of these aerials in a more convenient form, engineers engaged in providing tropical broadcasting services would be able to carry out their design work more easily.

Fig. 1.—Spatial power distribution diagram of a 4-element array.



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* Manuscript received 18th August, 1954. (Contribution No. 12).

† Central Rediffusion Services Ltd., London, S.W.1.

U.D.C. No. 621.396.677.

2. New Spatial Power Distribution Diagrams.

The Directorate of the C.C.I.R. have now prepared two diagrams, shown here as Fig. 1 and Fig. 2, which in due course will be included in the C.C.I.R. Antenna Diagrams Handbook as Figs. 38 and 39.

Figure 1 is the spatial power distribution diagram of a 4-element array. The dimensions of the aerial are clearly shown in the top right-hand three-dimensional sketch in this figure and it will be seen from this that ϕ is the azimuth angle and θ is the angle of elevation. The aerial itself, as will be seen from the diagram, consists of four elements, half-wavelength long each, each pair in a line and spaced half a wavelength apart in the horizontal plane and one-fifth wavelength above ground.

Figure 2 refers to a sixteen-element array, each of the elements being half a wavelength long, four elements in line and four such groups horizontally spaced from one another by half a wavelength distance. All elements are one-fifth wavelength above ground. The same convention as above applies to elevation and azimuth angles. (General arrangements, including interconnections, are given in the paper by Adorian and Dickinson,[1] Fig. 9.)

It should be noted in reading these spatial *power* distribution diagrams that the percentage figures shown on the diagram indicate the relative *power* densities compared with the power density in the direction of maximum radiation, which is shown as 100 per cent. The broken lines shown in Fig. 2 indicate zero percentage power density.

More information on this type of projection of antenna diagrams can be found in the C.C.I.R. Antenna Diagrams Handbook[2] and also in a paper by Hayes and MacLarty.[3]

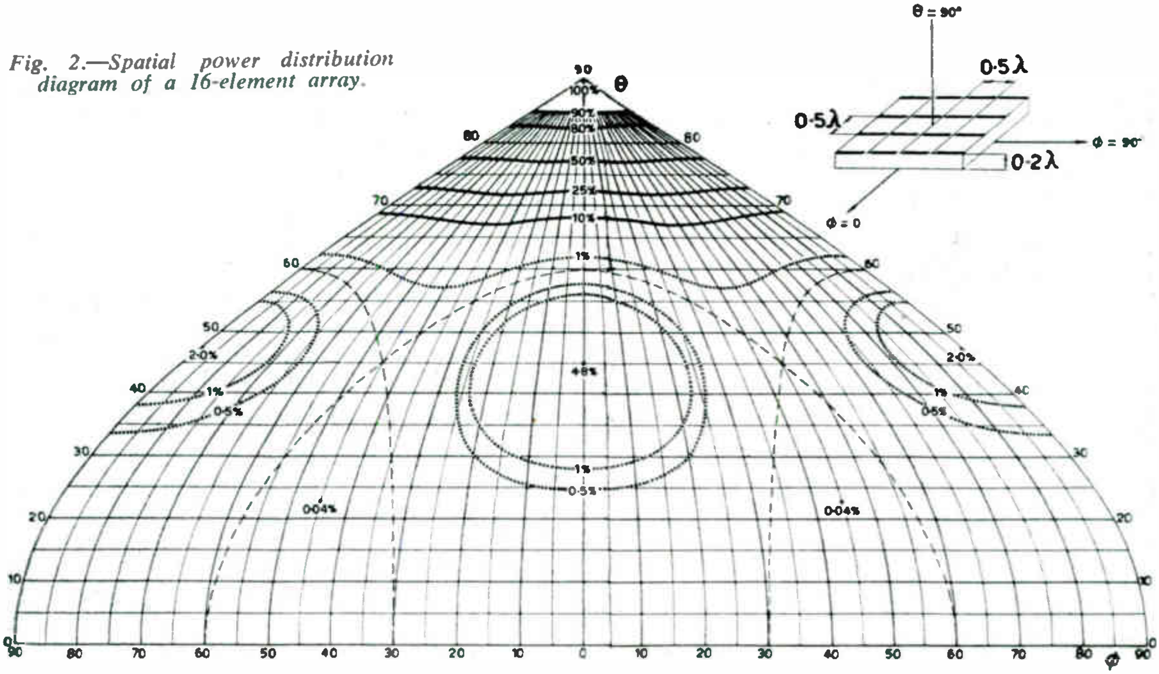
3. Acknowledgment.

Acknowledgment is due to the Vice-Director of the C.C.I.R., Geneva, Mr. L. W. Hayes, for permission to publish Figs. 1 and 2.

4. References.

1. P. Adorian and A. H. Dickinson, "High frequency broadcast transmission with vertical radiation." *J.Brit.I.R.E.*, **12**, February, 1952, pp. 111 - 116.
2. "C.C.I.R. Antenna Diagrams" (C.C.I.R., Geneva, 1943).
3. L. W. Hayes and B. N. MacLarty, "The Empire Service Broadcasting Station at Daventry." *J. Instn Elect. Engrs*, **85**, September, 1939, pp. 321 - 357.

Fig. 2.—Spatial power distribution diagram of a 16-element array.



AN ULTRASONIC METHOD OF GAUGING*

by

F. M. Savage†

A paper presented during the Industrial Electronics Convention held in Oxford in July, 1954.

SUMMARY

A method is described of measuring wall thickness accurately although only one surface may be accessible. A variable frequency oscillator is employed which sets up standing waves between the transducer and the reflecting surface. At the resonant frequency and its harmonics the oscillator anode current increases and measurement of the frequency interval between these peaks enables the thickness to be calculated. The paper describes:—(1) A portable instrument in which the frequency modulation is by a mechanically-rotated capacitor, and audible or meter indication is given; (2) A larger instrument employing electrically variable inductor tuning and direct reading c.r.t. presentation. Consideration is given to the design of transducers, choice of couplants, applications and limitations, and to accuracy and range.

1. Introduction

In many industries there exists a demand that the wall thickness of certain components and structures be accurately measured, although only one surface is accessible. Typical examples include hollow propeller blades, aircraft extrusions, hollow shafts, waveguide components, deep drawn or spun components, castings and forgings. It is also necessary to measure the wall thickness of pipes, pressure vessels, gasholders, tanks and the plates of ship's hulls whilst they are in service, to enable wastage due to erosion or corrosion to be accurately assessed. Any successful method must be simple to operate, reliable, accurate and in many instances the equipment must be completely portable.

The method to be described depends upon the phenomena of resonance of sound waves for its operation and in practice has proved to be highly successful. In some respects the method may be likened to the tuning of an organ pipe. The length of the air column in the pipe is adjusted until it resonates at the desired frequency, whilst in the ultrasonic method used in the thickness gauge the frequency is varied, since the thickness, corresponding to the length of the air column, is fixed but unknown.

Ultrasonic waves travel through metal or other material at a velocity that is a function of its density and elastic constants.‡ The relationship is expressed by

$$V = \sqrt{\frac{(1-m)\,.\,E}{d(1+m)(1-2m)}} \quad \text{..................(1)}$$

where V = velocity
E = Young's modulus
m = Poisson's ratio
d = density

Young's modulus is the ratio of the stress intensity to the resulting strain. Poisson's ratio is the relation between a change in width and the change in length causing it.

Ultrasonic waves are reflected at the boundary of two materials that have different acoustical impedances such as metal and air, or metal and water; in the case of metal-to-air the reflection is almost 100 per cent.

Acoustic impedance is determined by the elastic constants of the material and represents a characteristic of the medium closely related to electrical impedance. As in the case of electrical impedance, when a material of a given impedance is matched into another medium of like impedance, or when terminated in its own characteristic impedance, then the two will act as a single piece and no reflection at the boundary of the two materials will result.

Returning to the simile of the organ pipe, standing waves can be set up within the thickness of a piece of metal in the same manner that standing waves are set up within the air column of the organ pipe. (Fig. 1.)

The frequency of the standing waves will in one case depend upon the thickness of the metal

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* Manuscript received February 8th, 1954, and in revised form June 11th, 1954. (Paper No. 282.)

† Dawe Instruments Ltd., Ealing, London, W.5.
U.D.C. No. 534.2: 620.179: 621.376.3.

‡ W. C. Schneider and C. J. Burton. *J. Appl. Phys.*, 20, Jan. 1949, p. 49.

and the velocity of ultrasonic waves in it, and in the other case upon the length of the air column and the velocity of sound in air.

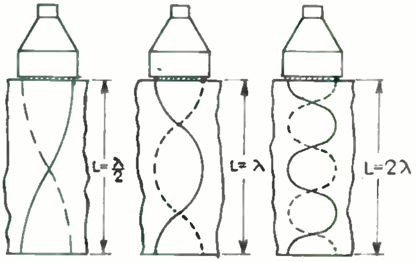

Fig. 1.—Standing wave patterns in material.

Since the relationship of wavelength, frequency and velocity $\lambda = V/f$ holds good for ultrasonic waves, the fundamental frequency at which thickness resonance occurs can be expressed:—

$$f_1 = V/2t$$

where f_1 is in cycles per second, t is in inches per second and V is the velocity of sound in the material in inches per second. Thickness resonance also occurs at all harmonics of the fundamental frequency

$$f_2 = 2f_1, f_3 = 3f_1, f_n = nf_1$$

The frequency difference between any two adjacent harmonics is equal to the figure for fundamental frequency.

When the fundamental frequency is known $t = V/2f_1$.

When two adjacent harmonic frequencies are known

$$t = \frac{V}{2\,(f_n - f_{n-1})}$$

The right-hand side of the equation contains no frequency sensitive term showing that velocity is independent of frequency. If this were not so the resonance method could not be used. Wood, Loomis and Hubbard have verified this* experimentally and reported that they could detect no change in the velocity of sound in different media at various frequencies.

The elastic constants of relatively pure metals and alloys are extraordinarily constant—the density varies only within close limits and any small variations are largely offset by slight changes of the elastic constants in the same direction. Moreover, the effect of such variations on the velocity are effectively halved by the square root on the right-hand side of the equation. Temperature will obviously have some effect on the density, but this is to a certain extent self compensating. Thus, if a coefficient of thermal expansion α is assumed, the density will be reduced by an amount proportional to 3α. Taking into account the square root the velocity will be increased by an amount proportional to $3\alpha/2$.

For such variations of E, d, and temperature encountered in practice the velocity changes only slightly. Tests carried out on many specimens of like materials show that the variation can be ignored when the accuracy required is in the order of 2–3 per cent.

Table 1

Velocity of Ultrasonic Waves in some Common Materials

Material	Velocity cm/sec × 10^5	Density gm/cm^3	Specific Acoustic impedance × 10^6
Air	0·331	0·00120	0·0000413
Aluminium...	6·30	2·65	1·70
Brass ...	4·52	8·4	3·79
Copper ...	4·70	8·9	4·18
Glass ...	4·8–5·9	2·4–5·9	1·80
Glycerine ...	1·99	1·26	0·25
Magnesium	5·5	1·70	0·935
Mercury ...	1·46	13·6	1·98
Nickel ...	5·6	8·85	4·95
Oil (light) ...	1·35	0·90	0·122
Quartz ...	5·75	2·65	1·51
Steel ...	5·89	7·4	4·59
Water ...	1·435	1·0	0·1435

Specific acoustic impedance is the product of velocity and density.

2. Generation of Ultrasonic Waves

Ultrasonic waves can be generated either mechanically or electrically; the limited frequency range of the mechanical devices, however, prevents their effective use as measuring instruments.

Crystal and magnetostriction transducers, driven by an electronic oscillator provide a convenient source of ultrasonic energy over a wide range of frequencies. Magnetostriction is limited to frequencies not exceeding 100 kc/s, whereas crystals can be used at frequencies of several megacycles per second. Mainly for this reason crystal transducers are used almost exclusively in ultrasonic measuring equipment.

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* R. W. Wood, A. L. Loomis and J. C. Hubbard. *Phil. Mag.*, 1927, p. 417; *Nature*, Aug. 6th, 1927.

The piezo-electric effect occurs in several natural and artificial crystals including quartz, but because of its mechanical strength and durability quartz is most commonly used.

3. Basic Circuit for Thickness Gauge

The circuit shown in Fig. 2 forms the basis of several instruments using the resonance method of thickness determination.

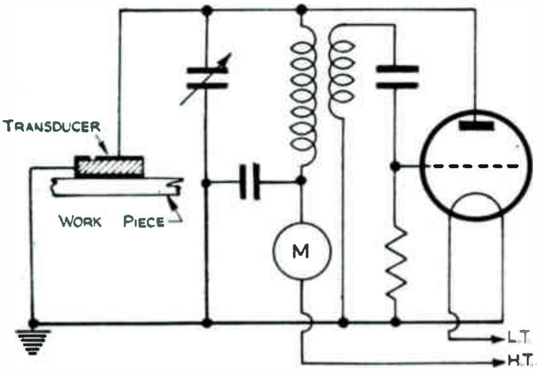

Fig. 2.—Basic circuit of thickness gauge.

The output from a variable frequency oscillator is taken to an X-cut quartz crystal which is held firmly against the wall or surface of the component being measured. A film of oil or similar medium between the crystal face and the surface of the component is employed to achieve good transmission of the ultrasonic waves into the component.

When the oscillator is tuned to a frequency which is equal to, or a multiple of, the fundamental frequency of the wave in the thickness of the material, there will be a considerable increase in the amplitude of the vibration in the part of the component immediately beneath the crystal. This is a condition of resonance and because of internal damping in the material, there will be an increase in the energy dissipated. This internal damping affects the oscillator as though a resistive component had been placed in parallel with the L-C circuit and consequently a considerable increase in anode current of the oscillator valve will take place.

4. Practical Instruments

Under ideal conditions the anode current of the oscillator may be doubled at resonance, but in practice the increase may well be only of the order of a fraction of 1 per cent. This small change will almost certainly be swamped by the normal variation of oscillator anode current when tuned over the full frequency range.

A more positive method of indicating resonance thus becomes necessary and Fig. 3 shows the arrangement used in one commercial instrument.*

The oscillator which is permeability tuned is frequency modulated over a small frequency range by means of a small motor-driven variable capacitor. Thus, when the average oscillator frequency is tuned to the frequency at which a thickness resonance occurs, pulses of anode current will result. These pulses are produced at an audio frequency rate, and are amplified by a l.f. amplifier.

After amplification the output is rectified, and indicated on a meter or fed to a pair of head-sets or loudspeaker. Resonance is indicated by an increase in the meter reading or by an audible note.

In the instrument depicted the capacitor vanes are so shaped that a similar change of capacitance takes place eight times for each revolution of the shaft. The motor driving this capacitor runs at about 1200 r.p.m., so that the oscillator is tuned about the thickness resonance frequency at 9600 times per minute or 160 times per second. Since this repetition rate is in the audio frequency band, amplification of the voltage produced by the pulses of anode current is carried out by a normal l.f. amplifier. Padding capacitors are placed in series with the variable capacitor, thus enabling modulated bands of various widths to be chosen. Narrow bands provide maximum selectivity and accuracy, whilst the wider bands are used when the surface is not smooth or when the material beneath the crystal is varying in thickness.

The oscillator covers a frequency range of 0·75 Mc/s to 2·0 Mc/s divided into two bands to give maximum scale width. Since the frequency swing of the oscillator does not greatly exceed 2 to 1, a single crystal is used at all frequencies with very little loss of sensitivity. If fundamental resonance indications only were used the thickness range would be of the same order as the frequency range, but by the use of harmonic resonance indications this range is extended to approximately 100 to 1.

For example, assuming the velocity of sound in steel to be 232 × 10^3 in./sec., the fundamental

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* "Ultrasonic Thickness Gauge," Dawe Instruments, Ltd.

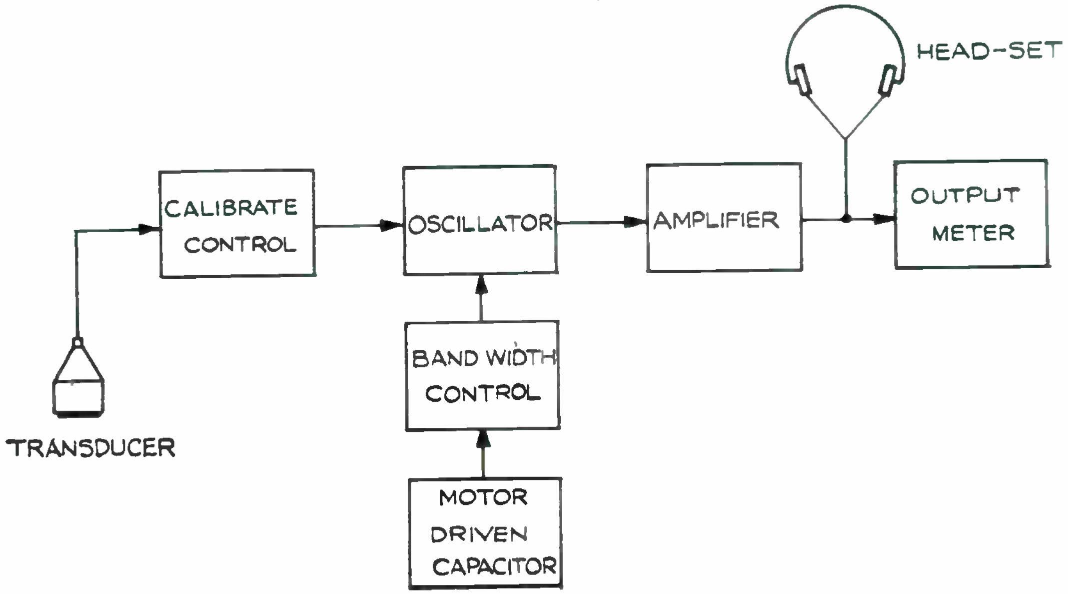

Fig. 3.—Block diagram of portable thickness gauge.

thickness resonance frequency for a piece of steel 0·060 in. will be 1·933 Mc/s, a figure which is within the range of the instrument. A steel plate of 0·308 in. thickness will have a fundamental thickness resonance of 0·3766 Mc/s. This figure is outside the frequency range in use, but resonance will also occur at:—

$$2f_1 = 0{\cdot}7532 \text{ Mc/s}$$
$$3f_1 = 1{\cdot}1298 \text{ Mc/s}$$
$$4f_1 = 1{\cdot}5064 \text{ Mc/s}$$
$$5f_1 = 1{\cdot}883 \text{ Mc/s}.$$

It will be seen that the third, fourth and fifth harmonics all fall within the operating band. The frequency difference between any two adjacent harmonics is taken to obtain the fundamental frequency.

A still thicker plate of steel 10 in. thick will have a fundamental resonance frequency of 0·0116 Mc/s which is well outside the range of the instrument. But harmonics from 70 (0·812 Mc/s) to 170 (1·97 Mc/s) all fall within the frequency band and the frequency difference of any two adjacent harmonics is again taken to obtain the fundamental.

The previous figures show that a frequency range of 2·5 to 1 represents a thickness range of greater than 100 to 1.

The tuning scale is calibrated in megacycles per second, but a form of circular slide rule fitted to the instrument permits rapid conversion to thickness using the equation $t = V/2f_1$.

Since the capacitance of the transducer and connecting cable is virtually in parallel with the oscillator tuned circuit, a small variable capacitor is connected across the cable to permit interchange of transducers and cables.

Calibration of the equipment is checked by the use of a test-block of known thickness. Test-blocks of suitable dimensions enable the instrument to be realigned when no signal generator is available. A test plate of steel 0·308 in. thick gives four check points covering practically the whole of the frequency range.

Because of its size no attempt has been made to provide a highly stable oscillator, the accuracy of thickness measurement being of the order of ±2 per cent.

4.1. *Direct Reading Gauges*

The use of the harmonic resonance indications prevents the instrument being directly calibrated in inches, a simple calculation being necessary for each fresh position of the transducer. When large areas have to be measured this may be a long and tedious process.

In order to overcome these limitations instruments have been produced which may be described as "automatic". They are automatic in so far that no manual tuning is employed and are directly calibrated in thousandths of an inch. A motor driven capacitor varies the frequency of the oscillator over a 2 to 1 range and the fundamental thickness resonance is displayed on a cathode ray tube fitted with a calibrated mask. The frequency range must not be greater than 2 to 1 otherwise harmonic resonance indications will be displayed, as well as the fundamental.

A separate transducer is necessary for each band to prevent loss of sensitivity.

A new direct reading automatic type of instrument* embodying interesting features has recently been produced. This instrument covers a wide thickness range of 0·015–6 in., the accuracy of measurement being of the order of 0·1 per cent. A block diagram giving the circuit arrangement is shown in Fig. 4.

The total frequency range of 0·75 Mc/s to 8 Mc/s, is divided into six overlapping bands, each band having a maximum frequency sweep of 2 to 1.

Instead of using a motor-driven capacitor to vary the oscillator frequency an electrically variable inductor working on the principle of the saturable-core reactor is employed. A plug-in oscillator unit is provided for each of the six bands, each unit containing a variable inductor, oscillator valve and associated components. Complicated switching arrangements are avoided by the use of these plug-in units and stray capacitances are reduced to a minimum.

A 50-c/s alternating voltage applied to a control winding on the inductor assembly causes the inductance to vary at a similar rate. Since this inductance forms part of the oscillator tuned circuit the oscillator is frequency modulated at 50 c/s.

The width of the band through which the oscillator is swept is determined by the amount of current flowing through the control winding. Adjustment of the voltage across the coil enables sweep bands of predetermined width to be obtained. As will be seen from the block diagram, the control voltage is derived from a stabilized source to maintain constant band width even though the voltage of the supply is fluctuating. A calibrated control provides sweep bands of predetermined widths ranging from 2 to 1 to 1·1 to 1. As will be seen later the use of the narrow sweep bands enable harmonic as well as fundamental resonance to be employed.

As in the case of the portable thickness gauge, pulses are produced at the oscillator anode, and these are amplified and taken to the vertical deflection coil of a cathode ray tube. The horizontal time-base is provided by the stabilized 50-c/s supply. Pulses also derived from the same source are applied to the grid of the tube to eliminate flyback. A very large cathode ray tube is employed to give maximum scale length, the advantage of which can be seen from Fig. 5, where a scale length of 17 in. represents a thickness range of 0·04 in.

A narrow frequency band will obviously represent a correspondingly narrow thickness range. But since the amplitude of the time base is always adjusted to keep the scale length

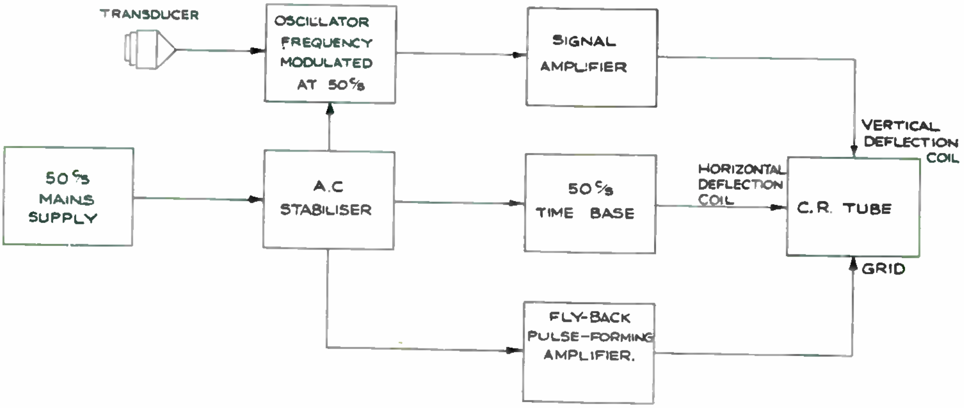

Fig. 4.—Automatic thickness gauge.

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* "Vidigage," Branson Instruments Inc., Stamford, Conn., U.S.A.

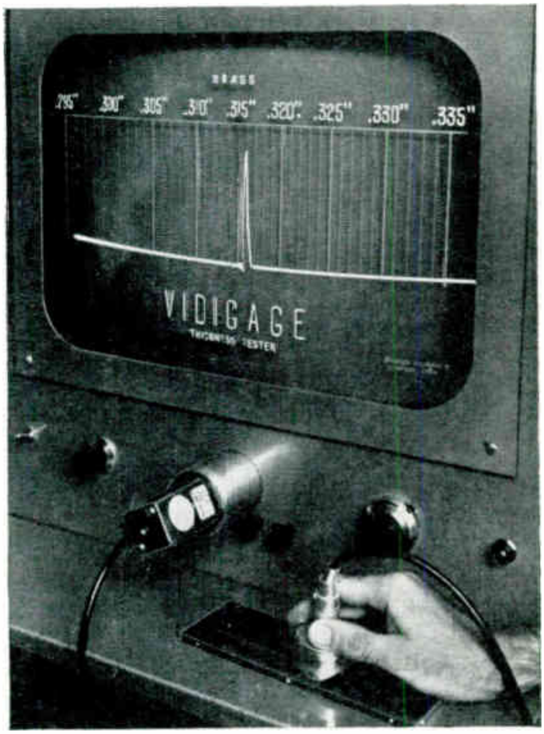

Fig. 5.—Automatic thickness gauge.

constant a reduction in sweep width effectually lengthens the scale and so allows a more accurate determination.

For thicknesses in the range 0·015–0·160 in. (steel) fundamental resonance indications are used. Above 0·160 in. harmonic resonance indications are used, correct choice of frequency band and sweep width ensuring that only a known harmonic is displayed.

A steel plate of 0·386 in. has a fundamental resonance of 0·3 Mc/s and harmonics occur at 0·6 Mc/s, 0·9 Mc/s, 1·2 Mc/s, 1·5 Mc/s, etc. Using the lowest frequency band of the instrument, 0·75 Mc/s–1·5 Mc/s (2 to 1 sweep width), three indications will be displayed, but by reducing the frequency band to 1·0 Mc/s–1·4 Mc/s the fourth harmonic only is displayed.

If the nominal thickness is known, prepared charts enable the user to select quickly the correct frequency band and sweep width ratio.

When the thickness is completely unknown a different procedure is adopted. The thickness scale is replaced by a frequency scale and the frequency difference between two indications determined. The thickness can now be calculated from $t = V/2f$ and if this is not considered sufficiently accurate the correct settings are now chosen and thickness read directly from the appropriate scale.

The instrument is much more complex than the portable gauge referred to earlier, but under ideal conditions thickness measurements accurate to within ±0·1 per cent. have been achieved.

5. Transducers

The X-cut quartz crystals referred to earlier constitute the heart of the whole system, since they are the medium whereby electrical energy is transformed into mechanical energy. Crystals are ground to resonate at various frequencies but when employed in the resonance method of measurement they must be driven below their natural resonance frequency, since at this frequency a resonance indication similar to the thickness resonance will be observed. At the same time they must not be operated at a frequency too remote from their natural frequency otherwise a considerable loss of sensitivity will result. In practice a frequency range not greatly exceeding 2 to 1 has proved satisfactory. (Fig. 6.)

A film of silver or other metal is deposited on both faces of the crystal. These layers provide surfaces on which the electric potential can be impressed and enable the charge to be evenly distributed over the face of the crystal. The face in contact with the work piece is sometimes left unsilvered, the earthed return lead being taken to the component itself. On new metal this is effective but for old metal, which may have a layer of paint or rust, or for non-conductive materials such as glass, silvering of both faces is essential.

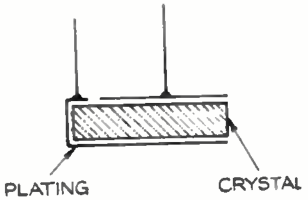

Fig. 6.—Plating on crystal blank.

Constant rubbing of the crystal face against the surface of the work piece may cause the silver to be worn off and eventually the crystal may be damaged. Chromium plating is more durable than silver, but when the crystal is subjected to arduous conditions a "wear plate" is a more satisfactory solution. This consists of a very thin wafer of quartz which is securely cemented to the face of the crystal with one of the resin-based adhesives. Some loss of sensitivity will result but if this can be tolerated the life of the crystal is made indefinite as the "wear plate" can be replaced without too much difficulty.

The crystal blank may be either round or square, but, since the latter is more easily chipped and is more difficult to mount, round crystals are invariably used. To facilitate handling and lead termination the crystal blank is mounted on a suitable base which is fixed into some form of holder. The base apart from providing a suitable mount for the crystal performs one other important duty.

In addition to the resonance indication obtained at the natural frequency of the crystal certain other spurious resonances may also be observed at various points in the frequency range, and are most noticeable when the crystal is undamped. Unless they are eliminated considerable confusion may take place. When the crystal is critically damped these unwanted resonances almost disappear and the base material is so chosen to provide sufficient damping to eliminate the unwanted resonances without drastically reducing the overall sensitivity of the crystal. In spite of these precautions many crystals have to be discarded because of excessive spurious resonances. The shape and construction of the holder into which the mounted crystal blank is fixed are not vitally important but must provide a secure anchorage for the connecting cable and be convenient to handle. Normally the transducer unit is held in the hand and pressed against the work piece with sufficient pressure to establish good contact without causing excessive wear. To enable large areas to be quickly scanned an extension handle is sometimes fitted to the holder and in such cases a form of gimbal mounting together with spring loading is used to ensure good contact and adequate pressure.

When a flat transducer is applied to a curved surface only a small area of the face is in contact with the work piece. Consequently, only a small amount of energy is transmitted into the material. A larger area of contact, giving a greater transmission of energy, is achieved by grinding the crystal to fit the surface curvature.

Although the operation is difficult, crystals can be ground to convex, concave and spherical shapes. Experience has shown that curved crystals must be used when the radius of curvature is less than 3 in. for convex surfaces or less than 24 in. for concave surfaces. Crystals have been ground to suit pipes with an outside diameter as low as $\frac{3}{4}$ in.

Although certain other crystals such as Rochelle salt can be used as transducers, because of its inherent strength and durability quartz has been used almost exclusively until quite recently. Within the past year or so barium titanate and barium titanate ceramic have been increasingly used with great success. The piezo-electric effect is greater in barium titanate than in quartz thus enabling transducers of much smaller dimensions to be used without loss of sensitivity. Since barium titanate is relatively brittle a "wear plate" should always be fitted. Barium titanate also requires polarization during manufacture and will become inactive due to de-polarization at temperatures around 100°C.

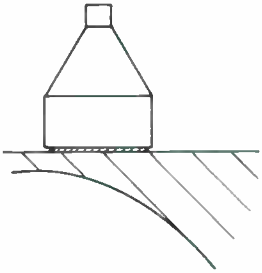

Fig. 7.—Typical example of excessive thickness variation.

6. Couplants

The crystal is held or pressed against the work piece but because of slight surface irregularities intimate contact is made only at a few points and an air gap is formed over a large part of the area, resulting in only a slight transmission of energy. (Fig. 7.) Table 1 shows that the specific acoustic impedance of air differs greatly from most other materials and therefore a coupling medium must be employed to enable sufficient energy to be transmitted into the component. This couplant can be regarded as a transformer matching the impedance of the crystal to the test-piece. Ideally it would take the form of a liquid whose specific impedance is somewhere between that of the crystal (quartz) and the test-piece. Mercury has about the right value of impedance but is poisonous and forms an amalgam with many metals and no satisfactory way of using it has yet been devised.

Fortunately when using the resonance method it is not essential that the maximum amount of energy be transmitted. Only sufficient energy is required to enable the condition of resonance to be easily detected. In practice the choice of couplant is usually determined by economic or practical considerations. On a smooth surface water with the addition of a suitable wetting agent works well, but may cause rust formation; light oil is relatively cheap and efficient but may not be tolerated if the component has already been degreased.

If the surface is pitted, as is the case of the hull plates of a ship in service, either extensive surface preparation must be carried out or a coupling medium chosen that will achieve better impedance matching with consequent increase in transmitted energy. Glycerine has a higher acoustic impedance than oil and provides the improved matching required, thus enabling the surface preparation to be reduced. Very occasionally it is necessary to measure wall thickness of pipes or vessels containing hot liquids or gases, and under such conditions silicone fluid which retains its viscosity over a wide range of temperature has proved successful.

The optimum thickness of a film of coupling medium can be calculated for any given frequency, but since the described method makes use of a variable frequency no advantage can be gained by using a film of predetermined thickness. The practical difficulties of maintaining such a film are virtually unsurmountable.

Standing waves within the thickness of the film can be set up, but in practice this is unlikely, since one half a wavelength in oil, even at 5 Mc/s, is of the order of 0·006–0·007 in. and a film of these dimensions is hardly likely to be maintained.

7. Materials

With the exception of lead, practically all the metals, glass and certain of the denser plastics can be successfully measured. With fine grained materials such as steel very little reflection takes place at the grain interfaces even at the higher frequencies. Copper, brass and bronze are of relatively coarser structure and some reflection and "scattering" occurs at the grain interfaces. Measurement of such materials is carried out at the lower frequencies when the effect is less pronounced. Porosity in cast materials gives rise to widespread "scattering" and reflection, making thickness measurement of low quality castings extremely difficult, and the lower frequencies, usually not exceeding 1·5 Mc/s, are best suited for measurement of such materials. Cast iron is particularly difficult to measure accurately, for not only does it suffer from porosity and large grain size, but also the elastic constants vary considerably for different specimens. Tests carried out on cast iron sections, dimensionally similar, but produced in different foundries have shown a variation in resonant frequency as great as 20 per cent. Measurement is made at the lower frequencies but unless a low accuracy can be tolerated is likely to be unreliable.

8. Accuracy and Range

The resonance method carefully used is capable of great accuracy, the degree of accuracy being essentially determined by the willingness of the user to provide suitable equipment. With commercial equipment the controlling factor is usually economic.

Since the accuracy of the method depends upon precise frequency measurement, the first essential is an extremely stable oscillator which has been carefully calibrated. The tuning range of the oscillator should be as narrow as possible or divided into a number of small bands. Power supplies for both the oscillator and associated equipment must be stabilized and any calibrated controls must be electrically exact and mechanically sound, particular attention being paid to the elimination of backlash. The electronic circuits should be highly selective so that the resonance indications are extremely sharp; if very narrow frequency bands are used, this is essential.

Although it has been previously stated that only small variations in velocity have been noticed for different samples of like materials, for extreme accuracy the user must be prepared to calibrate the equipment against test pieces of the material from which the component has been fabricated.

Using equipment properly designed and built, thickness measurements have been made with an accuracy of better than 0·1 per cent. of the total thickness. In general, however, such accuracies are not required, a more usual figure being ± 3 per cent. Measurement to within such limits is fairly easy even when using relatively simple apparatus. Under such circumstances variation of velocity in different samples is ignored.

With materials such as steel and aluminium having smooth parallel surfaces it is possible by using frequencies of up to about 20 Mc/s to measure thicknesses as low as 0·005 in. By making use of harmonic resonance indications thicknesses of several feet can be measured. In practice, however, it is usual to cover a range of 0·010 in. to 6 in.

9. Limitations

Most methods of measurement have certain limitations and the method under review is no exception. Its use is restricted to relatively large components, since the contact area must be at least as great as the area of the crystal face. The recent introduction of barium titanate as a transducer has enabled this dimension to be reduced and transducers with a surface area of 0·2 in.^{2} are now available.

Crystals can be ground to provide surfaces of convex, concave and spherical shapes, but it is not possible to produce crystals for use on surfaces or irregular contours.

Excessive thickness variations in the material within the contact area will make measurement impossible, as will also be the case when the material section is excessively wedge-shaped. Thickness variations often take the form of extensive pitting as is encountered when the material has suffered from severe corrosion. Generally, if the depth of the peak-to-valley pitting exceeds about 20 per cent. of the total thickness or is greater than one half of a wavelength no measurement is possible. One half of a wavelength in steel at 1 Mc/s is approximately 0·12 in.

Dense adherent scale on the inaccessible surface has a damping effect and may prevent a reading being obtained; when such a reading is possible the scale thickness is not measured.

DISCUSSION

G. Bradfield : I feel that a figure of 0·1 per cent. for accuracy of thickness measurement is very unlikely except in special circumstances; not only does the contact film thickness affect the reading obtained by the simple devices discussed but also the industrial materials themselves can vary widely in elasticity due to differences in crystallographic texture and this can thus cause serious errors in thickness indications. (See, for example, *Phil. Mag.*, Ser. 7, **44**, 1953, p. 437).

F. M. Savage (*in reply*): Mr. Bradfield is quite correct, a 0·1 per cent. accuracy is not a typical figure and can only be obtained under ideal conditions, for example, the measurement of wall thickness of a component fabricated from one piece of steel. If the instrument has previously been calibrated against a section of the same steel, then under these conditions it does, of course, become a comparator.

F. L. Steghart : I would like to learn whether it is possible to measure the thickness of plates without actually touching the material. Secondly, how great is the influence of the sort of contact?

F. M. Savage (*in reply*): The transducer must be in contact with the plate. The accuracy of the method is not greatly dependent upon the coupling but the sensitivity is. Good coupling will enable a measurement to be made whilst poor coupling usually results in no indication at all. Normal coupling agents, for example, oil, will help a lot and glycerine has been found to be an excellent couplant when the surface is inclined to be rough.

A. B. Clewes : Can Mr. Savage suggest the application of his thickness gauge to the measurement of the thickness of a rotating part on a lathe. I have in mind a maximum accuracy requirement of ± 0·0002 in. on $\frac{1}{10}$th in.

F. M. Savage (*in reply*): This is being done in several establishments but I do not advocate that the crystal face is kept in continuous contact with the rotating part as the wear on its face would almost certainly be extensive. A system of spot checks would be preferable. Mr. Clewes' requirement for accuracy may be asking too much in this application.