

# JOURNAL OF The British Institution of Radio Engineers

(FOUNDED IN 1925 - INCORPORATED IN 1932)

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

Vol. XIV No. 12

DECEMBER, 1954

## THE PROBLEM OF TECHNICAL EDUCATION

The last Institution meeting to be held in 1954 will take place on December 29th in order to discuss "The Education and Training of Radio Engineers." Few subjects remain topical for so long as the one of training, and the meeting on the 29th is of the same current interest as it was when first debated at an Institution meeting nearly 30 years ago.

Whilst the subject was of importance to very few countries before the war, the future supply of radio engineers is now a matter of great concern to nearly every country in the world. The development of communications and the application of industrial electronics has created new industries and a profession of greater size than could have been visualized 50 years ago.

The process of "growing up" has inevitably brought varying experiences, and new ideas are constantly arising, some by original research, and some as a result of industrial or technological processes. In the event, new subjects have been introduced into the curriculum of universities and technical colleges in order to pass on the knowledge and experience of pioneers in the academic and industrial worlds.

The shortage of engineers and/or technologists is not, of course, confined to the radio and electronic industry. In Great Britain, the Imperial Institute of Science, South Kensington, the College of Technology, Manchester, the Royal Technical College, Glasgow, and the University of Southampton, have been especially singled out for the British Government's newly announced plans for higher technological education, directed mainly towards the training of technologists.

These notes are, however, primarily concerned with the radio and electronic engineer. It is, however, a natural tendency for the Graduate and

corporate members to feel that their technical education is completed, and that they have only an academic interest in the subject. Those who have experienced the difficulty and tedium of study are in the best position to make constructive comment towards stimulating, and perhaps framing, the best type of training for the student who is not only required to succeed the present engineers, but also to meet the present shortage.

Training schemes, whether through the universities or technical colleges, are an expensive but necessary investment for the future, particularly in such a vast expanding industry. There must, of course, always be a return for any investment, and no doubt during the discussion meeting there will be an investigation of the reasons for the poor results shown in such examinations as those conducted by the Institution.

All too seldom are the views of universities, technical colleges and industry expressed at one meeting. Particularly since the war there has been a tendency for each section to make its own inquiry and to publish a corresponding report; indeed, since the original post-war reports issued by the Institution in 1944, three further reports have been published by the Institution on the education and training of radio engineers. It is hoped, therefore, that the meeting on December 29th will first of all bring together all who are interested in the subject, and that the ensuing discussion may result in agreement on some major points.

It is part of a man's responsibility to make contributions to the development of his own particular profession. The education and training of future radio engineers is a subject of foremost importance in ensuring the happiness and usefulness of the younger generation.

## NOTICES

### 1954-55 Programme of Meetings

The booklet containing the programme of Section Meetings for 1954-55 has just been published and each member of the Institution in the British Isles should have received his copy. Any member who has not yet received the programme, or wishes to obtain a further copy, should apply to the Institution's offices.

In addition, sheets bearing reminders of meetings, suitable for fixing in personal diaries and in appointment books, have been issued for groups of sections, and every member should have received one before Christmas. A few spare copies of these are available for members wishing to obtain sheets for other sections.

Details of any additional meetings arranged during the Session will be circulated by the Honorary Local Secretaries and announced in the *Journal* under "Forthcoming Meetings."

### Common Preliminary Examination

In the October 1954 Common Preliminary Examination of the Engineering Joint Examination Board there were 12 successful candidates in the British Isles. Of these, four were entered through the Institution with a view to their becoming eligible to sit the Brit.I.R.E. Graduateship Examination.

### Canadian Telecommunications

A recent article\* surveying the long-distance telecommunications network in Canada and their development shows that increased use is being made of the radio relays for supplementing transmission channels. In addition, with the growth of the Canadian television service, particular interest attaches to the setting up of a link from Montreal to Toronto via Ottawa with extension over the American border to Buffalo, as well as providing other links to Quebec and Winnipeg.

Both British and American systems are being installed. Operating in the 4,000 M/cs band, the systems are capable of accommodating several television channels and several hundred telephone channels in various combinations and arrangements. The article forecasts the establishment, within three to six years, of television networks required by the Canadian Broadcasting Company for coverage from Vancouver to Halifax and St. Johns, Newfoundland.

\* A. G. Lester, "Telecommunications in Canada," *Engineering Journal, Canada*, 37, No. 10, October 1954, pp. 1231-1245.

### B.B.C. Engineering Appointment

The B.B.C. has announced the appointment of Mr. Cyril R. Jephcott, A.M.I.E.E., A.M.Brit.I.R.E., as Engineer-in-Charge of the new temporary television transmitting station at North Hessary Tor, South Devon, commencing regular service on December 17th.

Mr. Jephcott was elected an Associate of the Institution in 1934 and was transferred to Associate Membership in 1937. He joined the Corporation in 1935 at the Droitwich Transmitting Station, where he became a senior maintenance engineer in 1941. In 1946 he transferred in that capacity to the B.B.C.'s short-wave transmitting station at Skelton, in Cumberland, which post he has held until taking up his present appointment.

### 1955 Radio Exhibitions

The Radio Industry Council has announced that the next National Radio Show will be held at Earls Court, London, from August 24th to September 3rd, a similar period to the 1954 Show.

A smaller exhibition, the Northern Radio Show, is to be held at the City Hall, Manchester, from May 4th to the 14th. The last Radio Exhibition held by the R.I.C. in Manchester was three years ago.

The 1954 German Radio and Gramophone Exhibition will take place in Düsseldorf over the same period as the London show.

Preliminary figures at present available indicate that a record total of over 140 stands will make up the Radio Component Show, to be held at Grosvenor House, London, from April 19th to 21st. An innovation this year is that instead of circulating admission tickets, application cards will be issued, one to be filled in and forwarded by each intending visitor, in return for which he will receive a ticket if his application is approved. Prospective overseas visitors, however, will receive their tickets as in previous years without application.

### Completion of Volume

This issue completes Volume 14 of the *Journal*. An Index to the Volume will be distributed with the January 1955 issue.

Members wishing to have their *Journals* bound by the Institution should send the complete set of issues and index to the Institution together with a remittance of 12s. 6d.

# WIRE STRAIN-GAUGE TRANSDUCERS FOR THE MEASUREMENT OF PRESSURE, FORCE, DISPLACEMENT, AND ACCELERATION\*

by

J. L. Thompson (*Member*) †

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

## SUMMARY

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

### 1. Introduction

In all branches of engineering, there are times when the experimental approach becomes indispensable.

In this association, matters are perhaps easier for the electronics engineer than for the mechanical engineer since, if the simplifying assumptions made by the electronics engineer prove to be too detached from reality, he has available a wealth of instrumentation to investigate the behaviour of every detail of his design, whether under static or dynamic conditions.

The Radio and Electronics industry is to-day barely thirty years old, but progress has never been hampered by lack of instrumentation. Probably because the same general theoretical considerations, and the same experimental circuit technique, apply both to the project under development and the method for measuring its behaviour, instrumentation in the field of radio and electronic engineering has kept pace with, even kept ahead of, development.

Until comparatively recently the Mechanical Engineer had little or no equipment to determine experimentally the dynamic behaviour of the structures or the machines that he designed.

The classical contributions of Hooke and Mariotte in the 17th century, Bernoulli, Euler, Lagrange and Coulomb in the 18th century, Young, Navieu, Poisson, Couchy, Saint Venant and Airy in the early 19th century, provided the

foundations for his theoretical and mathematical approach, but the formalized statements of the behaviour of engineering materials, and the empirical results of generations of his predecessors, were almost his only help in the practical interpretation of theoretical design work.

Through the still enormous extent of our ignorance of the forces and, in particular, the dynamic forces, present in a real structure, the purely mathematical approach to the analysis of these forces is strictly limited, indeed there exists a multitude of simple practical problems for which no theoretical solutions have yet been obtained.

In such cases, and in cases where the theoretical treatment demands too many simplifying assumptions, the experimental approach is the only reliable path to the solution of the problem.

As is generally known in dealing with the internal forces present in a body, use is made of an artifice called "stress," simply defined as "the force per unit area which resists a change in size or shape of a body." This is an abstract, rather than concrete conception for, as Dr. Southwell says in his book on Elasticity (p. 115)—"Stress never has been measured directly and almost certainly never will be." Strain, which may be defined as "the ratio of a change of dimension to the original dimension" usually bears a definite, and for small strains a linear, relationship to the stress producing it and, for any given material, this relationship can be determined experimentally, giving the typical result shown in Fig. 1.

Thus, if this change in dimension can be measured and if the relationship between stress

\*Manuscript received 17th May, 1954. (Paper No. 291.)

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U.D.C. No. 620.172.222.

and strain is known, the stress operating can be evaluated.

The dimensional changes that are measured are those occurring on or near the surface of the body under test. This is fundamental to all strain measuring devices. In any homogeneous material maximum stress always operates on or near the surface—failure always begins as a crack on the surface—the advantages of case hardening in steel, and the “armouring” of glass, derive from the better mechanical properties given to the surface.

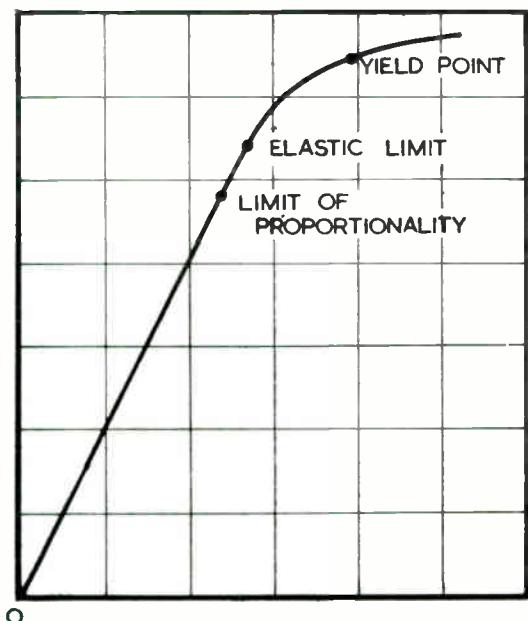


Fig. 1.—A typical stress/strain curve.

Clearly, if the designer, by surface strain measurement, can evaluate the operating stresses in his structure, he can then proceed to modify appropriately his design; he can reduce unnecessary strength and weight, he can eliminate unforeseen weaknesses.

Carrying out such measurements, does, however, demand the accurate determination of displacements which are very small compared, for example, with what can be measured with an ordinary workshop micrometer.

Thus, even with large strains in the region of 0.1 per cent. measurement with an accuracy of 1 per cent. involves a change of 10 micro-inches

in a total length of one inch. There are, moreover, many practical cases where the strain may be 0.01 per cent. or lower and in such cases the changes are 1 micro-inch or less.

A high degree of magnification is therefore essential, and the strain resistance relationship for metallic wires has long been appreciated as a means for measuring such mechanical movements.<sup>1, 2</sup> The first engineering application appears to have been designed about 1930 by R. W. Carlson<sup>3</sup> who developed an unbonded type of gauge for the measurement of strains in concrete. A refinement of this principle was developed about 1945 by Meyer<sup>4</sup>.

The idea of bonding the resistance element directly to the body under test was first conceived at the California Institute of Technology by Simons and reported by Clark and Datwyler<sup>5, 6</sup> in 1938. The resistance wire was laid longitudinally on four successive faces of a bar in a zig-zag fashion and coated with glyptal as a binder.

At about the same time Professors Ruge and de Forest, at the Massachusetts Institute of Technology,<sup>7, 8</sup> conceived the idea of simplifying this technique by bonding the resistance filament to a paper which, itself, could be bonded to the surface of the body under test.

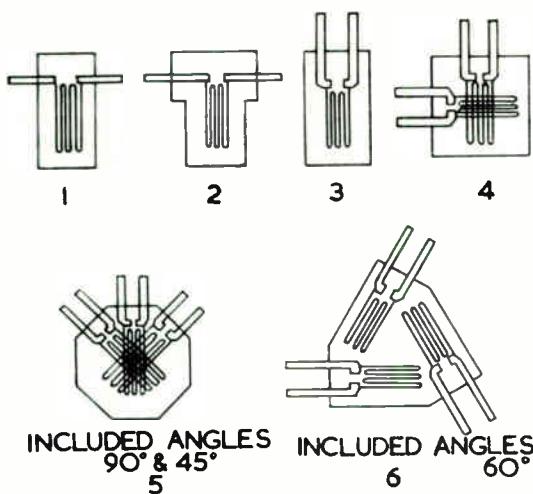
It is this type of gauge that is most used to-day and, with the improvements in technique over the past ten years, British and American gauges are now available in a variety of gauge lengths, and gauge resistances, and with a high degree of uniformity of their physical constants.

Most of the gauges in commercial production employ a metallic filament made of 45/55 copper-nickel alloy of 0.001 in. diameter.

For special applications, Staybrite, Nichrome and Iso-elastic wire have also been used. Typical gauge dimensions and resistance values are shown in Fig. 2.

The salient characteristics of resistance wire gauges as strain measuring devices may be summarized as follows:

- (1) The fractional change of resistance against strain is a linear function for strain values up to at least 0.2 per cent.
- (2) The gauge has negligible weight, and hence exerts negligible influence on the member to which it is attached. Since it is flexible, and is cemented in position, it can be attached to curved surfaces as easily as to plain surfaces.



Approx. Resist. (ohms)	Gauge Factor	Gauge Dimen. (mm)	Total Dimen. (mm)	Gauge Form
100	2.0	17×2.5	24×9	1
50	1.8	8×1.5	14×4	2
100	1.9	8×1.5	14×4	2
100	2.0	17×2.5	31×9	3
200	2.2	17×1.5	31×9	3
1,000	2.15	51×6	59×9	3
500	2.1	24×6	32×9	3
2,000	2.3	5×6	59×9	3
1,000	2.25	24×6	32×9	3
100	2.0	(3)17×1.5	34×35	6
100	2.0	(3)17×2.5	27×27	5
200	2.2	(3)17×1.5	27×27	5
100	2.0	(2)17×2.5	27×27	4

Fig. 2.—Some typical gauges, and their dimensions.

- (3) Such gauges are equally suitable for both tensile and compressive strains, the calibration remaining sensibly the same for both. The accuracy is of the order of 1 per cent. and strains of the order of  $10^{-5}$  can be indicated.
- (4) Because the inertia, inductance, and capacitance are negligible, the upper frequency response is limited only by the wavelength with which the alternating stress is transmitted through the material and, of course, by the frequency response of the ancillary measuring equipment.
- (5) The gauge is subject to temperature changes but these can be effectively compensated.
- (6) The output from several gauges can be added, subtracted, averaged, or combined electrically, to give direct reading of average stress, bending moments, shear, torsion, and direction of principal stress.
- (7) The impedance is relatively low, and the output can thus be observed or recorded remotely or, if desired, telemetered through a radio link.
- (8) The measuring equipment for static strains is very simple, needing, in the most elementary form, only a battery and galvanometer. For dynamic work, the ubiquitous cathode ray oscilloscope will fill many requirements.
- (9) Finally, as distinct from the usual extensometer, the resistance strain-gauge is a true strain measuring device, and no reference to the original length of a specimen is therefore necessary.

These features, allied to its low cost, make the resistance strain-gauge a most effective instrument, not only for measuring strain as such, but also for measuring any other physical quantities that can conveniently be related to the strain in an appropriately designed mechanical structure.

## 2. Pressure Transducers

Consider a hollow cylinder, as shown in Fig. 3a, subjected to an internal hydrostatic pressure. Provided the Limit of Proportionality for the material used is not exceeded, the relation between stress and strain will be a linear one, and the circumferential expansion will be directly proportional to the internal hydrostatic pressure.

For the general case, it can be shown that, for a long tube where the end restraints can be neglected, the relation between the internal pressure and the maximum stress in the tube is given by:

$$f_1 = p.(s^2 + 1)/(s^2 - 1)$$

where  $p$  = internal fluid pressure,

$f_1$  = maximum stress in tube wall,

$s$  = ratio of outer to inner diameter.

(a)

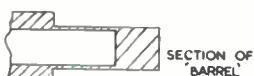


Fig. 3.—A "barrel" type of pressure transducer.

(a)—The basic mechanical structure.

(b)—Typical method of construction.

This maximum stress occurs at the inner face of the tube. At the outer face, the stress will be smaller, considerably smaller in thick tubes; the stress at the outer surface is:

$$f_2 = 2p/(s^2 - 1)$$

This stress, in combination with an axial stress of half the value, due to pressure on the ends of the cylinder, will give rise to a circumferential strain:

$$e = f_1(2m - 1)/2mE$$

where  $\frac{1}{m}$  = Poisson's ratio

$E$  = modulus of elasticity.

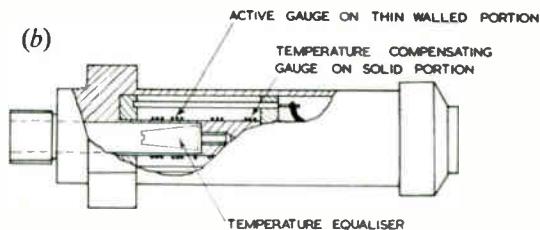
If, now, a strain-sensitive filament is wound around the periphery of the tube, this strain will lead to a change in resistance which is a linear function of the internal pressure.

A typical pick-up of this type is shown in Fig. 3b. The cylinder is made from beryllium copper and carries four windings, two active and two compensating, the windings being connected in the form of a Wheatstone bridge. Thus, as the temperature changes, the resistance of all four arms will change to an equal extent and the balance will be unaffected.

The whole of the area carrying the active gauges is, however, in contact with the pressure medium, whereas this is not the case for the solid end portion carrying the temperature compensating gauges. Thus, there can be a considerable temperature gradient between the two, the magnitude of the gradient being a function of time and of the temperature of the medium

above the ambient temperature. A copper slug is therefore provided, whose purpose is to convey heat to the compensating gauges, and thus reduce the temperature equalization time to a minimum.

The thinness of the wall that can be achieved is limited by practical difficulties in machining, and this in turn limits the minimum pressure range to something in the region of 0-250



lb./in.<sup>2</sup>. The high pressure limit is dictated by the strength of available materials. However thick the walls are made, the maximum stress will always be somewhat greater than the fluid pressure, thus setting an upper limit which is in the region of 50,000 lb./in.<sup>2</sup>.

Units of this type can be used for the measurement of both static and dynamic pressures without any serious limitation due to resonance effects, the natural frequency being comparable to the acoustic resonance of a pipe of similar dimensions with one end closed.

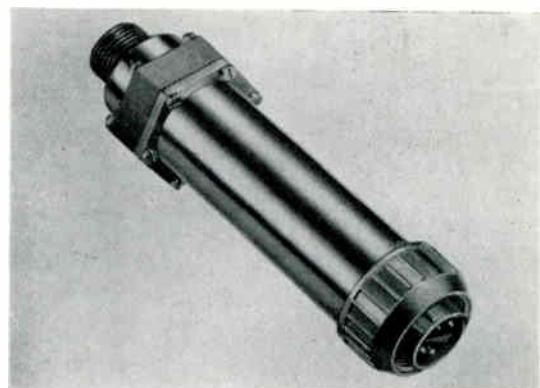


Fig. 4.—A current type of "barrel" transducer.

A typical commercial transducer of this type is shown in Fig. 4.

For pressures between 25 and 250 lb./in.<sup>2</sup>, a modified form of this pressure transducer can be used, in which the tube is made elliptical in section.<sup>9</sup>

This results in a structure which is more flexible for a given wall thickness, and hence better adapted to the measurement of lower pressures. Moreover, the tensile stresses at either end of the minor axis of the ellipse are supplemented by corresponding compressive bending stresses at either end of the major axis. Thus, the simple helical winding appropriate to a cylindrical tube, should, for the case of an elliptical tube, be replaced by four separate gauges giving a bridge network with four active arms carrying, alternately, tensile and compressive loads.

For pressures below 25 lb./in.<sup>2</sup> a transducer of the type shown in Fig. 5 can be used.

This takes the form of a diaphragm loaded on one side by the pressure and on the other by a cantilever beam. Deflection of the diaphragm causes a deflection of the cantilever beam, and the corresponding strain at the root is measured by means of the wire strain-gauge.

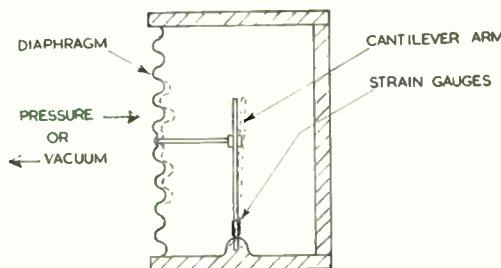


Fig. 5.—A transducer for low pressures.

The displacement of the cantilever is controlled by the diaphragm displacement for a given pressure loading. From elementary theory it can be shown that, at the gauge position, the strain is

$$e = 6pAl/bt^3E$$

where  $E$  = Young's Modulus.

$b$  = breadth of the beam.

$t$  = thickness of the beam.

$p$  = fluid pressure.

$A$  = area of diaphragm.

$l$  = distance from the point of application of the load to the point of measurement of the strain.

In practice, one gauge is mounted on the front of the beam and a second gauge on the back, one being thus subjected to tension, and the other to compression. With the two gauges connected to form the adjacent arms of a

Wheatstone bridge, this has the effect of doubling the output and at the same time maintaining thermal symmetry. In some types of pick-ups four gauges are used, two on either face of the beam. Thus, there are four active arms, completely temperature compensated, developing an output four times greater than that from a single gauge. With suitable diaphragms and correctly proportioned beams, pressures as low as 6 in. water gauge can be measured, but the frequency response of this type of pick-up is very much lower than that of the barrel type.

Even so, by careful design, natural frequencies of the order of 100–200 c/s can be obtained.

### 3. Vibration Transducers

Resistance strain-gauges may be used to measure vibrations by attaching the gauges directly to an elastic member of the structure under investigation, thus determining directly the alternating strains which can lead, ultimately, to fatigue and failure.

On the other hand, it may be more convenient or more appropriately to measure the movement of the structure as a whole, for which the first requirement is a reference point that remains fixed while the structure vibrates. The ground may serve for this, if it is not itself being shaken too violently in the neighbourhood of the vibrating body. But even this resource is not available for tests in an aeroplane during flight, or in any other moving vehicle.

In such circumstances, the reference point, against which the amplitude of the vibration can be measured, must be provided by a seismic

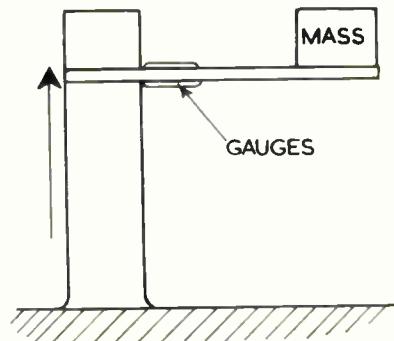


Fig. 6.—Cantilever as a seismic vibration transducer.

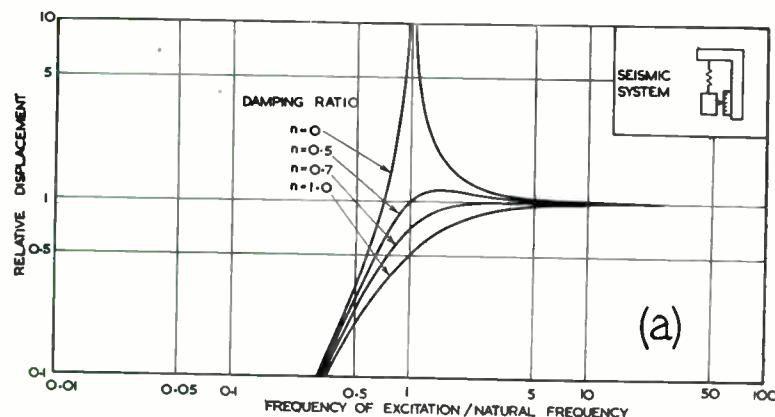


Fig. 7a.—Response of seismic system with constant displacement input.

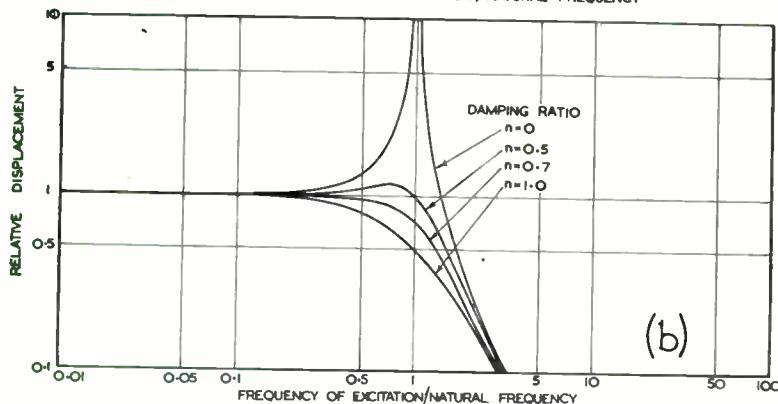


Fig. 7b.—Response of seismic system with constant acceleration input.

system, so called because it was first used in earthquake recorders. This arrangement consists, essentially, of a mass suspended inside some form of outer casing by a spring. If the seismic system is mounted on a vibrating structure, it will be found that, while the case necessarily vibrates with the structure, the mass remains substantially stationary in space, so long as the vibration frequency is considerably higher than the natural frequency of the mass suspended on its spring. Thus, the relative movement between the case and the suspended mass gives a true measure of the vibration amplitude.

A cantilever, as shown in Fig. 6, provides a convenient seismic system for a vibration transducer using resistance strain-gauges, the dynamic response of such an arrangement being shown in Fig. 7a.

These curves demonstrate that over the working range of frequencies, well above resonance the response is unaffected by the

degree of damping, provided this is not altogether excessive. None the less the appropriate degree of damping must receive due attention, even if there are no vibrations present to excite a resonant response in the seismic system, since chance irregularities in the excitation will still give rise to oscillatory transients, at the natural frequency of the suspended mass which, superimposed on the vibration being measured, will confuse the results.

In Fig. 7a, the degree of damping is given in terms of the ratio between the damping present in each case, and the "critical damping" needed to make the transient response non-oscillatory. Examination of these curves shows that damping which is about two-thirds of the critical value actually gives a uniform response extending furthest into the lower frequencies.

Eddy currents induced by a permanent magnet are an accurate and controllable means of supplying the required degree of damping,

but the magnet is liable to assume massive proportions unless every care is taken to keep the mass and stiffness of the seismic system low.

Oil damping is also used widely, and is very effective where viscous flow of the damping fluid, and constant immersion of the damping vane have been satisfactorily achieved. On the other hand, the eddy formation and variable inertia which are found, for example, when the damping is provided by a plunger moving in and out of the oil, introduce frequency-dependent and non-linear factors which can give rise to curious effects at high frequencies or large amplitudes.

Two further considerations must be taken into account when designing seismic instruments for measuring vibrations of large amplitude or very low frequency.

Clearly, if the seismic mass is to remain stationary in space, the linear dimensions of the seismic suspension, and the instrument as a whole, must be large in relation to the amplitude of the vibration to be measured. Thus, resonance tests on a flexible structure, such as an aircraft, or the measurement of road shocks in a motor vehicle, are both instances where a seismic instrument designed to measure, specifically, the amplitude of the vibrations would be impractically large.

Such applications involve also very low frequencies, and this again imposes limitations on the design of the transducer, since a good response to very low frequencies implies a still lower natural frequency for the seismic system, and this, in turn, implies a large static deflection of the seismic mass under the influence of gravity. The natural frequency (in cycles per second) of any simple vibratory system is connected with the static deflection by the simple but important relationship:

$$\text{Static deflection (inches)} = 9.8 / (\text{frequency})^2$$

Thus, supposing it was intended to measure the vibration due to irregular firing in an internal combustion engine idling at 360 r.p.m., or six revolutions a second. This, in a four-stroke engine, would involve vibration frequencies down to 3 c/s, so that the measuring instrument would require a natural frequency in the region of one cycle a second. The above expression shows that, under the influence of gravity, the corresponding static deflection would attain the wholly impracticable figure of 9.8 in.

The difficulties encountered when attempting to measure vibration amplitudes with a seismic instrument at very low frequencies may, however, be circumvented by using an accelerometer. Moreover, acceleration is, commonly, the more appropriate parameter for vibration in machinery, since the vibratory forces transmitted through bearings to a rotating part, or from an unbalanced rotor to a flexibly mounted machine, are all inertia forces proportional to the acceleration, as distinct from elastic forces proportional to the displacement.

#### 4. Accelerometers

The measurement of acceleration involves a seismic system similar to that used for measuring the amplitude of vibrations, the only basic difference being that the natural frequency of the system is now above the working range of frequencies, instead of below. Under such conditions the static deflection, mentioned above, becomes negligible.

If the curves of Fig. 7a, showing the response of a seismic system to an input of constant amplitude, are redrawn for a constant acceleration input, the result will be shown in Fig. 7b, from which it will be seen that, for frequencies up to one-third of the natural frequency, the relative movement between the seismic mass and its support is proportional to the applied acceleration.

So far as the sensitivity of an accelerometer is concerned, the static deflection of a seismically suspended mass is the same as would be produced by an acceleration of 32 feet/second/second ( $=g$ ). The sensitivity over the working range of frequencies is thus proportional to the static deflection due to gravity.

Moreover, this static deflection is inversely proportional to the square of the natural frequency, as has already been mentioned. As a result, the deflection ( $x$ ), due to an acceleration ( $a$ ), is given by:

$$x = a/\omega^2$$

where  $\omega = 2\pi \times \text{natural frequency}$ .

As before, damping which is about three-quarters of the critical value extends the working range furthest into the resonant region of the seismic system, and gives an adequate suppression of oscillatory transients. In addition, Fig. 8 shows that this degree of damping gives a phase shift which is proportional to frequency. This, for a complex waveform, is equivalent to constant time delay for

the fundamental and all the harmonics, thus preserving the actual shape of the wave, an important matter in vibration measurement where the peak value, and not the r.m.s. value, is the significant feature of a complex wave-form. In this respect, the accelerometer is technically superior to seismic instruments measuring amplitude, which cannot be made to give either zero phase shift, or one proportional to frequency, the two alternative conditions for the true reproduction of a complex wave-form.

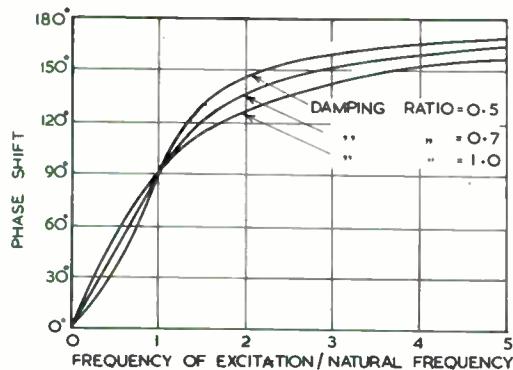


Fig. 8.—Phase characteristics of seismic system.

Vibration measurements are ordinarily concerned with the possibility of structural failure due to sustained effects in which transients play little part. On the other hand, in measuring the recoil of guns and similar ballistic investigations, the transient response is all important.

One characteristic of a seismic accelerometer used for measuring transients is the overshoot which sudden acceleration will produce if the damping is less than the critical value. With no damping at all, this overshoot will be 100 per cent., while Fig. 9 shows that when the damping is two-thirds of the critical value, the overshoot is reduced to about 5 per cent.

The other significant characteristic for transient measurements is the delay before the seismic mass attains its new position of equilibrium. This interval is never less than a quarter cycle of the undamped natural frequency, exceeding this by an amount which increases with the damping ratio till, for critical damping, the mass approaches its new position asymptotically, and, theoretically, the delay becomes infinite.

Clearly, for a rapid response, the natural frequency of the seismic system should be made

as high as possible. This, however, will reduce the sensitivity, as has already been shown, though this raised no particular difficulty in the case of the resistance strain-gauge accelerometer shown, diagrammatically, in Fig. 10.

In this instrument, designed to measure accelerations up to 2000g, the spring element in the seismic system consists of a tubular duralmin strut, integral with the means of attachment at one end, and the mass at the other, bonded resistance gauges being attached to the tubular portion, as shown. The natural frequency of this accelerometer is about 5000 c/s and the overall length 2 inches.

## 5. Force Transducers

Force measuring devices can be made in a number of forms. For tensile loadings one of the most useful is that of a proving ring or dynamometer ring, a commercial example of

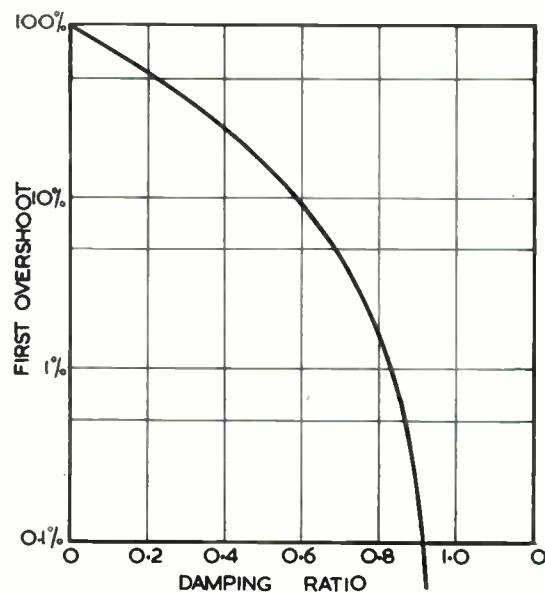
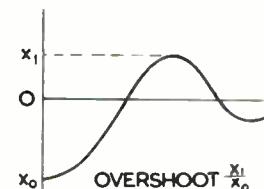


Fig. 9.—Transient response of seismic system.

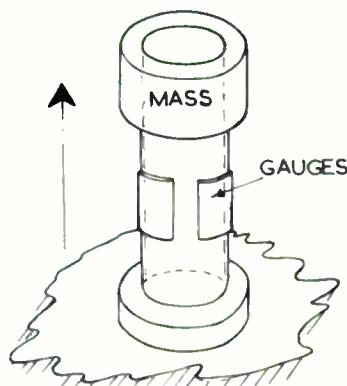
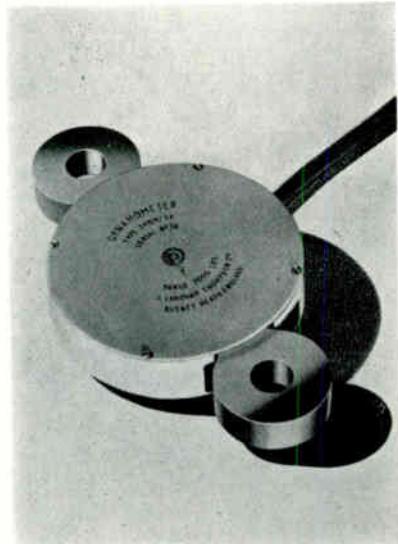


Fig. 10.—Simple seismic transducer with high natural frequency.

which is shown in Fig. 11. The ring is made from beryllium copper of rectangular cross-section and carries four gauges mounted as shown in Fig. 12.

Under load, the two gauges mounted on the vertical axis of the ring are in compression; the two mounted on the horizontal axis are in tension. The four gauges thus form a bridge circuit with all four arms active and temperature compensated, the out-of-balance voltage being directly proportional to the applied load.

For a ring of rectangular cross-section, the maximum compressive and tensile stresses are, respectively,



$$f_c = -\frac{P}{A} \frac{1}{\pi(1-k^2)} \left( \frac{1}{k^2} \cdot \frac{1}{a-1} - 1 \right)$$

$$f_t = \frac{P}{A} \left( \frac{1}{\pi(1-k^2)} - \frac{1}{2} \right) \left( \frac{1}{k^2} \cdot \frac{1}{a-1} - 1 \right)$$

where  $P$  = total load.

$R$  = mean radius.

$t$  = radial thickness.

$A$  = area of cross-section.

$a = 2R/t$

$$k^2 = \frac{1}{2} a \log_e \frac{a+1}{a-1} - 1$$

The natural frequency being high, these rings can, in addition to static loads, be used for the measurement of shock loads in haulage cables, lifting tackle and the like.

They can be made to carry loads from 50 lb. to 10 tons, and with a suitable crane hook assembly, they are the basis of an electronic weighing system. The out-of-balance voltage produced under load conditions can be recorded on one of the standard chart recorders, or used to operate an electrical printing machine which will type on a card, or form, the actual weight.

If a visual indication only is required, the ancillary equipment becomes very simple comprising only a battery and indicating microammeter. Being completely self-contained, such a device can be easily installed in mobile crane cabs so that the crane driver can have visual indication of the load lifted and avoid damage due to overload.

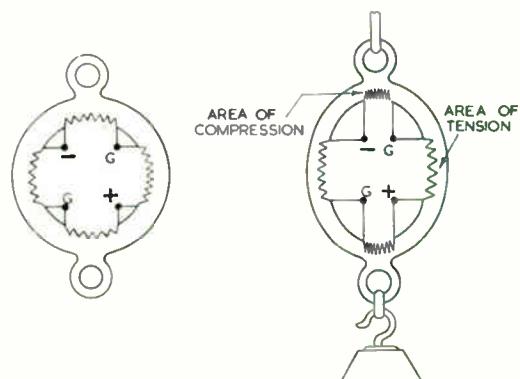


Fig. 11 (left).—An example of a ring dynamometer.

Fig. 12 (above).—Diagram of ring dynamometer under load.



Fig. 13.—Indicator unit for ring dynamometer.



Fig. 14.—Double indicator, for measuring the prestressing in concrete re-inforcements.



Fig. 15.—Converter for using tension dynamometers in compression.

Figure 13 shows a visual indicator suitable for such an application and Fig. 14 an indicator for accepting the input from two rings and used to measure the tension in the reinforcing rods during the manufacture of pre-stressed ferro-concrete beams.

For purely compressive loads a ring dynamometer can be mounted in a thrust converter Fig. 15 or the dynamometer element can take the basic form shown in Fig. 16. In this case the compression of the solid member—usually steel—is measured by the gauges shown mounted vertically. The two gauges mounted horizontally are subject to tension due to Poisson's ratio effect, and are connected to form the temperature compensating arms of the four arm bridge. The top of the member carries a self-aligning semi-spherical thrust pad. Dynamometers of this type have been constructed for loads up to 1,200 tons.<sup>10</sup>

## 6. Torque Transducers

Consider the case of a round shaft subject to torsion. The principal stresses lie at 45 deg. to the axis of the shaft. If now a strain gauge is mounted so that it follows a 45-deg. helix on the surface of the shaft it will be subjected to maximum strain due to torque on the shaft.

However, it would not be compensated against temperature nor would it be unresponsive to any bending or thrust. These objections are removed if two gauges are used mounted as shown in Fig. 17a, i.e., on two contrary 45-deg. helices on the shaft surface.

Under pure torque loading, one gauge will be subjected to tension and the other to an equal compression. Connected as adjacent arms on a bridge network, they will therefore combine to give an output proportional to the torque.

On the other hand, thrust loading, bending and temperature effects will subject both gauges to tension, or both to compression, so that the bridge balance is unaffected.

A torque meter based on this principle was described by A. C. Ruge in 1943.<sup>11</sup> He also describes a variation whereby thrust can be measured independent of torque or bending moments. This takes the form shown in Fig. 17b. with such a pair on either side of the shaft.

## 7. Unbonded Strain-gauge Transducers

The usual type of wire strain-gauge, bonded to a paper base, is a very convenient form of gauge for experimental stress analysis, and for



Fig. 16.—A compression type of dynamometer, or "load cell."

many other purposes. But the unbonded strain-gauge, as developed by Statham Laboratories of Los Angeles, also has many applications, particularly where a displacement transducer is required for incorporation in some permanent form of measuring equipment<sup>4</sup>.

This type is shown in basic form in Fig. 18. The unit comprises a four-element filament array, each element being under definite initial stress. The mechanical construction is simple and comprises two principal components, a frame (F) and an armature (A), which moves within the frame. The armature

is mounted within the frame by a flexible coupling (S), at each end, and its movement in each direction is restricted to 0.0015 in. by a yoke (Y) mounted across the frame. This prevents damage to the sensitive elements in event of accidental overload.

The four resistive elements are wound between eight posts and are insulated from them. Four posts are mounted on the frame and the other four on the armature. One end of each element is fixed to a frame post, the other to an armature post. When the armature moves within the frame, the tension of the four elements will vary, as will their resistance. The four elements are connected in a Wheatstone bridge with all four arms active.

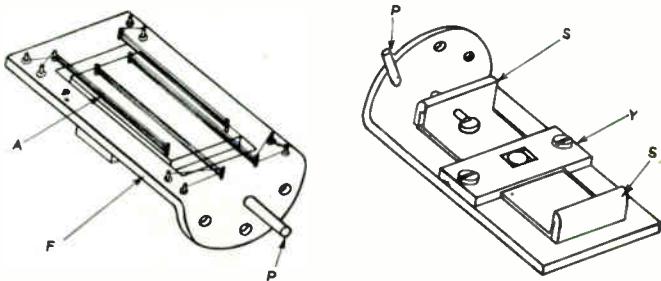


Fig. 18.—The structure of an unbonded strain gauge.

The force or movement to be measured is applied to the armature by a pin (P) connected to it and protruding through the frame at one end.

It should be noted that the symmetry of electrical, as well as mechanical, components plays an important role in the maintenance of calibration and the minimizing of temperature effects. Calibration is permanent provided that the gauge remains undamaged. The armature weight is only 2 gm, or slightly more in some models, and, as a result, provides negligible loading on the system to which it is coupled. The gauge elements are totally enclosed and are protected from mechanical damage at all times. The units may be subjected to a substantial overload, since exceeding the rated limits of the gauge simply results in no further output. The gauge is accordingly neither damaged, nor is the calibration impaired.

This basic design lends itself to a wide variety of transducer applications. For use as

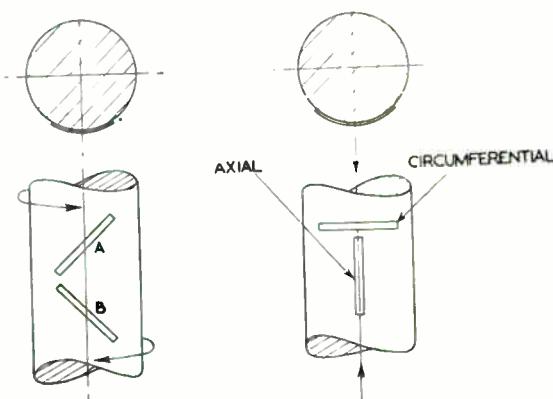


Fig. 17.—(a) Gauges arranged to measure only the torque in a shaft.

(b) Gauges arranged to measure only the thrust in a shaft.

a dynamometer the load to be measured is applied directly to the pin (P), the gauge of the filament arrays and the number of turns controlling the magnitude of the force that can be applied for full scale deflection. With the same control factors, a diaphragm connected to pin (P) will actuate the armature and produce a change of resistance directly proportional to the hydrostatic pressure acting on the diaphragm. Small displacements can be measured by direct movement of the pin whilst with a suitably designed mass attached to the armature control pin, the unit behaves as an accelerometer.

It will be seen from the foregoing that strain-gauge transducers cover a wide range of physical measurements, and have applications not only in research and experimental laboratories but also in process control, and every other field where reliable and simple remote-indicating instruments of rapid response can make an effective contribution.

## 8. Resistance Strain-gauge Technique

Although the paper design of a strain gauge transducer may seem basically quite simple, there are several design factors and fabrication problems in connection with the gauges themselves that must be taken into account if the measured performance is to approach the calculated performance, and maintain any degree of reliability.

### 8.1. Temperature Effect

As the fractional change of resistance  $\Delta R/R$  is in all cases small, less than 1 per cent. even in extreme cases, precautions must be taken to eliminate as far as possible changes in resistance due to causes other than strain. The most serious effect is due to temperature.

Consider, in a resistance strain gauge, an element of length  $L$ , with a resistance temperature co-efficient in the unstrained state  $\alpha$ .

Its fractional change of resistance for a temperature rise  $\Delta t$  is:—

$$\Delta R/R = \alpha \cdot \Delta t$$

With a co-efficient of linear expansion  $= \beta$  its change in length for the same temperature rise is:—

$$\Delta L/L = \beta \cdot \Delta t$$

Assume the specimen on to which the gauge is applied has a co-efficient of linear expansion  $\gamma$ . When the gauge is stuck to the specimen,

the co-efficient of expansion of the stronger material, i.e., the specimen, takes charge, altering the length of the conductor with temperature to the same extent as would a strain of magnitude:

$$\Delta x/x = (\gamma - \beta) \cdot \Delta t$$

This apparent strain acting on the conductor produces a fractional change of resistance.

$$\Delta R/R = s \Delta x/x = s(\gamma - \beta) \cdot \Delta t$$

where  $s$  = the strain sensitivity of the conductor.

Thus the composite resistance temperature co-efficient of the mounted conductor alters from  $\alpha$  to  $\alpha + s(\gamma - \beta)$  and the total fractional change of resistance becomes:

$$\Delta R/R = [\alpha + s(\gamma - \beta)] \Delta t = \alpha_1 \Delta t$$

where  $\alpha_1$  = total effective temperature co-efficient of the mounted gauge.

Consider a gauge of resistance 100 ohms on a specimen and subjected to a strain of 0.1 per cent. For a gauge factor of 2, the change in resistance due to this strain will be 0.2 per cent. i.e., 0.2 ohms. If we are endeavouring to make readings to an accuracy of 1 per cent., we must measure this change of resistance to 0.002 ohms, i.e., with an error not exceeding 2 parts in 100,000. Errors due to temperature must therefore be kept below this, i.e., the product of the total effective temperature co-efficient  $\alpha_1$ , and the temperature change expected during an experiment must be less than 2 parts in 100,000.

For a copper-nickel gauge mounted on aluminium, the respective co-efficients of thermal expansion are 15 parts in  $10^6$  and 24 parts in  $10^6$  per  $^{\circ}\text{C}$ , respectively. The resistance temperature co-efficient for copper-nickel is about 30 parts in  $10^6$  per  $^{\circ}\text{C}$ . The composite resistance temperature co-efficient is  $[30 + 2(24 - 15)] = 48$  in  $10^6$ , and for a rise in temperature of  $10^{\circ}\text{C}$ , the fractional change in resistance can rise to 480 parts in  $10^6$ , equal to an apparent reduction in strain of 24 per cent.

Clearly, for the static or slowly varying strains, some means of balancing out this effect must be used if we are to obtain any accuracy in our measurements.

This is achieved, in practice, by mounting a gauge of similar characteristics to the measuring gauge, preferably from the same batch and if possible made from the same reel of

wire, on to an unstrained part of the same material as the test piece. This "compensating gauge" is then used as a standard of reference.

The temperature compensating gauge, in addition to being as nearly as possible identical to the measuring gauge, should also be mounted in the same way and with the same adhesive as the measuring gauge. The drying process should also be identical, the measuring and compensating gauges being so treated together.

In an endeavour to achieve the same thickness of adhesive, equal weights (1-2 lb.) should be placed on top of each gauge. If the weights are of brass amalgamated with mercury, it will be found that the cellulose-nitrate cement will not adhere and that they can be readily removed.

### 8.2. Fixing the Gauge

The importance of a good bond between the gauge and the specimen under test cannot be over emphasised. The strain in the specimen is transmitted to the gauge through the adhesive matrix, and imperfect sticking can give rise to serious errors in the interpretation of the observed results.

The most widely used adhesive for fixing the gauge to the specimen is cellulose-nitrate. The surface of the specimen must be thoroughly cleaned of all rust and scale. The surface should be roughened with grade 0 emery paper and thoroughly cleaned to remove all traces of grease. A thin layer of cellulose-nitrate cement is then smeared on the surface and allowed to dry. Meanwhile the back of the gauge is cleaned with alcohol and the gauge immersed in dilute cellulose-nitrate cement. A thin coat is then applied to the surface; the gauge removed from the dilute adhesive, all surplus removed, and then placed in position on the specimen. The gauge should be pressed on with a rolling movement so that surplus adhesive is rolled out at the ends of the gauge. Before sealing pressure is applied, the gauge should be correctly orientated to the gauge lines previously scribed on the surface.

The effectiveness of the bond depends upon the individual interpretation of "cleaning the surface" and the method of drying adopted once the gauge has been affixed.

The makers of the Baldwin-Southwark gauge, under the heading "what we mean when we

say 'Get the surface thoroughly clean'" succinctly state:

- (1) Scrub with a hard brush and tolitol.
- (2) Then using another brush, scrub with carbon tetrachloride.
- (3) Then, with yet another brush, scrub with acetone (this brush must have natural bristle, not nylon.)
- (4) Apply gauge promptly. Handle with care; do not touch surface with fingers.

The natural tendency is for the ends of the gauge to curl upwards when adhesive is applied to the underside of the gauge. A faulty bond at the ends of the gauge results in serious loss of gauge factor; E. Jones quotes a reduction of gauge factor from 1.98 to 1.64 due to this effect.<sup>12</sup> The effect is much less severe when the ends are firmly fixed, and the centre of the gauge is left unstuck. For this condition, the measured gauge factor (in tension) was found to have increased from 1.98 to 2.04.

The tendency for the gauge ends to curl up is much reduced by immersion in dilute adhesive, but, where possible the gauge should be held in position by means of a clamp, particularly on curved surfaces. The leads from the gauge should also be fixed securely, to avoid undue strain on the junction, and to prevent the possibility of the gauge ends lifting.

When a cellulose acetate bonded gauge is first affixed to a specimen it will be found that its resistance starts to rise, reaches a maximum and then slowly returns to a value a little higher than the original. The maximum change, of about 0.25 per cent., is reached after five to six hours, but a steady state is not reached until a further drying period of at least 48 hours.

In particular cases where this drift is not of serious importance, for example, in dynamic applications, short run measurements can be taken after a 24 hours drying period, but it is inadvisable to carry out any precise measurements until after a drying period of at least 48 hours and preferably 5-7 days.

In cases where this long drying out period must be reduced, several methods of hastening the process have been suggested; the gauge can be ironed with a small electric iron (taking care to see that the temperature does not exceed 70°C and that the gauge is not damaged); a hot air blower can be employed;

or the normal gauge current can be passed through the gauge, thus providing a measure of self-heating. With such methods, the drying time can usually be halved but it should be noted that the magnitude of the change of resistance with drying time will also increase, and may reach a higher value in the steady state. For this reason the temperature compensating gauge should also be fixed and dried under identical conditions to the measuring gauge.

The drying time can also be reduced by the use of "high solids" cellulose acetate cement. These cements are rather more difficult to use, because rapid drying commences as soon as they are applied to the surface, and the gauge must be pressed into position immediately.

It is most important that the drying is not accelerated too greatly, otherwise there is the danger that the solvent vapour will form air bubbles under the surface and create an entirely new set of errors of much greater magnitude.

For instrumentation purposes, where a high, long-term stability is essential, considerable refinements in technique are necessary. The gauges are kept in a desiccator for several days before fixing. After fixing, the complete gauged unit is placed in a desiccator and allowed to dry at 16°C for 24 hours. It is then placed in an oven and baked at 35°C for 24 hours. The temperature is then raised to 70°C and the baking continued for 5 days. Such units always include the temperature compensating gauge as an integral part of the design. When cellulose nitrate cements are used with bakelized gauges, even longer drying times must be allowed since the evaporation of the solvent is only possible at the edges of the gauge, the body being relatively impervious. The bakelized gauge is, however, much more robust and, for special applications, this advantage may well be worth the extra drying time.

These bakelized gauges are also the appropriate type to use with bakelite cement, giving an installation of great permanence and resistance to atmospheric conditions. The preparation for cementing with bakelite follows the same lines as those already described for cellulose acetate cement, but, as the bakelite is a thermo-setting cement, oven-drying at 85°C is essential, thus making this an impracticable method for many applications.

### 8.3. Humidity

The effect of humidity on a mounted strain gauge can have serious effects, unless proper precautions are taken. With cellulose acetate gauges, or bakelite gauges secured with cellulose nitrate cement, it is well known that exposure to a humid atmosphere reduces the gauge response and that with prolonged exposure of 100 per cent. humidity, the response falls to zero, i.e., the absorption of water by the matrix and/or the adhesive destroys the bond between the gauge and the test surface.

The action of moisture upon the wire also causes erosion due to electrolytic action. This results in an increase in resistance of the gauge, followed by ultimate failure. This effect is much less marked if the gauge is made positive with respect to the test surface, i.e., with the gauge wire acting as an anode and the surface of the specimen as cathode. In a report by Manson<sup>13</sup> dealing with vibration measurements at very high temperatures (and therefore under conditions of very high humidity on cooling down) it is stated that in every case where the gauge was at a potential negative to the specimen, failure occurred due to corrosion, but that, where the gauge was operated at a potential positive to the specimen no trouble was experienced. Completely satisfactory results were also obtained if the specimen was isolated from the gauge circuit, i.e., the complete gauge circuit was left ungrounded.

The resistance of the gauge is also affected by the shunt resistance formed by the moisture path. If the temperature compensating gauge has been treated in exactly the same way as the active gauge, and is subjected to the same conditions, this effect will be largely self-compensating when the active and compensating gauges are used in adjacent arms of a bridge measuring circuit.

The effect of a shunt resistance  $R$  of a very high value across a resistance  $r$  of low value can be calculated from

$$\Delta r/r = r/R$$

With a gauge resistance of 500 ohms a shunt resistance of 10 megohms will produce a change in gauge resistance equivalent to a strain of  $10^{-4}$ . The importance of high insulation resistance therefore becomes obvious when measuring strains which ordinarily do not exceed  $10^{-3}$ .

#### 8.4. Waterproofing

Sufficient has been said of the effects of moisture upon the gauge to show the necessity of adequate waterproofing even under conditions of laboratory use. Only in particular instrumentation applications can the bonded gauge be hermetically sealed. It is usual therefore to cover the bonded gauge with some waterproofing compound. The essentials of such a compound are:—

- (1) It must be relatively simple to apply, i.e., compounds requiring heat treatment do not have a general application.
- (2) The shrinkage after application must be negligible.
- (3) It must exercise no restriction upon the movement of the gauge.

The method generally adopted in this country is to cover the whole of the mounted gauge, and a fair area surrounding it, with DiJell, Grade 171. DiJell is a petroleum wax in paste form, with a comparatively low melting point, practically no mechanical strength, and the property of bonding well with metal.<sup>14</sup> The DiJell should be warmed sufficiently to enable it to be thickly smeared over the element and the immediate surface area. It should not be liquefied and poured on; if this is done the gauge may be impregnated with it, and this may cause slip. The DiJell is applied immediately after the baking process, and whilst the mounted gauge is still warm. In the case of air-drying it is advisable to apply the DiJell only after the gauge has been dissipating its normal current for some 2 or 3 hours, to prevent any possibility of trapping moist air.

The protection recommended by the Baldwin Southwark Company is to coat the gauge with Petrosene wax. In cases where the whole of the mounted gauge area can be raised to 60°–70° C, this forms a protection superior to DiJell, but the operation is fraught with a certain amount of danger of damage to the gauge. In cases where the temperature cannot be raised, the application of the hot wax to a cold surface can lead to a false sense of security as it is by no means certain that a good waterproof bond between the surface and the wax will result and without good bonding, moisture creep will inevitably result. After the application of the DiJell, various forms of protective covering can if necessary be devised to prevent the coating and the gauge from damage.

#### 8.5. Drift under Load

The strain sensitivity is influenced by a further factor which is termed "memory" effect, or lag. This effect is a function of the change of resistance and the time duration of the strain causing it. For a unit step increase (or decrease) in strain, there is an overshoot in the direction of the strain of the order of 1 per cent. of the change with a decay time of 1 minute, i.e., for a unit step strain of 0.15 per cent. the zero shift corresponds to a strain of  $1.5 \times 10^{-5}$ . E. Jones<sup>12</sup> has suggested that this effect is not due to changes in the wire filament, but is bound up entirely with the material of the matrix and the adhesive, but tests on unbonded gauges, i.e., with no matrix or adhesive, exhibit this same effect.

#### 8.6. Drift during Warming-up

Drift during this time is due, mainly, to temperature difference between the active and the compensating gauges. The magnitude of this effect is bound up with the relative heat dissipating conditions of the two gauges, since the active gauge is on the test body and the compensating gauge on a slip of the same material. With the widely differing physical conditions that can result from such an arrangement, it is not uncommon for an apparent change in resistance of 0.01 per cent. to occur over a period of four hours. With high gauge currents this change can easily be doubled.

In instrumentation applications, where the active and temperature compensating gauges are mounted in such a manner as to achieve as nearly identical operating conditions as possible, this effect is very small, usually less than an apparent change in resistance of 1 part in  $10^{-5}$ .

The value of the current through the gauge plays an important part, since the heat generated by the gauge itself is mainly dissipated by the surface on to which it is stuck. Reduction of gauge current will always assist in reducing this "warming-up" drift but the output from the gauge is reduced in the same ratio.

#### 9. Conclusion

The resistance wire strain gauge has been discussed in some detail because although the techniques and effects described may be well known to the stress analysis engineer, they may not be so well known to the radio and electrical

engineer unless it has been his lot to be associated with the design of instrumentation in this field. Even when this is the case, there is a tendency to concern oneself only with the associated electronic problems (usually more than sufficient!) and not with the application problems as such. Perhaps the information included here may contribute towards a more comprehensive view.

## 10. References

1. William Thomson (Lord Kelvin). "The electrodynamic qualities of metals." *Phil. Trans. Roy. Soc.*, 146, 1856.
2. Elie Wartman. "The effect of pressure on the electrical conductivity of metallic wires." *Phil. Mag., London*, 17, 1859, p. 4.
3. R. W. Carlson. "Five years' improvement of the elastic wire strain meter." *Engineering News Record*, 114, May 1935.  
*Note*.—These first three references are of historical interest only.
4. R. D. Meyer. "Application of unbonded type resistance gauges." *Instruments*, 19, March 1946, p. 3.
5. D. S. Clark and D. S. Datwyler. "Stress-strain relations under tension impact loadings." *Proc. Amer. Soc. Mech. Engrs*, 38, 1938.
6. Edward E. Simmons, Jnr. U.S. Patent. Serial No. 320,327.
7. A. V. de Forest and H. Lederman. "The Development of Electrical Strain Gauges." N.A.C.A. Tech. Note 774.
8. Arthur C. Ruge. U.S. Patent. Serial Nos. 410,865, 413,333, 451,063, 453,505.
9. D. S. Dean. British Patent Application No. 21479/53.
10. R. B. Sims, J. A. Place, and A. D. Morley. "A 1200-ton load cell for a hot rolling mill." *Engineering*, 173, 1952, p. 116.
11. A. C. Ruge. "The bonded wire torque-meter." *Experimental Stress Analysis*, 1, 1943, p. 2.
12. E. Jones. "Some Physical Characteristics of the Wire Resistance Strain Gauge." "Physics in Industry." (Institute of Physics, 1948.)
13. S. S. Manson, R. H. Kemp, and W. C. Morgan. "High temperature strain gauges and their application to measurement of vibratory stresses in turbo-supercharger buckets." *Experimental Stress Analysis*, 2, 1944, p. 1.

14. DiJell is obtainable from: Aston, Boisseiler and Lawrence.
15. E. P. George. "High Frequency Strain Gauges." "Physics in Industry." (Institute of Physics, 1948.)
16. R. Baumberger and F. Hines. "Practical reduction formulas for use on bonded wire strain gauges in two-dimensional stress fields." *Experimental Stress Analysis*, 5, 1947, p. 1.

## 11. Bibliography

H. C. Roberts, "Mechanical Measurements by Electrical Methods" (The Instruments Publishing Co., Pittsburgh, U.S.A., 1946).

G. E. Bennett, G. R. Richards and E. C. Voss, "Electronics Applied to the Measurement of Physical Quantities" (Royal Aircraft Establishment Report No. INSTM 1, September 1947).

W. B. Dobie and P. C. G. Isaac, "Electric Resistance Strain Gauge" (English Universities Press, Ltd., 1948).

R. J. Roark, "Formulas for Stress and Strain" (McGraw-Hill Book Co., New York, 1943).

"Experimental Stress Analysis" (Proceedings of the Society for Experimental Stress Analysis, Cambridge, Mass.).

## 12. Appendix 1: Strain Sensitivity

The strain sensitivity, or the gauge factor, of a resistance strain-gauge is defined as the ratio of the fractional change of resistance to the strain producing it.

i.e.  $s = \Delta R / R - \Delta L / L$  or  $\Delta R / R = s \Delta L / L$   
where  $\Delta R / R$  = the fractional change in resistance,  $\Delta L / L$  = the fractional change in length, or the strain.

The proportional change of resistance is not equal to the proportional change of length of the surface under strain. An increase in the length of the wire is accompanied by a decrease in its cross-sectional area (and vice-versa). Calculated on dimensional factors alone, the original unstrained resistance of the wire would be subject to the two simultaneous causes of variation each of like sign.

Let  $L$  = unstrained length of gauge

$D$  = unstrained diameter of wire

$R$  = unstrained resistance

$l/m$  = Poisson's ratio (approx.  $\frac{1}{3}$ )

then  $(R+\Delta R)/R = (L+\Delta L)/L \times (D+\Delta D)^2/D^2$   
substituting  $\Delta D/D = \Delta L/L$   
and simplifying:

$$\frac{dR}{R} = (1+2/m) \frac{dL}{L} = 1.6 \frac{dL}{L}$$

The gauge factor or strain sensitivity should thus be 1.6. As Poisson's ratio is approximately the same for most metals it would be expected that the strain sensitivity would also remain constant for different metals.

Experiment shows that this is not the case. As will be seen from Table 1 (due to de Forest and Lederman<sup>7</sup>), they vary between -12.1 for nickel to +6.0 for platinum and for most commercial gauges using 45/55 copper-nickel wire the gauge factor is approximately 2. This wide variation must be caused by some factor other than dimensional changes. The exact cause is still unknown—it is assumed that the specific resistance varies with strain and that Poisson's ratio does not hold for fine diameter wires.

It is fortunate that this change in resistivity is a linear function of strain and that some advantage in sensitivity is gained with the alloys of low-temperature coefficient.

### 12.1. Strain Sensitivity at High Frequency

An investigation by E. P. George<sup>15</sup> has shown that the change of resistance of ferromagnetic wires with tension is found to be much greater if the measurements are performed using a.c. of high frequency than if d.c. is used. Using a steel wire of 26 S.W.G. dynamic tests were made at 20 Mc/s. Under conditions of equal h.f. and d.c. dissipation the signal was 40 times as great using the 20-Mc/s excitation than with d.c. The relationship between the change of resistance and strain was not linear. At a test frequency of 200 kc/s. the signal was approximately twice as great but, again, not linear. The effect is adjudged to be due to the effect of stress upon the circumferential permeability. Non-magnetic wires gave little change from the d.c. condition.

Apart from the drawback of non-linearity, measurement techniques at radio frequencies are not particularly simple, and the possibility of error is quite appreciable, so that it is doubtful if any advantage can be taken of this.

### 13. Appendix 2: Effect of Gauge Geometry on Gauge Factor

Consider the gauge, shown in Fig. 19, to be mounted on a specimen, the only strain acting

upon the specimen being in the direction shown.

The strain sensitivities given in Table 1 then become modified by the geometry of the winding.

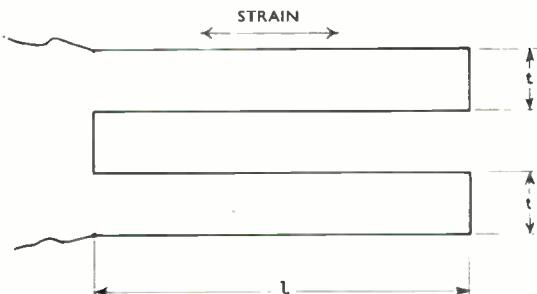


Fig. 19.—Cross sensitivity in a gauge winding.

**Table 1**  
Strain Sensitivities and Relative Temperature effects.  
(Due to de Forest & Lederman)

Material	Strain Sensitivity for single wire	Relative Tempera- ture effect*
Platinum	6.0	—
Manganin	0.47	— 400
Nickel	12.1	-13,500 (Non-linear)
Nichrome	2.1	2,100
Phosphor bronze	1.9	7,800
5% Iridium platinum	5.1	11,600
Advance—Eureka ferry	2.1	— 30
CopelM	2.4	— 200
Monel	1.9	8,000
Iso-elastic	3.6	5,000

\* Expressed as the Stress (lb/in.<sup>2</sup>) equivalent to 1°C temperature change when the gauge is attached to a steel specimen.

The four strands, each of length  $l$ , are sensitive only to the strain parallel to their axis. The extension of each strand is therefore:

$$\Delta l = l.e \quad \text{where } e = \text{strain in specimen.}$$

The three strands of length  $t$  have no direct strain acting parallel to their axis but due to Poisson's ratio will suffer a compressive strain of magnitude  $e/m$ . The resulting decrease in length will be:—

$$\Delta t = t.e/m$$

If  $n$  = the number of strands and  
 $n_1L = L_A$ ;  $n_2t = L_T$ ;  $L_A + L_T = L$   
 $\Delta L = (L_A - L_T/m)e$ .

Due to this, the expression

$$\Delta R/R = s\Delta l/l \text{ will modify to}$$

$$\Delta R/R = k\Delta l/l$$

or  $\Delta R/R = s\Delta L/L = s(L_A - L_T/m)e/(L_A + L_T)$   
hence  $k = s(L_A - L_T/m)/(L_A + L_T)$

The length of the wire in the end loops thus has a limiting effect on the gauge sensitivity. Due to the manufacturing technique there is a definite limit to the size of the loop. On very short gauge lengths the inactive portion is a high proportion of the total length of wire used, and the gauge factor is seriously reduced. To overcome this effect, the flat helical winding is generally employed for gauge lengths shorter than 0.25 in. In this construction, the end loops are perpendicular to the

plane of the gauge and are a very small proportion of the total length.

The effect of Poisson's ratio can usually therefore be ignored, so far as the direct sensitivity is concerned.

### 13.1. Cross Sensitivity

The fact that a gauge is in some degree responsive to lateral strain must, however, be taken in account when it is used in a general strain field, or serious errors can result. This factor is discussed in some detail by R. Baumberger and F. Hines<sup>16</sup>, and methods for the calculation of this effect and the correction factors to be applied are dealt with in some detail.

Cross sensitivity is defined as:

$$= \frac{\text{lateral strain sensitivity}}{\text{axial strain sensitivity}} = \frac{\text{width of gauge grid} \times \text{axial sensitivity}}{\text{active gauge length} \times \text{number of turns}}$$

## DISCUSSION

**R. K. Vinycomb (Associate Member):** I would like Mr. Thompson to tell us a little more about the elliptical-tube pressure transducer because he has explained that its great advantages over the barrel-type are a high overload capacity and wide range. Can he in fact say whether these advantages are obtained at the expense of natural frequency?

**J. L. Thompson (in reply):** The natural frequency is, of course, considerably reduced but is still in the order of hundreds of cycles per second. The great advantage of this type of pressure transducer is the comparatively thick wall for low pressure ranges and the enormously high overload factor. For example, with a wall thickness of 0.020 in., a strain of 0.13 per cent. was obtained for an applied pressure of 50 lb/in.<sup>2</sup>. With 1,000 lb/in.<sup>2</sup> applied, the elliptical tube deformed into a circular cross-section but did not burst until the pressure was increased to 1,200 lb/in.<sup>2</sup>. In many cases the almost certain guarantee that peak pressures, many times in excess of the normal working pressure, will not

cause the tube to fracture and so result in a leak in the oil pressure line is of even greater importance than a very high natural frequency.

**A. B. Clewes:** I am contemplating work involving the measurement of torques on rotating shafts by means of strain gauges. This will call for the use of slip rings and I would like to ask Mr. Thompson what difficulties are likely to be met.

**J. L. Thompson (in reply):** The limiting factor is undoubtedly the ratio of the signal voltage to the slip-ring noise voltage. You will probably do best by using silver rings and silver graphite brushes and it might also be best to use more than one brush on each ring. The R.A.E. have designed a form of pneumatically operated slip-ring brush whereby the brush is only in contact with the ring during the actual recording period. For long-term tests this obviates the necessity for the frequent replacement of brushes. Rolls-Royce have developed a form of mercury slip ring which is very satisfactory.

Another possibility is to mount an oscillator with its associated modulator unit on to the rotating shaft, thus using a radio link and dispensing with slip rings altogether or to use the slip rings only to supply the necessary valve potentials.

**J. G. G. Hempson:** Dealing first with Mr. Thompson's remarks on strain gauge pressure transducers, I am surprised that he considers that there is only 60 per cent. overload margin. With similar types of tubular gauges we normally work to a stress of only about one-fifth of the ultimate stress to avoid fatigue failure. Thus there is a very large margin to take care of temporary overload, but perhaps his applications deal with static measurements where fatigue is not involved.

We agree that a high-strength aluminium alloy, such as Duralumin, is often most satisfactory for such gauges and gives more rapid temperature compensation than beryllium copper, due to its high thermal conductivity.

The single-ended construction of the gauge involving a "T" connection into the line is often inadmissible where high-frequency transients are involved, but, again, it may be adequate in the applications foreseen.

The table of suitable material for strain gauge wires on page 599 does not include two alloys which we have found to be most satisfactory, "Karma" and "Jelliff 800." These have temperature coefficients of resistance comparable to manganin, high mechanical strength and specific resistance greater than nichrome. I am surprised that they have not found wider application in this country.

Regarding the reference to slip-ring difficulties; where silver is mentioned, is pure silver meant or one of the harder high-silver-content alloys? There is one type of almost noiseless slip-ring assembly, that using a mercury-pool pickup.

**J. L. Thompson (in reply):** The overload limitation is, of course, dependent upon whether the transducer is to be used for static or dynamic work. With stresses of the order of 0·1 per cent.,

pressure barrels made of beryllium copper have satisfactorily stood many millions of repetitive pressure cycles. The actual strain that is decided upon for any one application is very often controlled by the sensitivity that is required from the transducer.

With regard to the materials that Mr. Hempson has mentioned; when one is winding one's own strain gauges, as for example, in barrel pressure transducers, the choice of wire to be used rests entirely with the designer, but in the majority of cases the normal paper-backed strain gauges have to be used and the choice of material, with the gauges that are available in this country, is strictly limited.

**W. Nock:** I notice that Mr. Thompson avoids any mention of the accuracies that can be expected from strain-gauge-type load cells. Very high long-term accuracies are required when the system is used for tanks weighing up to 100 tons where zero balances of the gauges will only be possible at long intervals. Also I should like to know what frequency range he obtains with barrel-type pressure transducers.

**J. L. Thompson (in reply):** Although with certain types of cells we have obtained repetitive accuracies of the order of one part in 15,000, the problems of drift, hysteresis, matrix, adhesive and temperature all tend to increase this error figure and I would doubt whether commercial devices would have a long-term accuracy better than  $\pm 1$  per cent. This might be improved if the range of any particular cell was limited down to half of its nominal full range.

Our experience is that electronic weighing is only satisfactory for loads in excess of a ton and that if you have to weigh something less than this it is much better to use one or other of the conventional methods.

The natural frequency of barrel-type pressure transducers is of the order of several thousand per second.

## MEMBERS OF INSTITUTION COMMITTEES

**Christmas Cyril Evans** was born in 1906 in Merthyr, Glamorgan, where he received his general education. In 1924 he entered the University College of Swansea where he read Physics and Mathematics, obtaining his B.Sc. in 1927, and the M.Sc. in 1928 for a thesis on Magnetic Dispersion.



turer in 1940 and seven years later became head of the Department of Physics and Mathematics in which post he is responsible for all courses in Physics, Mathematics and Radio Engineering.

Shortly after his election as an Associate Member of the Institution in 1953, Mr. Evans took a leading part in the formation of a Local Section in South Wales, and became first Honorary Secretary of that Section. (See Annual Report for 1953/54, page 449.)

**Charles Walter Miller** was born in 1915 in Leeds, where he received his general education. In 1933 he entered Leeds University, obtaining a B.Sc. Degree in Physics and Electrical Engineering in 1936. He then joined Metropolitan-Vickers Electrical Co., Ltd., Manchester, as a post-graduate apprentice and was subsequently appointed Research Physicist in the Research Department.

Between 1937 and 1939 Mr. Miller was engaged in research on the production of vacua and the design of diffusion pumps, and he was awarded the M.Sc. degree for a thesis on this subject.

During the war, Mr. Miller was concerned with the design of high-power radar equipment; subse-



quently he has worked on the application of radar techniques to the field of particle accelerators. His present work has included the design of travelling wave linear accelerators, of which some of the industrial uses were described in his two papers read at the 1954 Industrial Electronics Convention. Mr. Miller is also the author of a number of other technical papers.

Elected an Associate Member of the Institution in 1942, Mr. Miller has taken an active part in the work of the Institution in the Manchester area. From 1945-46 he was Honorary Secretary of the North-Western Section and earlier this year he was appointed Chairman.

**Wilfred John Perkins**, who was born in 1917 at Rushden, Northamptonshire, joined the Royal Air Force in 1937. He received his technical training at the Electrical and Wireless School, Cranwell, and subsequently at the Northampton Polytechnic, obtaining the Full Technological Certificate of the City and Guilds of London Institute in Telecommunications Engineering.

After passing his final examinations at Cranwell, he was appointed a lecturer in radio on the Aircraft Apprentices' Course. From 1942-46 he served in the Far East, being principally concerned with the installation and operation of v.h.f. stations.



On demobilization, Mr. Perkins joined the National Institute for Medical Research, where he was given the task of establishing the Electronics Laboratory of the Instrument Division. His work includes both design and production of special electrical and electronics apparatus for medical research and advisory duties on measuring techniques.

Mr. Perkins qualified for transfer to Associate Member in 1951. Since July 1952 he has served on the Education and Examinations Committee of the Institution; he has recently been appointed examiner in the subject of Principles of Radio Engineering of the Graduateship Examination.

# DIFFERENTIAL TRANSFORMERS FOR MECHANICAL MEASUREMENTS\*

by

L. W. Blick (Associate Member)†

A Paper presented during the Industrial Electronics Convention held in Oxford in July 1954

## SUMMARY

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

### 1. Principles of Differential Transformers

A differential transformer<sup>1, 2</sup> is a device which in general consists of three inductive windings together with a magnetic core, so arranged that movement of the core, or part of it, varies the coupling between one winding, the primary, and the other two, the secondaries. The arrangement of the windings is made in such a way that the coupling between the primary and one secondary increases whilst the coupling between the primary and the other secondary decreases—that is, the secondaries respond differentially to the movement of the core. Frequently, the primary is wound between the two secondaries, with a small magnetic rod-like core, or armature, threaded through the three coils, as shown in Fig. 1. If the primary is energized at a suitable voltage and frequency, and the secondaries are connected in opposition, there will be one position of the armature where the voltages injected into the two secondaries are equal, and therefore the voltage appearing across the secondary terminals at the energizing frequency will be zero. It is this type of differential transformer which is the subject of this paper.

As a differential transformer is an inductively operated device, it is apparent for the best results that no other coupling should exist between primary and secondary. Resistive coupling is easy to avoid, and electrostatic coupling could be avoided by means of a Faraday screen, but in practice this fortunately turns out to be unnecessary. As the secondaries

are connected in opposition, the starts of the two windings are connected together, and the two finishes are used for the output. Therefore, any electrostatic coupling from the primary will affect both secondaries equally and will not appear in the output. The complete transformer of course to be robust has to be encased in a box, and as long as this is metallic it acts as an electrostatic screen against external fields, whilst magnetic interference from outside is very heavily attenuated due to the method of connecting the secondaries. Only if external magnetic fields are strong, causing modulation of the energizing signal because of the non-linear characteristics of the armature, do they become troublesome.

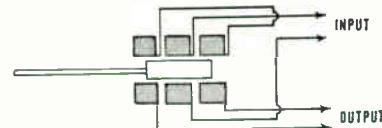


Fig. 1.—Basic arrangement of a differential transformer.

The differential transformer, in common with any other transformer, operates on alternating current, and for the best performance the choice of the operating frequency may be an important matter. The equivalent circuit<sup>3</sup> is given in Fig. 2, neglecting stray coupling capacitances for simplicity, and for the reasons already given.

It may be seen from the diagram that as the frequency of the energization of the primary increases, the output from the secondary at first increases at a rate proportional to frequency. As the frequency rises, this rate of increase slows down, due to the increasing internal

† Manuscript received May 7th, 1954. (Paper No. 292.)

\* Boulton Paul Aircraft Ltd., Wolverhampton.  
U.D.C. No. 621.314.214.5: 620.17.

impedance produced by  $L_L$  and  $L_S$  in series, and then for a wide frequency range the output will remain substantially constant. At some high frequency the output will start to drop, giving an overall characteristic rather like a normal transformer. Fig. 3 shows a typical response curve.

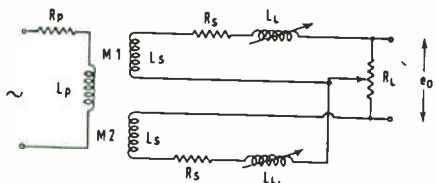


Fig. 2.—Simplified equivalent circuit of differential transformer (neglecting stray capacitances).

For this graph, the output from the secondaries has been converted into a sensitivity factor of millivolts output from the secondaries per volt applied to the primary per thousandth of an inch movement of the armature. This is a more useful criterion of performance, and is the normal way of specifying the performance of such a device.



Fig. 3.—Sensitivity/frequency characteristics of typical differential transformer.

For the majority of applications, the transducer is initially balanced to give zero output at the energizing frequency, and measurements are taken from either side of the balanced position. However, due to the presence of harmonics in the energizing signal, whose conditions of balance may differ from those of the fundamental and to the fact that the armature is essentially non-linear in its magnetic properties, the output from the transducer is never zero at balance, but consists of a band of frequencies harmonically related to the energizing signal. Therefore, frequencies below the flat part of the characteristic, although useable, should be avoided if possible as the residual signal is then higher. Similarly due to rapid phase changes occurring near the high frequency slope of the

curve, frequencies of this order should be avoided, as again the residual signal is higher. The useful band of frequencies in the case of the transducer of Fig. 3, is centred about 2 kc/s, which has been chosen as being a good compromise between all the factors for the particular transducers to be described.

## 2. Design of Differential Transformers

In the design of differential transformers, many of the aims are incompatible, and as in the majority of design matters, a compromise must be effected. Design aims include: high sensitivity; low output and input impedances for flexibility of use; insensitivity to extraneous fields; low residual signal at balance; large coils for high sensitivity, yet these must be as near the armature and each other as possible; small size to permit use in as many places as possible; low moving mass in the armature to achieve high frequency response; high stability of characteristics; low temperature coefficient; symmetry of response on either side of balance; and output directly proportional to movement of the armature.

High sensitivity may be achieved by providing a large number of ampere turns in the primary circuit, which implies working the core material at high flux density. This, however, as already shown, gives a high residual signal at balance, so sometimes the primary voltage is reduced or increased to suit the requirements of the time.

Low input impedance is readily achieved by energizing at low voltage and high current, but in the case of the secondaries, the output voltage and therefore the sensitivity is directly proportional to the number of secondary turns, that is to the square root of the output impedance. In the case of the transducers mentioned later, the input and output impedances are of the order of a few hundred ohms, thereby permitting long leads to be used.

As mentioned in Section 1, the transducers are inherently insensitive to extraneous fields and little trouble is experienced from this cause.

The residual signal at balance may be reduced in a number of ways, by energizing with a pure signal, by reducing the level of energizing, by reducing the primary resistance and by using a suitable magnetic core.

It may be shown that if the input impedance of a transformer is purely inductive, then a pure sinusoidal flux is produced in the core for a

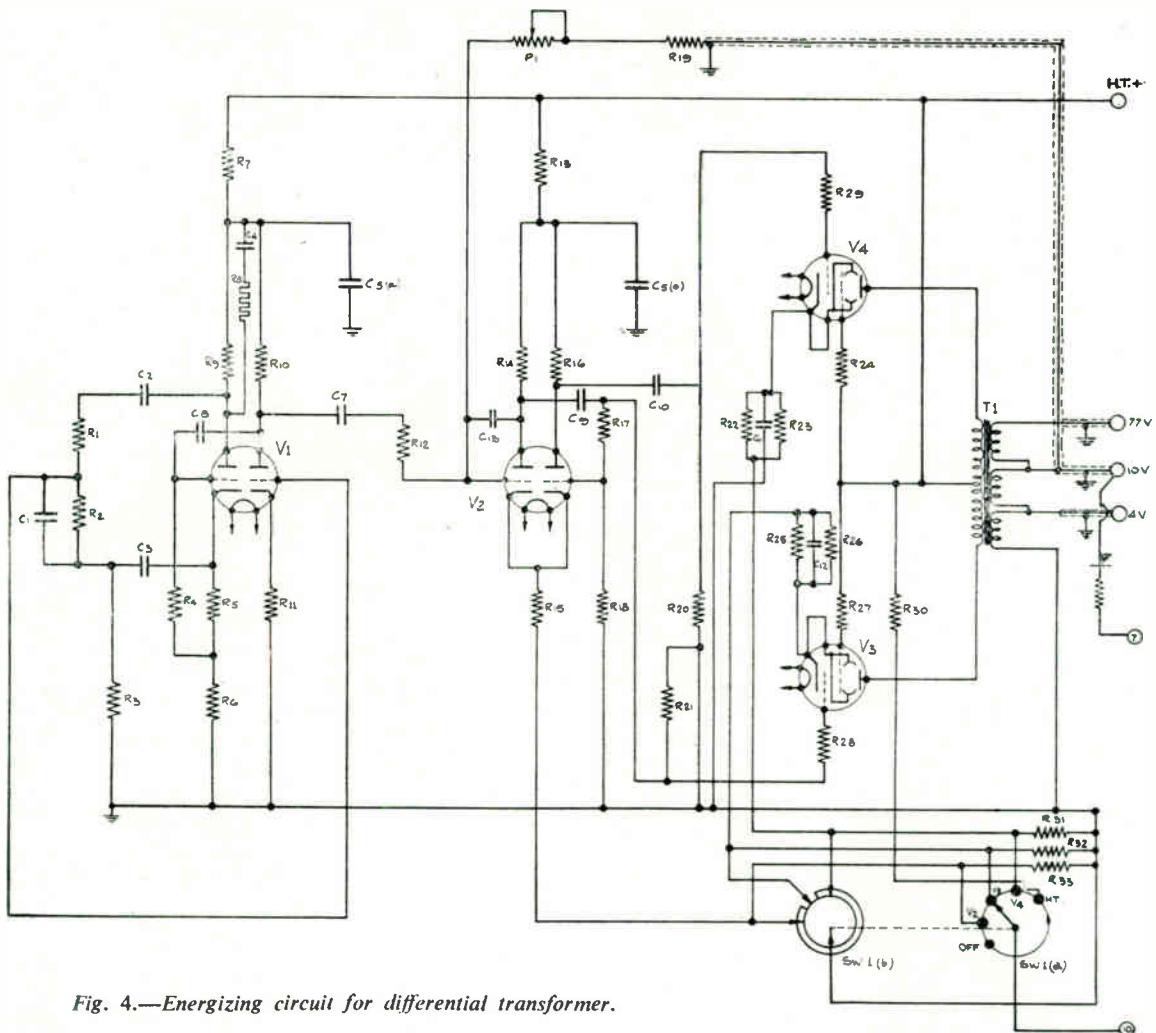


Fig. 4.—Energizing circuit for differential transformer.

sinusoidal voltage applied,<sup>4</sup> and therefore no harmonics are generated, so improvements may be made by reducing the input losses. In the case of the armature, this should be as nearly loss free as possible for the same reason, and should be a material with a *B-H* curve as nearly straight as possible over the operating range, or at least with no sharp changes in slope, and of as low remanence as possible.<sup>5</sup> Obviously, any remaining magnetism in the armature will reduce the linear range of field strength, and will introduce distortion, and drift.

The requirements for large coils near each other and the armature, and for small size are

manifestly mutually exclusive and in general designs may be produced with characteristics to meet the particular case. A general purpose transducer such as those illustrated is designed for the best possible performance in a given space. (See Fig. 7.)

Fortunately, the requirements of small size and small, light armature are similar and little need be said. In the case of the transducer shown in Fig. 8a, the moving mass for a shortened extension rod is about 1.0 gm., enabling very high frequencies to be followed.

Stability of characteristics and low temperature coefficients may be achieved by suitable choice

of bobbin and core materials, and by the use of carefully wound coils made of annealed wire. However, it should be emphasized that the desired stability will apparently not be achieved unless the object to which the transducer is attached is also stable. For example, an apparent drift with temperature will be noticed unless there is a substantially zero temperature coefficient between the points to which the transducer body and armature are affixed.

Symmetry of response about balance and an output directly proportional to armature movement is achieved by winding two stable identical secondary coils with the primary accurately positioned between them, and by accurately machining the armature. The linear range may be extended by suitably shaping the coils, but the improvement so achieved is not great.

### 3. Circuits for use with Differential Transformers

As has been stated, the optimum energizing frequency lies at about 2 kc/s for most purposes. With standard transducers the input impedance is of the order of several hundred ohms, and in order to maintain a low level of residual signal and to reduce drift from heating effects, the energizing signal is restricted to 10 V. This gives an energizing power of less than 1 VA, and therefore several transducers may be driven from a small valve-type energizing unit. As the output from a transducer is proportional to the primary energization, it is important for all open loop applications that this voltage should be maintained constant. A satisfactory performance in this respect has been produced by a thermistor stabilized Wien bridge oscillator, followed by a low power output stage with negative feedback, such as shown in Fig. 4.

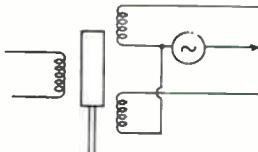
This unit maintains its output voltage constant within limits of better than  $\pm 1$  per cent. for all normal variations of mains and load, but is sensitive to slow drifts due to temperature, as the thermistor stabilizer is of course temperature operated. However, the performance is entirely satisfactory, assuming the output voltage is periodically monitored, and the necessary adjustment made.

In one position of the armature the output from the secondary will be zero, so that the operation of the differential transformer is similar to that of a normal bridge. In order to achieve a true balance, the completion of a bridge circuit is necessary, and this may be achieved

by adding a variable potentiometer across the secondaries, as in Fig. 5.<sup>2, 3</sup>

The voltage induced into the secondaries may be regarded for the purpose of explanation as being represented by a generator in the position shown. Then the bridge will be balanced if the two secondaries  $S_2$  and  $S_1$  are equal in inductance, that is, if the armature is in a central position, and the resistor slider is electrically exactly halfway along the track. Only a partial null can be achieved, however, for other positions of the armature, as both the secondary inductances and the effective induced voltages are different.

In spite of the above, however, a null balance may be achieved at any armature position, if the effective secondary inductances are adjusted to equality, when the same conditions will prevail as in Fig. 5, but with the armature in a different position. This adjustment may be made



*Fig. 5.—Bridge circuit arrangement of differential transformer.*

by shunting the appropriate secondary with a variable inductance or capacitance of the correct value.

The transducers which have been described produce an output voltage of the order of 20 mV per thousandth of an inch, and except for large displacements the output is insufficient to operate a meter directly, so some sort of amplifier has to be introduced into the system. The amplifier needs to have adequate gain, to be stable under all conditions of operation, and to have a low noise level, and if possible it should be able to operate a remote meter. The circuit of a suitable amplifier providing stable, switched gain from 400 to 100,000 is given in Fig. 6. This amplifier, together with a displacement transducer of the type shown in Fig. 7a and a suitable filter, is capable of providing a full scale deflection for a displacement of 0.0001 in., that is, one microinch is 1 per cent. of full scale reading.

The amplifier bandwidth required with a transducer energized at 2 kc/s is of course a relatively narrow pass band centred on 2 kc/s. From theory it may be shown that the minimum number of points required to define a sine wave is two per cycle, so the theoretical maximum

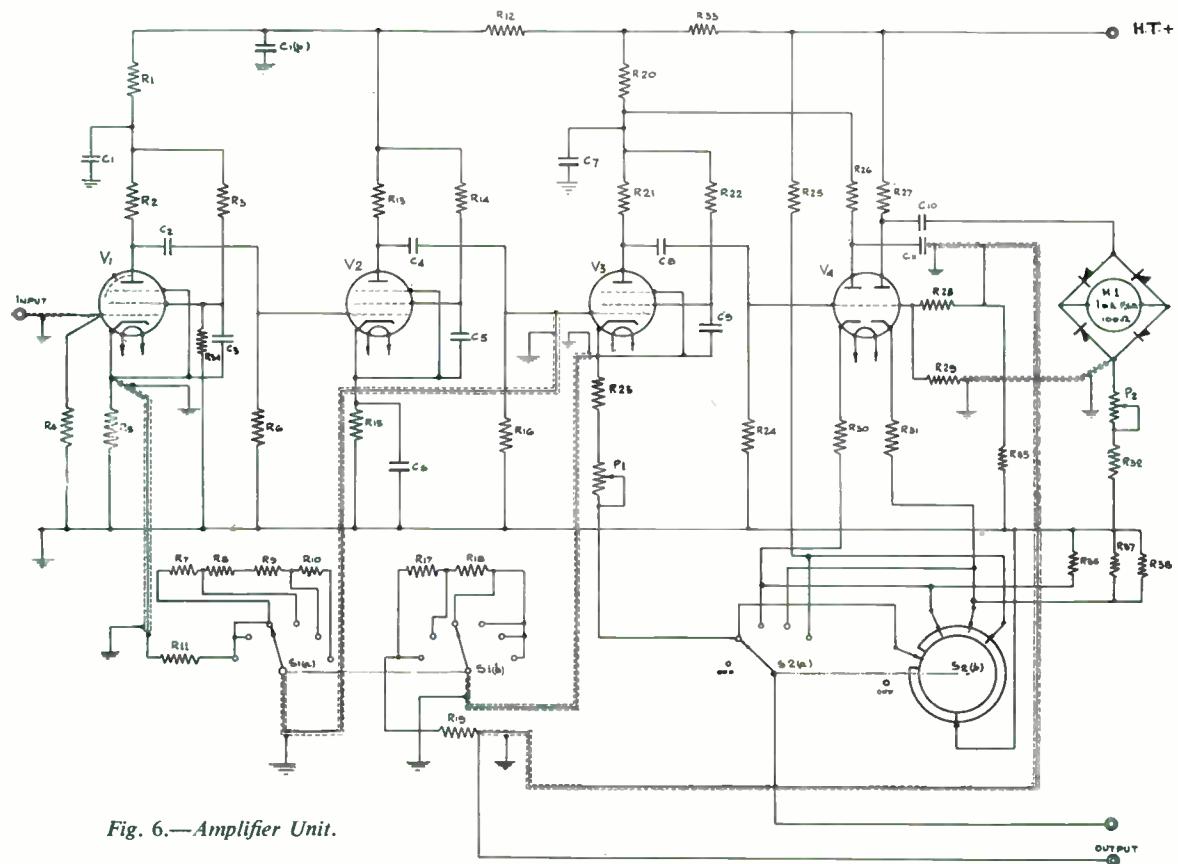


Fig. 6.—Amplifier Unit.

frequency at which the carrier may be modulated is 1 kc/s. However, in practice, the maximum useful frequency is 500 c/s, and the bandwidth required is therefore 1,500 c/s-2,500 c/s, to obtain the maximum use from the transducers.

If there is significant response at 4 kc/s and above, the harmonics left at balance will be amplified, and will blur the indication for small movements, so for high sensitivity it is advisable to restrict the frequency response. However, for ease in design, it is preferable to use an amplifier with a wide bandwidth, for then the amplifier may be used for other purposes, and to remove the unwanted frequency response by means of a filter in the input. The amplifier must hence have a low noise level, but this may be readily achieved by suitable design. This is the method adopted with the amplifier shown in Fig. 6.

In an amplifying system of high gain, which

may employ long leads, care must be taken to avoid hum loops, to avoid which well-known techniques used in audio frequency work may be adopted,<sup>6</sup> or in the event of great difficulty, the low frequency response of the amplifier may be reduced.

As has already been mentioned, a filter is necessary to reduce the residual signal so that advantage may be taken of the available sensitivity. Further, to ensure stability and to enable a properly matched filter to be used, the transducer itself should be suitably matched. A typical figure for output impedance of a transducer is 800-900 ohms, with a phase angle of about 70 deg., so no great difficulty is presented. For the case of a transducer type E.P.302 (Fig. 7a) with the amplifier of Fig. 6, the following figures are obtained:

Input required for full scale deflection at  
at maximum gain = 250  $\mu$  V.

Output from transducer for 0.0001 in. deflection with 10 V energizing signal = 2 mV off load.

Interfering harmonic residual = 2 mV off load.

On loading the transducer with 800-900 ohms, the signal is reduced by 2:1, but owing to the fact that the internal impedance increases with frequency, the residual is reduced by between 3:1 and 4:1. Taking the worse figure, the gain margin is 4:1 with a net residual of about 650  $\mu$ V. A loss of 10db can be tolerated in the matching to the filter, giving a small margin of gain in hand on signal, and reducing the residual to about 200  $\mu$ V. If a residual deflection of 1 per cent. of full scale is permitted, that is 2.5  $\mu$ V input, the filter must introduce an attenuation of unwanted harmonics relative to the desired signal of 200/2.5 or 80:1. As the lowest frequency to be rejected is the second harmonic, this is readily achieved.<sup>7</sup>

#### 4. Transducers employing Differential Transformers

Differential transformers may be used as simple displacement transducers in which form they find many uses as is detailed in Section 5. In conjunction with diaphragms or Bourdon tubes, they can measure hydraulic or pneumatic pressures, or when the armature is mounted on a suitable spring suspension they become seismic pickups or accelerometers. A pressure transducer reading up to 3,000 lb./in.<sup>2</sup> in four ranges is illustrated in Fig. 7b.

An interesting application for a differential transformer transducer is shown in Fig. 8. This is a load cell,<sup>8</sup> and in this case the transducer measures the deflection of the cell body under the applied load. An extensometer is mounted on a torsion bar inside the cell, giving a mechanical magnification of about 6:1, and the resultant sensitivity of the transducer is about 100 mV for full load with a safety factor of 6:1. The load cell gives readings under compression repeatable within  $\pm 1$  per cent of full scale for a truly axial load, and for reasonable amounts of non-axiality the accuracy is still  $\pm 2\frac{1}{2}$  per cent. For the worst possible case, of a load concentrated over the transducer to such a degree that the steel at the point of contact is on the point of crushing, the load cell gives an indication only 8 per cent. high. Load cells of this nature may be manufactured up to about 1,000



Fig. 7.—(a) Displacement transducer.



(b) Pressure transducer.

tons load each, and find wide applications in load measurements in rolling mills, power presses and similar devices.

Some of the transducers mentioned, particularly the displacement and pressure types are the electrical counterparts to well known existing mechanical instruments, and to justify their use must offer some particular advantage. One advantage of great importance, which is common to all the types mentioned, is the fact that the transducer itself may be mounted in a position which is completely inaccessible to a mechanical gauge, which is usually larger, and readings may be taken on a remote meter. For the types illustrated, working with the equipment

described, lead lengths of several hundred feet may be used with no difficulty. This property also enables all indications for process control to be located at a central point, and can offer considerable savings in cost, or in the case of a hazardous process or experiment, can offer complete protection to the personnel concerned. The second major advantage, in particular for length measurement, is the wide frequency response which may be achieved, which considerably facilitates dynamic measurements. Many mechanical devices, such as micrometers, can hardly be said to possess a frequency response at all.

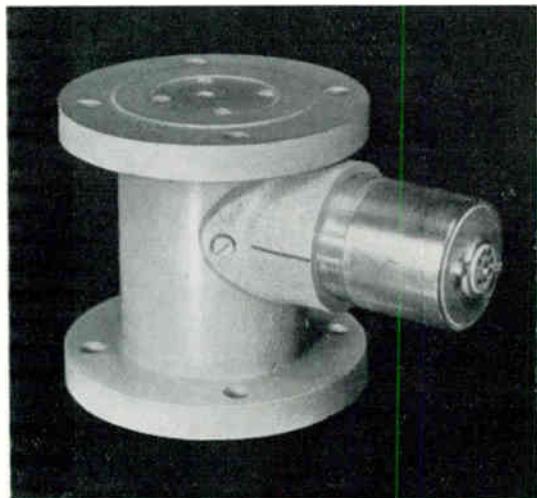
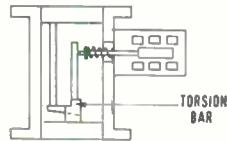


Fig. 8.—(a) (above) Typical load cell.

(b) (right) Cross-section of cell.



Very high sensitivity with robust construction coupled with relatively low cost is also offered by an electrical transducer, and the absence of backlash enables continuously reversing readings to be taken with high accuracy.

A further most important advantage is that the high available sensitivity may be readily reduced by simply altering the amplifier gain, no other adjustments being necessary, and as mentioned above, all operations, including shifting the zeros, may be performed remotely.

## 5. Complete Equipments employing Differential Transformer Transducers

Differential transformer transducers may be readily employed as the controlling element in a servo-mechanism, when by using the out of balance signal to operate a servo motor via some intermediate device to return the transducer to null, an extremely accurate instrument may be evolved. A good example of an instrument of this class is shown in Fig. 9.

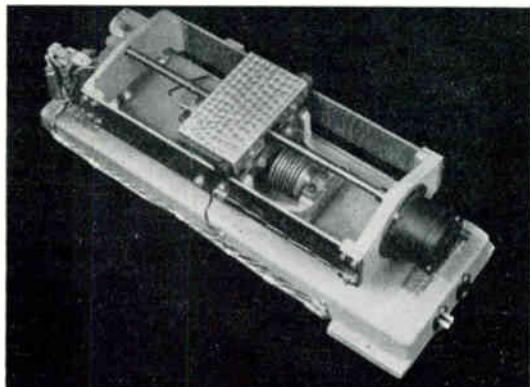


Fig. 9.—Weigh beam unit of precision manometer.

This is a precision manometer, reading, in the example shown, pressures from 0 to 72 in. of mercury. The sensitivity of the manometer is 0.005 per cent. of maximum reading, and the absolute accuracy is 0.015 per cent. of full scale. The transducer shown in the top left-hand corner, is mounted on the base plate and the armature is attached to the beam. A pressure variation applied to the capsules results in unbalancing the beam and consequently shifts the transducer from its null point. The signal produced is amplified and applied to a velodyne<sup>9</sup> servo-mechanism which, via a transmitter and repeater motor, drives the weight shown along the beam until the transducer returns to null. Remote indication is performed by a dial type indicator also driven from the velodyne.

A further typical application employing a transducer, together with a velodyne servo-mechanism, is sketched in Fig. 10.

In this case, the servo again drives the system to a null balance, and the work table is moved along in fixed increments, equal in the case shown to one third turn of the lead screw. Each turn may be made any reasonable length desired, and as the transducer will come to null at a

given cam reading, by suitably spacing the nulling points round the cam periphery, steps of any value may be made. The servo is prevented from showing null readings on undesired parts of the cam by a system of contacts, and the complete mechanism may be controlled by a punched tape or cards,<sup>11</sup> to provide completely automatic operation. If the work table is part of a machine tool, then automatic repetitive machining may be undertaken, and of course, by changing the controlling paper tape, and if necessary the cam, a wide variety of operations may be carried out without recourse to expensive jigs or tooling.

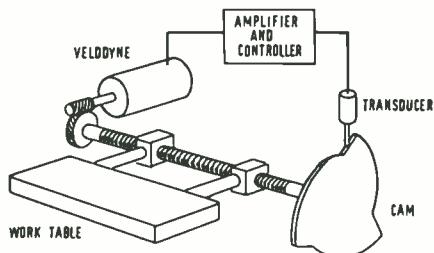


Fig. 10.—Velodyne type of servo-mechanism employing differential transformer.

The accuracy achievable may be seen from the example below. Employing the E.P.302 displacement transducer (Fig. 7a), this can give a clear-cut indication for displacements of a few microinches. If this transducer is mounted with a cam 4 in. in diameter with 45 deg. slopes for operating it, then a radial displacement of 0.0001 in. corresponds to a signal of about 2 mV.

If a velodyne servo will operate off this, and in the author's laboratory a velodyne has been made to operate from a signal of less than 0.25 µV, the positioning may be achieved to 0.0001 circumference of the cam, for 45 deg. slope. This corresponds to about  $0.0001/12.5 = 0.000008$  revolution of the lead screw, so the limiting accuracy clearly depends on the accuracy to which the lead screw itself may be made. Furthermore, the accuracy of positioning depends on the lead screw alone, within the limits given.

Although differential transformer transducers are capable of achieving such high performance with closed loop feedback systems, they may be used with advantage with simpler direct reading equipment where accuracies of the order of  $\pm 1$  per cent. of full scale are acceptable.

The E.P. 302 transducer, with a "Pendeford"

indicator is being used at present for many applications outside normal engineering work, for example in hospitals for blood pressure measurements, and at a biological research unit for the investigation of nervous reactions by indicating muscle movements. Due to its high sensitivity, it may also be used for creep measurements, and for accurate gauging of precision components, when used as a comparator.

By mounting a transducer behind a work piece in a lathe or grinder, metal may be removed until the transducer gives no output. Large numbers of pieces may be machined accurately without recourse to continuous check measurements, and if required, a system may be devised to stop the machine feed at this point. By further elaboration, a servo-mechanism may be employed to control the feed in a way analogous to that already described.

## 6. References

1. C. M. Hathaway. "Electrical instruments for strain analysis." *Proc. Soc. Exp. Stress Anal.*, May, 1943.
2. P. S. Dickey and A. J. Hounfleck. "Electronic type instruments for industrial processes." *Trans. Amer. Soc. Mech. Engrs*, July, 1945.
3. Boulton Paul Aircraft Ltd., Technical Report No. 90, July, 1951.
4. K. A. Macfadyan. "The calculation of waveform distortion in iron-cored audio frequency transformers." *Proc. Instn Elect. Engrs*, 97, Part II, December, 1950.
5. Symposium of Papers on Ferromagnetic Materials. *Proc. Instn Elect. Engrs*, 97, Part II, April, 1950.
6. "Valves, Tubes and Circuits." Mullard Technical Report. Also, F. Langford-Smith (Ed.) "Radio Designers Handbook." (Iliffe & Sons, London, 1953.)
7. E. A. Guillemin. "Communication Networks." (John Wiley & Sons Inc., New York, 1931.)
8. British Patent Application No. 29786/53. Boulton Paul Aircraft Ltd., and L. W. Blick.
9. F. C. Williams and A. M. Uttley. "The velodyne." *J. Instn Elect. Engrs*, 93, Part IIIA, No. 7.
10. British Patent Application No. 722/54. Boulton Paul Aircraft Ltd. and L. W. Blick.
11. British Patent Application No. 721/54. Boulton Paul Aircraft Ltd. and D. P. Whatley.

## DISCUSSION

**J. N. Fletcher:** With reference to Section 2 of Mr. Blick's paper, dealing with the design of differential transformers and the importance of minimizing secondary harmonic voltages, it is stated that "if the input impedance of a transformer is purely inductive, then a pure sinusoidal flux is produced in the core for a sinusoidal voltage applied." This is not true; it would be more correct to say that if a sinusoidal voltage could be entirely accounted for by linkage of the core flux with the primary winding, then the applied voltage and core flux would have similar waveshapes. In addition to resistance, this excludes leakage inductance from the primary circuit, for relative to their impedance at fundamental frequency, leakage inductance has the more serious influence in distorting the waveform of core flux. In fact, the insertion of linear inductance, rather than resistance, in the primary circuit, is more effective in constraining the current to follow a sinusoidal waveform, and this is the converse of the present requirements.

In terms of the quotient formed on dividing the  $n$ th harmonic in core flux by the  $n$ th harmonic in excitation current, this quotient tends to be increased uniformly for all harmonics by the insertion of linear inductance in the primary winding, whilst the increase caused by resistance would attenuate as the order of harmonic or fundamental frequency increased. Consideration of phase shifts also indicates a less serious tendency towards distortion in the case of resistance.

The core flux, however, is not the essence of this problem: the relation between the primary and secondary voltages is the true criterion, and this depends upon the flux common to both windings, whether inside or outside the core.

**L. W. Blick (*in reply*):** Some of the arguments put forward by Mr. Fletcher are too involved to be answered without reference to the literature, but the main point made in the paper is that for a primary circuit of zero resistance, that is, zero resistance in the generator and also in the transformer primary, the flux produced must follow the energizing voltage faithfully. If a secondary winding is then coupled to the primary, the induced

voltage must necessarily be of the same form as the energizing voltage. Mr. Fletcher mentions that the presence of linear inductance in the primary circuit is more effective in constraining the current to follow a sinusoidal waveform for a sinusoidal voltage applied, but this misses the point. We are not concerned about the current waveform, but that of the flux—indeed in a loss-free iron-cored transformer, which would give a pure secondary waveform for a pure primary input, the primary current must contain harmonics, due to the non-linearity of the primary inductance. These points are supported by Macfadyan,<sup>4</sup> wherein it is stated in the Introduction "The correctness of this view is shown by the fact that, if internal resistance is absent (i.e. with a constant-voltage supply), and if the primary copper resistance is also negligible, waveform distortion in the secondary circuit cannot occur, since the waveform of the flux-density is maintained sinusoidal."

These conditions cannot be completely achieved in practice, but a good approximation may be made with an output stage with heavy negative feedback, to give a low impedance source, and by winding the primary with thick wire, running at low current density. A further reduction in distortion may be achieved by reducing the value of  $B$  in the core, for a practical core naturally is not loss-free.

Mr. Fletcher points out that the relation between primary and secondary voltages is the true criterion—this is so, and the contribution to the flux threading the secondary made by the core is only part of the whole. It is thus of importance also that the energizing voltage should be pure for other considerations than core distortion, and this point is dealt with elsewhere in the paper.

Leakage inductance is certainly troublesome, and this is reduced as far as possible by the use of an annealed core, or a core of high-grade alloy, and by winding the primary and secondaries as closely as possible to each other. However, using thick wire means a large winding, and requiring a certain linear movement necessitates a certain spacing between the centres of the windings, and it is difficult to see any practical method of reducing leakage inductance arising from such causes.

## APPLICANTS FOR MEMBERSHIP

New proposals were considered by the Membership Committee at a meeting held on November 25th, 1954, as follows: 38 proposals for direct election to Graduateship or higher grade of membership and 34 proposals for transfer to Graduateship or higher grade of membership. In addition, 90 applications for Studentship registration were considered. This list also contains the name of one applicant who has subsequently agreed to accept a lower grade than that for which he originally applied.

The following are the names of those who have been properly proposed and appear qualified. In accordance with a resolution of Council and in the absence of any objections being lodged, these elections will be confirmed 14 days from the date of the circulation of this list. Any objections received will be submitted to the next meeting of the Council with whom the final decision rests.

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 FIRTH, Frank Leslie, B.Sc.(Eng.). Stockport.  
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 SCOTT, Christian Frederick Cable. London, S.W.16.  
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DEAN, Robert. Port Glenone, Ulster.

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\* Reinstatements.

## LOAD-CELL FORCE TRANSDUCERS \*

by

Denis L. Johnston, B.Sc.(Eng.)†

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

## SUMMARY

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

## 1. Relative Performance of Transducers

The general subject of transducers for measurement and control has not been digested sufficiently in the literature to enable the practical engineer to make a clear choice of systems in solving a particular problem. This is partly because many of the devices are rather new, and partly because of over-specialization in the several subjects of electronics, electro-mechanics, pneumatics and hydraulics, with few engineers taking a broad view of all the available "know-how." Frequently the elegant solution to a practical problem such as a servo system is a composite design embodying all these techniques.

It is therefore desirable to make it clear just where load-cells lie in the "spectrum" of available devices, and the chart (Fig. 1) may help to provide a visual image and convey an idea of the ranges of magnitude of both power level and conversion efficiency for available devices. This presentation could be extended, if we wished, by adding a third axis perpendicular to the plane of the chart, representing frequency response or time constant.

In the chart power level is the base line, and the ordinate is the efficiency of the transducer as an energy converter. Thus a transducer which also amplifies is shown as over 100%, or above unity power gain, and is represented by a dot at the normal input signal level, extended as a line to the right with an

arrow head at the corresponding output power level. The line is extended, dotted, to the left to indicate the minimum detectable signal level. Transducers of less than 100% conversion efficiency have their arrow heads pointing the other way, the output power level being lower than the input.

The most efficient transducers are electro-magnetic motors, either rotary or linear, but for practical reasons of construction they become less efficient as the size is reduced. These and other transducers such as capacitor and piezo-electric devices are reversible and may act either as motors or generators. Alternatively they may be employed as modulators, providing amplification: both microphones and motor generators can be used to obtain amplification of 10—100 times per stage. Other well-known devices are those based on magnetostriction, and force-balance pneumatic and hydraulic systems.

A further form of transducer is irreversible unless it is made part of a complete servo system. These can amplify and an interesting example is the micro-potentiometer<sup>1</sup> which was developed originally as a position transmitter driven by a moving coil, and having sufficient output to drive itself. On the chart this is shown as detecting a maximum signal of  $5 \times 10^{-4}$  watt and amplifying it to  $3 \times 10^{-3}$  watt, with a dotted extension to the left down to  $10^{-5}$  watt, the minimum signal to which it will respond.

Another transducer of similar capabilities is the triode device<sup>2</sup> in which an external probe modulates the anode current by physically displacing the electrode spacing through a flexi-

\* Manuscript received 31st May, 1954. (Paper No. 293.)

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U.D.C. No. 620.172/3:681.26.

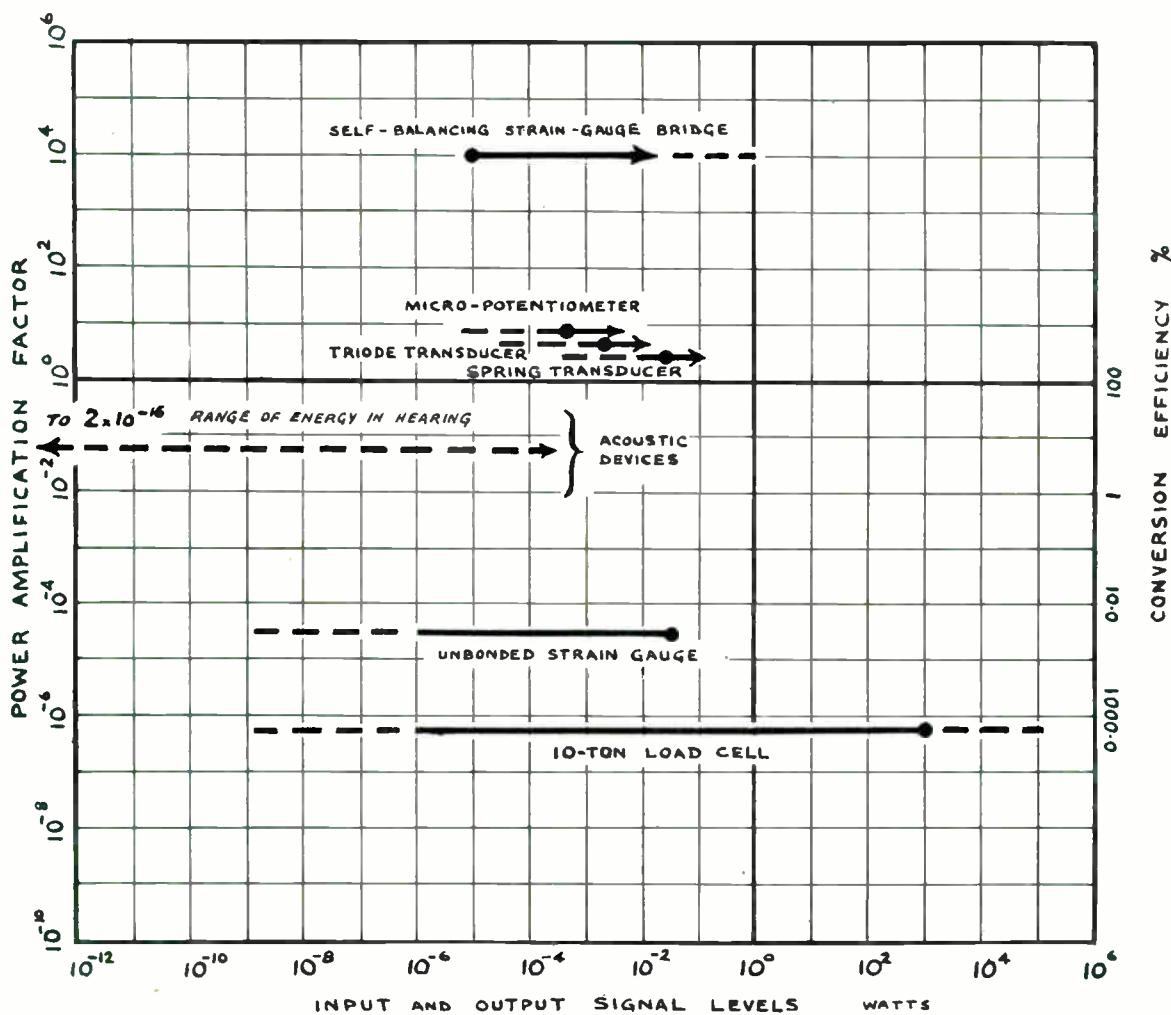


Fig. 1.—Power level and efficiency spectrum of transducer devices.

ble diaphragm. The spring transducer<sup>3</sup> is also nearby on the chart: in this case turn-turn contact of a helical spring wound with variable tension is employed as a variable resistance.

Transducers are used as sensing elements in measuring and control systems, and in many cases are intended to replace or perform better the function of a human operator. The mechanical and the human control performances can be compared in the parameters of power sensitivity, conversion efficiency in terms of power output in response to input energy

of stimulus, and in speed of response. Comparison breaks down when the physiological and psychological factors of fatigue and intuitive intelligence are introduced.

The widest range of response to power level is found, surprisingly enough in the physical senses, that of hearing being effective between the sound energy levels of about  $10^{-16}$  to  $10^{-4}$  watts per square cm. Acoustic devices such as loudspeakers and microphones are generally reversible and have conversion efficiencies in the range 1-30 per cent. It is of

interest that of the other physical senses, sight will distinguish an energy level of about  $10^{-15}$  watts, and touch about  $10^{-9}$  watts at low frequencies. This comparison of the mechanical devices has been made at 100 c/s, but their "bandwidths" will, of course, not all be alike. The photo-electric type of galvanometer is probably the most sensitive, as it will detect "mechanical noise" or Brownian movement. For most practical purposes this optical-lever amplification is too subject to vibration, and is limited in frequency response. A number of other transducers are discussed, in a useful paper, by Woodcock.<sup>4</sup>

## 2. Range of Application for Load-Cell Transducers

The load cell has a peculiar place in this "spectrum" that has been defined for the family of transducers. The bonded strain gauge type is, in fact, the least sensitive and the least efficient of all the devices shown, but it is the only type which in simple form will deal with very large forces, and this is its special merit. If the third axis of frequency in the chart is plotted, its response would be seen to be the highest of all the devices, as it has the maximum stiffness, being the elastic characteristics of a cylinder of steel in compression.

To use load cells of this type for any but large forces is poor engineering, as the other transducers are more suitable. Where forces of several hundred tons are available the low conversion efficiency of the load cell is of no importance, for considerable energy is available with only a minute deflection.

In practice load cells are used over the range of loads where they can be inserted as structural elements, about 1 ton to 1,000 tons, and for a particular cell several ranges of sensitivity can be provided by means of amplification in the measuring equipment. It is usually more convenient to vary the sensitivity of an amplifier to obtain the required load range, than to design special sizes of load cell for each application.

## 3. Construction of Strain Gauge Load Cells

After the development of the well-known "SR-4" bonded wire resistance strain gauges,<sup>5</sup> Ruge originated the load cell for portable weighing apparatus.<sup>6</sup> In the simplest form of the cell the load is sustained by a structural member in tension or compression, with the

strain gauges bonded to it so that they act as resistance extensometers.<sup>7</sup> They may also be used in torsion as torque-meters<sup>8</sup> and in hollow form as pressure gauges of high frequency response.<sup>9</sup>

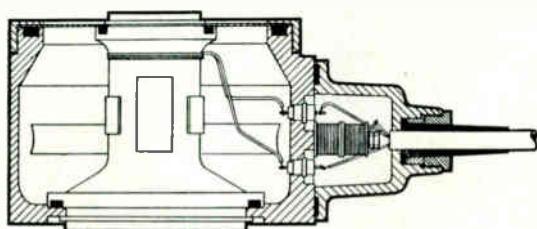


Fig. 2.—Cross-section of load cell.

One type of load cell is illustrated in Fig. 2: the compressive load is taken by a parallel gauge-section of a central cylinder of high tensile steel, worked well within its elastic limit at up to about 30 tons per square inch. Under load the active section tends to deform elastically to a barrel-shape, so that strain gauges bonded to the surface axially are in compression and gauges bonded diametrically are in tension. If there are a pair of each all four may serve as active arms in a bridge circuit. Where space permits eight or sixteen are used to reduce errors due to uneven or off-centre loading on the cell.

If the load cell is of steel with a modulus of elasticity  $25 \times 10^6$  lb./in.<sup>2</sup>, the maximum load will correspond to a strain of about  $2.5 \times 10^{-3}$ . In practice with 20V across the balanced bridge circuit, the output under load will be about 60mV. The gauge factor of the wire in the strain gauges is slightly more than two, but the axial and diametrical gauges are not equally stressed.

To detect 1 cwt. change in a 30-ton load (1 part in 600) it is necessary to have a zero stability and measurable indication corresponding to only 0.1 mV. To assure this various precautions are necessary such as bonding the strain gauges with non-hydroscopic adhesive, and hermetically sealing the enclosure of the load cell. No mechanical joints in the bridge circuit are admissible, and final resistance balancing is provided with a shunt potential divider. Resistance bobbins are fitted within the load cell casing for the final adjustment to



*Fig. 3.—Load cells and associated magnetic amplifiers.*

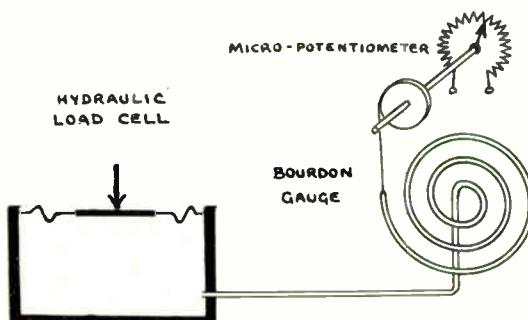
secure interchangeability. A group of load cells and their associated magnetic amplifiers is shown in Fig. 3.

#### 4. Load Cells for Higher Sensitivities

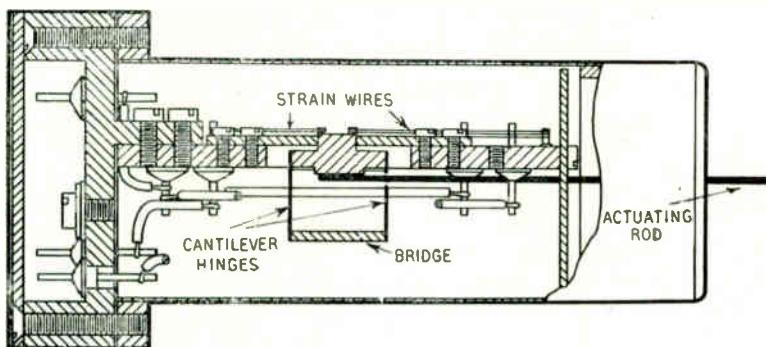
Below ratings of about one ton, the element of an elastic load cell becomes too small to accommodate the strain gauges, and it is then better to use a system of higher energy conversion efficiency. An interesting arrangement is that shown in Fig. 4, where hydraulic principles are used; a cylinder is sealed with a flexible diaphragm containing oil, and coupled to a pressure gauge, to which a micro-potentiometer may be connected, or any other of the remote indicating pressure detectors in common use in the process control industry.

The example given represents the hydraulic analogy of an impedance transformer of 100 per cent. efficiency, connected to the micro-potentiometer which is capable of amplification.

The ultimate sensitivity of the purely resistive strain gauge devices is indicated by Prof. Hill's weighing experiment<sup>10</sup> in which the resistance of a 46-s.w.g. nickel chrome wire changes by 0·37 per cent. for a load of 100



*Fig. 4.—Schematic arrangement of electro-hydraulic load cell.*



*Fig. 5.—Cross-section of an acceleration transducer.*

gm. This is really a demonstration of the strain-resistance relationship discovered as long ago as 1856 by William Thomson (Lord Kelvin).<sup>11</sup>

Low conversion efficiency in the simple load cell is, of course, due to the fact that not only the resistance wire is stressed, but also a much greater cross-section of the load cell itself. The unbonded type of wire resistance transducer originated by Statham provides the minimum constraint, the greater part being that due to the strained wires.

At a frequency of 100 c/s the conversion efficiency of a typical model (Fig. 5) is about 0.03 per cent., as shown in the chart of Fig 1; a typical instrument has these parameters :

10 volts across 100 ohm bridge

100 microamps maximum output =  $10^{-6}$  watt  
for 1 pound force, 0.003 inch displacement

A ten-ton load cell has very nearly the same parameters as that quoted above for a one-pound load, so its conversion efficiency is about 0.0000013 per cent. Clearly the unbonded type of transducer can be used for the intermediate

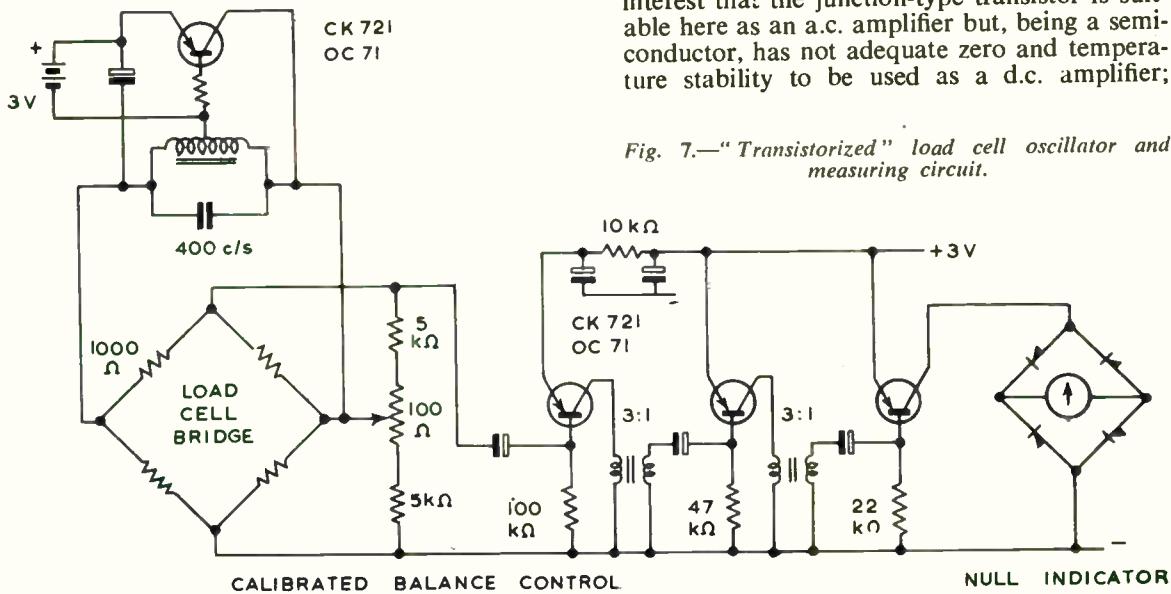


Fig. 6.—Magnetic amplifier load cell indicator.

cases where something in between these two extremes of efficiency is required.

## 5. Measuring Circuits and Applications

The bonded or unbonded strain gauge transducers can be used with either a.c. or d.c. across the bridge. Both have their respective advantages, the former being most suitable with valve amplifiers and the latter with magnetic amplifiers, or directly to a microammeter or null balancing potentiometer recorder. It is of interest that the junction-type transistor is suitable here as an a.c. amplifier but, being a semiconductor, has not adequate zero and temperature stability to be used as a d.c. amplifier;

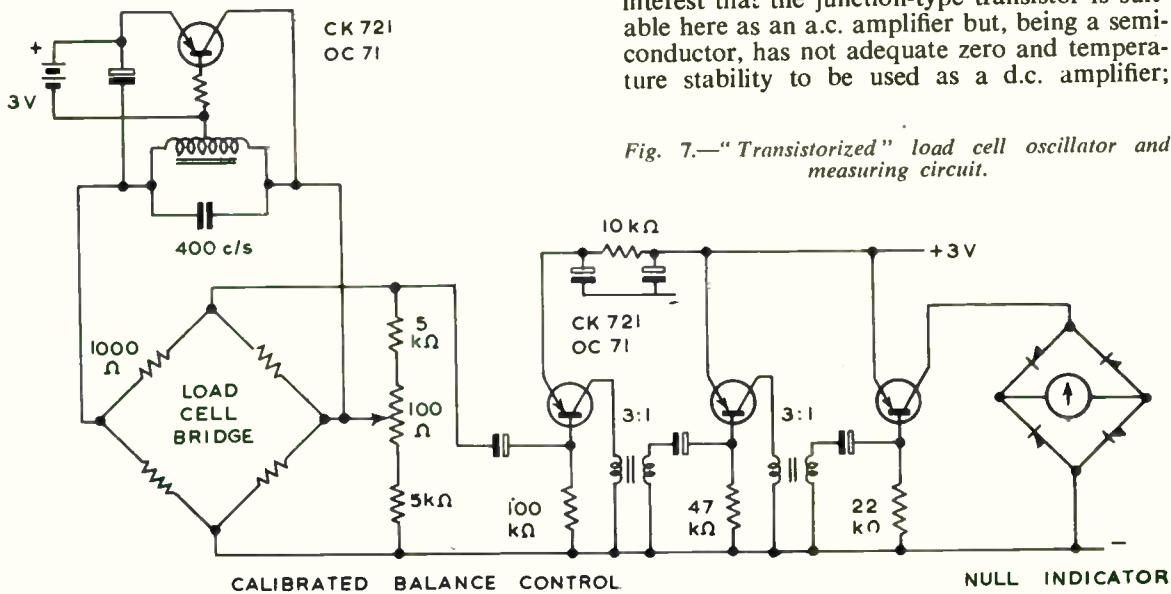


Fig. 7.—“Transistorized” load cell oscillator and measuring circuit.

d.c. excitation of the bridge is, however, quite practical if stable d.c. valve amplifiers are used. The transistor has only limited application in measuring circuits because its impedance is much lower than that of a valve, but with load cells this does not matter.

A simple and rugged industrial arrangement is that using a 3-stage magnetic amplifier,<sup>12</sup> as shown in Fig. 6. The outputs of a number of load cells may be summed or the differences taken by either paralleling the bridge circuit outputs, or connecting them to separate input windings of the magnetic amplifier. Load cell signals can be fed into a computing network, and operations such as integration and differentiation performed.

A simple a.c. measuring circuit can be provided using transistors for local oscillator and amplifier, as shown in Fig. 7, and only a 3-volt battery supply is necessary. For simplicity the circuit shown employs a "slide-back" potential divider, calibrated in terms of load, and the meter is used only as a null indicator. Alternatively, if the oscillator is stabilized in level and the amplifier stabilized in gain, a direct reading can be provided on the meter.

The basic "slide-back" measuring circuit can be used as a self-balancing bridge (Figs. 8



Fig. 9.—Self-balancing bridge load indicator.

and 9) designed in the form of a standard process-control indicator, recorder or controller. This type of equipment has been further developed for strain gauge measurements in wind tunnels: automatic balancing is provided for both quadrature and phase (Figs. 10 and

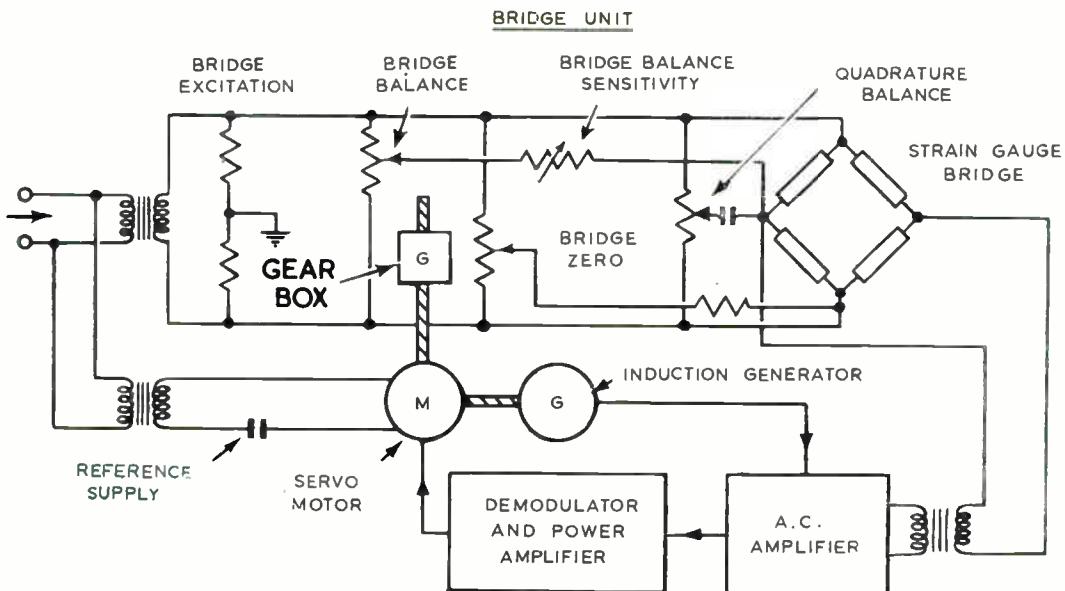


Fig. 8.—Self-balancing bridge circuit.

11) with 6 volts, 625 c/s on the bridge, and a balance to 0.3 microvolt is obtained in 5 seconds.

In the U.S.A., and recently here, self-balancing potentiometers for load cells have been developed as direct-reading cyclometer-dial instruments,<sup>13</sup> which may be called the "new look" in instrumentation. These have been extended to print the readings, and are used as such for cattle-weighing in stockyards.

#### 6. Acknowledgments

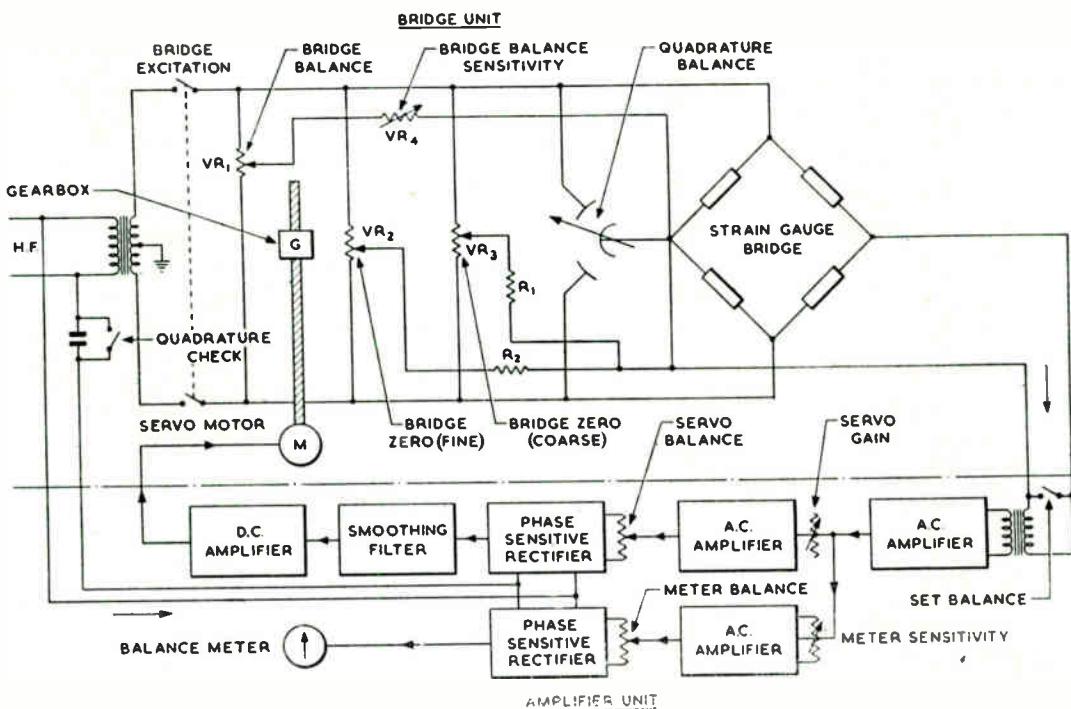
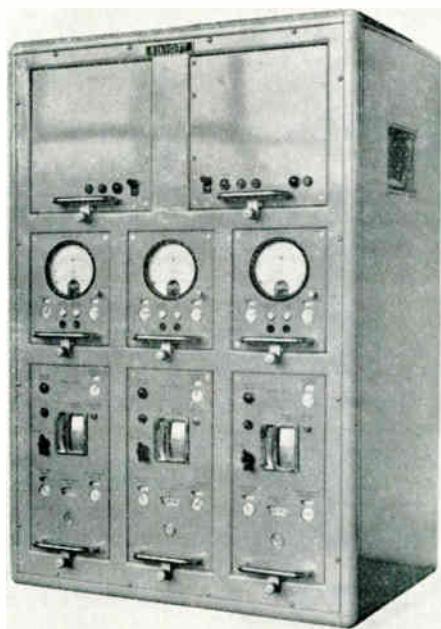
The author is grateful for assistance with information and illustrations provided by Messrs. Elliott Brothers (London) Ltd., and J. Langham Thompson, Ltd.

#### 7. References

1. Helipot Corporation, "Model T Potentiometer." *Proc. Inst. Radio Engrs*, 40, April, 1952, p. 65A.

*Fig. 10 (right).—Automatic precision bridge for wind tunnel force measurements.*

*Fig. 11 (below).—Schematic arrangement of automatic precision bridge.*



2. "Mechano-Electronic Triode Transducer." RCA Valve Data Sheets, type 5734, November, 1948.
3. W. A. Wildhack, "Mechano-Electric Transducers (spring transducer)" British Patent No. 671,161 (Convention date U.S.A., 14th March, 1949).
4. F. J. Woodcock, "Some electrical methods of measuring mechanical quantities." *Proc. Instn Elect. Engrs*, 97, Part I, July, 1950, pp. 136-155.
5. C. H. Gibbons, "The use of the resistance wire strain gauge in stress determination." *Proc. Soc. Exper. Stress Analysis*, 1, 1943, pp. 41-45.
6. A. L. Thurston and R. W. Cushman, "Precision determination of weight by means of bonded strain gauges." *Proc. Soc. Exper. Stress Analysis*, 3, 1945, pp. 62-70.
7. R. B. Sims, J. A. Place and A. D. Morley, "Loadmeter for industrial mills." *Engineering*, 173, 25th January, 1952, pp. 116-119 and 1st February, 1952, pp. 137-139.
8. R. B. Sims and A. D. Morley, "Torquemeter for industrial applications." *Engineering*, 174, 4th July, 1952, pp. 20-21.
9. F. M. Gross and G. Lane, "An accurate wire resistance method for the measurement of pulsating pressures." *J. Sci. Instrum.*, 30, January, 1953, pp. 1-2.
10. A. V. Hill, "A simple electrical strain gauge for recording small tensions." *J. Sci. Instrum.*, 26, April, 1949, p. 128.
11. D. L. Johnston and D. W. Hobbs, "Electronics in strain measurement." *Instrument Practice*, 7, January, 1953, pp. 3-11.
12. E. H. Frost-Smith, "The study of a magnetic inverter for amplification of low-input-power d.c. signals." *Proc. Instn Elect. Engrs*, 100, Part II, August, 1953, pp. 362-375.
13. "Livestock weighing by electronic equipment." *Electronics*, 22, November, 1949, pp. 116, 118, 134.
14. W. B. Dobie and P. C. G. Isaac, "Electric Resistance Strain Gauges." (English Universities Press Ltd., London, 1948.)
15. J. Yarnell, "Resistance Strain Gauges." (*Electronic Engineering Monograph*, London, 1951.)
16. J. J. Koch and others, "Strain Gauges—Theory and Application." (Philips Technical Library, Eindhoven, 1952.)

## DISCUSSION

**R. K. Vinycomb (Associate Member):** I have some doubts about the sensitivities given by Mr. Johnston. He first states that load-cells are the least sensitive and then quotes an output voltage of 60 mV for 20 V across a balanced bridge circuit. It seems to me that this would require an extraordinarily large strain in the cell and the actual outputs obtained in practice are considerably smaller even than these.

**D. L. Johnston (in reply):** I think you will probably find that the discrepancy in the arithmetic of the numerical example lies in the fact that these

are open circuit voltages and the figures are somewhat rounded. All four arms of the bridge are active, and we come to the conclusion that the signal is rather more than twice the proportionate strain. Of course, if you are going to work the galvanometer direct, the obvious thing is to get as much power as you can out of the circuit, so you match the powers of the particular project to the detector and if you get maximum power out, it makes the best of the voltage available, which is then less at the detector because of the electrical loading.

## DISCUSSION ON

**"A Critical Review of Synchronizing Separators with particular reference to Correct Interlacing"\*\***

**G. B. Townsend (Communicated)†:** In Section 4, Dr. Patchett writes: "Since the time bases interlaced correctly on ideal pulses, it would appear that the fault is not due to the time base itself, but due to the method of synchronizing. Means of limiting the flyback as have been suggested do not therefore seem to be the correct solution."

I believe that changes in the frame flyback constitute the only reasonable explanation of those television rasters in which consistent lack of interlace over the scan accompanies an apparently equally consistent interlace of the flyback lines and fairly accurate timing of the commencement of alternate frame flybacks: I agree with Dr. Patchett that the method of synchronizing can be shown to be the prime cause of such variations. I would qualify his statement that the fault is therefore not due to the time base, by saying that some types of time-base oscillators can be shown to be more susceptible to changes in synchronizing signal than are other types. Further, it is possible to design time bases which will interlace even when synchronized by pulses which differ on alternate frames in shape, provided that the leading edges of such pulses are correctly timed. Such variations in shape may be due to the method of separation, or to pick-up from the line time-base, or to impulsive interference.

Surely both methods of obtaining good interlace, that is to say by using exactly similar synchronizing pulses on alternate frames, or by using a time base which ignores such differences, are equally as acceptable philosophically in the lecture room, as they are economically on the production line.

It is even possible to argue that the time base which ignores pulse differences is the preferable solution, since it allows more freedom in designing the synchronizing separators for good immunity to impulsive interference. Time bases which stabilize the flyback fall into this class, of course.

In Section 5.4, Dr. Patchett advocates the use of equalizing pulses. I must agree with him that these appear, theoretically, to be very desirable.

In 1952, the B.B.C. and the British Radio Equipment Manufacturers' Association co-operated in a series of tests on equalizing pulses. The B.B.C. incorporated equalizing pulses in certain trans-

missions, and the industry studied the variation in performance of a large number of commercial and special receivers operating in widely different parts of the service and fringe areas. In these tests the majority of investigators reported no significant change in performance. This was not, of course, because all receivers interlaced perfectly all the time. Some observers were able to increase the frame synchronizing pulse integration time constant when receiving equalizing pulses, so as to obtain improved protection against impulsive interference without losing the timing accuracy of the leading edges of the derived frame pulses. These results are in line with our own experience of field testing 625-line receivers in Europe.

**Dr. G. N. Patchett (in reply):** I agree that it is possible to make a time base which will interlace when synchronizing pulses differ on alternate frames but I should have thought it would be difficult to maintain this condition on production. I have not tried the time bases which stabilize the flyback. It is not only necessary to stabilize the magnitude of the flyback, but also the starting time of the scan since this also causes lack of interlace and in some circuits this is controlled by the back edge of the synchronizing pulses.

A large number of different types of time base has been tested with ideal pulses (with no interference from a line time-base) and I have not been able to get a time-base to show any lack of interlace under these conditions. As a result of these tests I feel that the cause of faulty interlace is due to (a) different pulses on odd and even frames, or (b) interference from the line time-base.

I was interested to see the remarks concerning tests with equalizing pulses. Unfortunately, I have not had the opportunity to perform any tests under these conditions, but I feel that, where lack of interlace does occur with the use of equalizing pulses, it is most likely due to line pulses fed from the line time-base.

Although I can see some advantage in using a time base which is immune from differences in frame pulses I still consider that the better approach is to design a synchronizing separator which produces similar pulses. In my own experience this results in perfect interlace so long as suitable screening is used to prevent line pulses being fed to the time base.

\* G. N. Patchett, *J. Brit. I.R.E.*, 14, May 1954, pp. 191-214.  
† Received by the Institution on September 3rd, 1954.

# AN X-RAY THICKNESS GAUGE FOR THE MEASUREMENT OF HOT-ROLLED STRIP STEEL\*

by

F. H. Gottfeld and D. Tidbury†

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

## SUMMARY

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

### 1. Introduction

Sheet thickness measurements using a penetrating radiation have the advantage of being applicable as a non-contact, continuous measuring method and are therefore especially useful for thickness measurement during the rolling process in a hot or cold mill. The measuring accuracy of the method is largely independent of surface conditions, of the position of the material between source of radiation and measuring instrument and partly independent of the speed of rolling. The result obtained gives an indication of the mean thickness over the length of material which has passed through the gauge during a given time interval. The type and wavelength of the radiation chosen depend entirely on the material to be measured and its thickness. Thick sections and materials of high atomic weight demand more penetrating radiations, but the accuracy obtained is not so high as with softer radiations.

X-rays have the advantage that their wavelength and so their absorption characteristics can be selected within very wide limits to the type of material and its thickness, and this combined with the high radiation intensity obtained from an X-ray generator will allow an indication to be obtained in a time as short as 0·1 sec.

Extensive investigations in the U.S.A.‡ and Germany§ have shown that for the range of steel thicknesses from 1–10 mm. only X-rays will permit measurement with the speed and accuracy required. In the X-ray gauge described below a specially designed X-ray tube emits two identical beams of X-rays perpendicular to each other. These beams pass respectively through

a standard absorption wedge, and the strip to be measured, and the difference in absorption is measured by means of two Geiger counter tubes. The signals from these counters are fed into a differential circuit which records the out-of-balance current on a mirror galvanometer with a large dial.

### 2. Theory of the Measuring System

Two different systems can be employed to measure thickness differences between the comparison standard and as-rolled strip. With the "constant absorption" method both X-ray beams pass initially through a set of identical standard wedges. The voltage on the Geiger counters is adjusted until no out-of-balance current is shown on the galvanometer. The standard wedge in the measuring beam is then replaced by a wedge of a thickness which when added to the nominal thickness of the strip will be equivalent to the thickness of the original standard. For example:

Thickness of standards	=	$\frac{1}{2}$ in.
Nominal thickness of strip	=	$\frac{1}{8}$ in.
Thickness of measuring standard	=	$\frac{3}{8}$ in.
Total thickness	=	$\frac{1}{2}$ in.

Any deviation from the nominal thickness of the strip will cause a change in the intensity of the radiation received by the measuring counter. This in turn will unbalance the differential circuit and cause an out-of-balance current to give an indication on the galvanometer. The latter may conveniently be calibrated in units of thickness.

‡ R. B. Sims, "Gaugemeter for strip mills," *Engineering*, 175, 9th January, 1953, pp. 33-34.

§ A. Trost, H. W. Fritze and W. Kolb, "Thickness measurement using penetrating radiations," *Stahl und Eisen*, 72, No. 16, July 31st, 1952, pp. 941-45.

\* Manuscript received May 26th, 1954. (Paper No. 294.)

† Solus-Schall Ltd., London, W.1.  
U.D.C. No. 621.386 : 621.771.

With the "constant absorption" method (abbreviated CA) the thickness to be penetrated remains constant. The X-ray set can therefore be continuously operated at the same setting which considerably improves the life expectancy of the X-ray tube. Once the set has been switched on and the circuit has been balanced, a process which incidentally need not be repeated for some hours, only the measuring standard has to be set in accordance with each change of thickness in the rolling programme. The unit can easily be operated by unskilled labour.

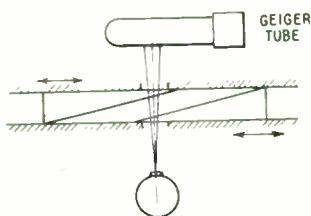


Fig. 1.—Principle of operation of reference wedges.

Simplicity and speed of operation are the advantage of this method. Its accuracy is, however, affected by the fact that the standard must be as thick as the heaviest sections likely to be measured during a day's work. The voltage used may in some cases therefore be higher than actually needed for a thin section. Since the wedge in front of the strip acts as a filter of the radiation and effectively absorbs the softer components, a relatively hard radiation will enter the thin strip and will pass easily through it. Small variations of thickness may under these circumstances give only small changes in absorption and the accuracy of the instrument will be reduced accordingly.

If the "variable absorption" method (abbreviated VA) is used, the setting time of the gauge will be much longer but its accuracy will be improved. With the VA method standards identical to the thickness to be measured are placed in both beams. Subsequently the counters are balanced after which the standard in the measuring beam is replaced by the strip. Any variation from the nominal thickness will now be shown in the same manner as before. Because of the frequent changes in most rolling programmes both counters must be re-balanced with each change and the voltage and current on the X-ray tube may have to be altered to give optimum results. This resetting must be done

by a skilled operator and may take a few minutes, which is obviously too long under modern rolling conditions. The accuracy of the instrument is, however, very high over a wide range of thicknesses. The choice of system depends obviously on local conditions and upon the accuracy of measurement required. A combination of both can be used, CA for the thinner and VA for the heavier sections.

The accuracy of measurement is affected by the temperature of the hot strip. The X-ray absorption of the hot steel is reduced as the temperature increases. Since the standards themselves are cold, compensation has to be made for this difference in temperature and therefore in absorption. Under normal hot rolling conditions at temperatures round 1400°F. this difference is approximately 2 per cent. over a fairly wide range of temperature. Consequently cold standards used in hot mills must be 2 per cent. thinner than the required nominal thickness.

Variations in the carbon content do not affect the accuracy when measured against normal mild steel standards but larger additions of vanadium and other heavy metals may have some effect. In this case either different standards must be used or conversion tables.

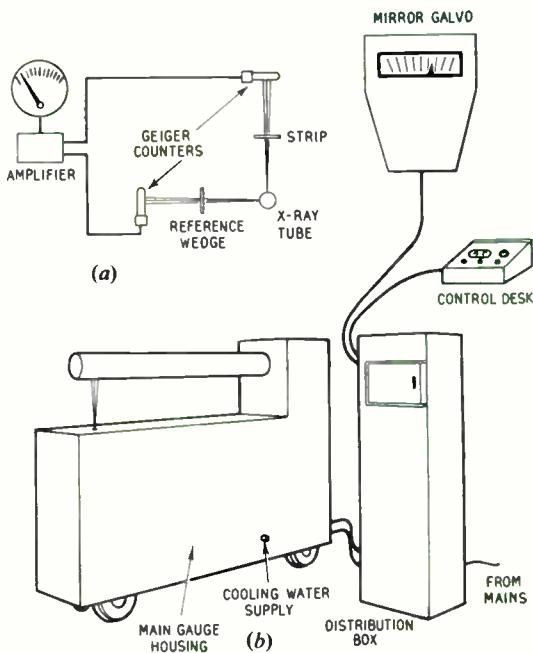


Fig. 2.—(a) Block schematic of complete thickness gauge  
(b) Component units of thickness gauge.

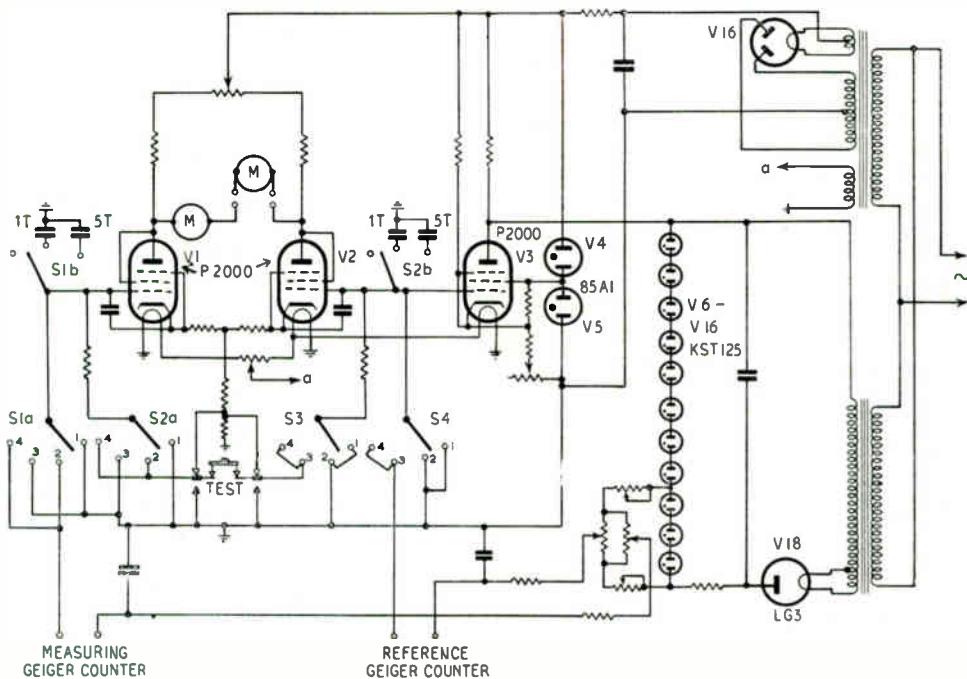


Fig. 3.—The differential counting circuit.

### 3. Description of the Gauge

The gauge described in this paper was designed to work in a continuous hot mill operating at a speed of approximately 2,200 ft./min. and rolling strip up to 0.33 in. thick and 6 ft. wide. For work in a hot mill the gauge must be especially robust and well cooled since it has to work in close proximity to the red-hot strip; in addition it must fit between two guide-rollers which are not more than 2 ft. apart, and it must be easy to operate. The effective length of the arm holding the measurement Geiger-counter above the strip must be such that the widest strip can be measured at any point between one edge and its centre. The external dimensions of the equipment in use in this country are about 2 ft. wide and 8 ft. long. Each standard consists of a continuously variable pair of wedges allowing measurement from 1 to 10 mm. They are driven by an electric motor and are geared to selsyn transmitters so that their setting may be clearly visible at any point near the gauge. These are remotely controlled by a push-button system from the control table of the gauge which is installed in the mill control pulpit. Remote

control is essential partly because of the restricted access to the gauge, which is of course partially below the level of the apron of the mill, but principally because of radiation hazards. In connection with this hazard, the maximum permissible dose is recorded at a radius of 8 ft. from the X-ray tube window at floor level with the set working at its maximum rating.

The gauge described consists of five main components. The main housing contains the high-tension generator with high-tension transformer, filament transformers, capacitor, rectifying valve and X-ray tube. Also placed inside are the reference wedge system and the two standards as well as the Geiger-counter measuring the standard absorption. In the vertical column projecting from the housing the reference-wedge driving motor, selsyn transmitters and differential electronic equipment are placed together with the remotely-controlled gauge traversing motor. The horizontal cross-arm at a height of 2 ft. above the upper face of the strip is built as a water-tight tank and contains the counter measuring the strip absorption. The base of the main housing is built as a

large tank filled with distilled water which is circulated by a motor-driven pump through the X-ray tube and the two Geiger-counters. The distilled water in this tank and in the horizontal cross arm is in turn cooled by water from a mains supply. The high-tension generator case is immersed in the distilled water tank. The use of distilled water for the closed internal cooling circuit eliminates the danger of blocking of the cooling channels in the X-ray tubes or Geiger-counters by sediment or impurities. The control table can be positioned anywhere near the mill, preferably in the control pulpit. It contains the control gear for the X-ray unit. Both the X-ray set and the differential counting circuit are supplied from a mains-voltage stabilizer. The unit can be operated at 65 kV 15 mA, 80 kV 15 mA, 100 kV 15 mA, 120 kV 12.5 mA and 150 kV 10 mA. With the CA measuring method between about 100 and 120 kV is required to penetrate up to about  $\frac{1}{2}$ -in. steel.

After a long rest period and on starting initially the X-ray unit and the differential equipment must be left for about 15 minutes to allow the set to settle down before measuring is started.

The high-tension circuits are interlocked with the cooling water system. In case of a failure in the latter the high tension cannot be switched on. Also a thermostat is provided which will switch the high tension off if the temperature of the cooling water gets too high and an excess current relay is fitted in the circuit. The control desk also contains selsyn receivers for the reference wedge system, showing on dials the thickness setting of the gauge. Another selsyn is linked to the travelling system of the main housing indicating the position of the X-ray beam in the run-out table of the mill. Thus it can easily be ascertained where on a strip a measurement was carried out. On the control desk are the push-buttons for the remote control of the reference wedges, differential counting equipment, high-tension circuit and for the travelling motor which operates the movement of the main housing. With two push-buttons the gauge can either be moved into measuring position or can be retracted. A third push-button operates an emergency retraction if a large cobble should develop in the strip. It may be mentioned here that for the protection of the horizontal measuring arm of the gauge a strong guard made of 1-in. steel plate is fitted 2 ft. above the run-out table. Finally, the control table includes a

resistance control for altering the sensitivity of the galvanometer and a "calibration-shim" button about which more will be said later.

To arrange for the replacement of the standard by the measuring wedge a photocell is placed at a suitable position between the last stand and the gauge. When no strip passes through the mill the standard will be in the X-ray beam between tube window and measuring counter and the galvanometer will read zero. When the red-hot strip passes the photocell a signal will be replaced by the pre-set measuring wedge. When the strip has passed the whole procedure will be reversed and the galvanometer will again read zero. By arranging the photocell at a suitable distance from the X-ray beam the time lag between the strip passing the cell and the introduction of the measuring wedge is such that an excessive deflection of the galvanometer can be avoided. The photocell has also been fitted with water cooling because of its nearness to the strip.

The main gauge housing is motor driven and travels on rails into the measuring position or alternatively can be retracted for maintenance work.

The large, centre zero, mirror-galvanometer can be positioned anywhere near the mill. The total length of the scale ( $2\frac{1}{2}$  ft.) corresponds at normal operating sensitivity to a change in thickness of 0.008 in. If this range should not be sufficiently large the sensitivity can be reduced to one-half or one-third. By pressing the "calibration-shim" button on the control desk a 0.002-in. steel sheet is introduced into the standard beam. This will of course be registered on the galvanometer and by means of the sensitivity control the degree of deflection can either be reduced or increased. The galvanometer can be viewed from both sides.

The X-ray tube is of the earthed anode type, the anode itself consisting of a copper tube,  $\frac{5}{8}$  in. diameter and 3 in. long with the target set at an angle of 45 deg. The anode is enclosed by a slightly larger brass cylinder with a 1-mm. thick aluminium end plate. The cooling water circulates between these two cylinders. The cathode consists of an annular filament with automatic focusing of the electron beam. External focusing coils are employed. Water pressure gauges are used in both inlet and outlet water-cooling pipes, the difference between the two readings indicating the pressure at the anode surface which must not exceed 22 lb./in.<sup>2</sup>

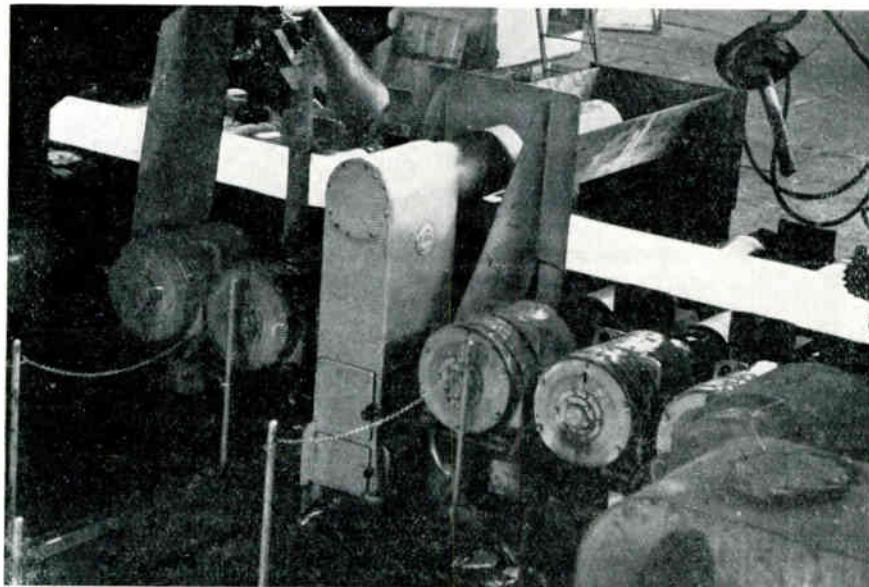


Fig. 5.—X-ray thickness gauge in position alongside a hot-strip mill.

Approximately 10–12 pints ( $4\frac{1}{2}$ – $5\frac{1}{2}$  litres) of water per minute must flow through the tube and a thermostat is introduced into the outlet pipe system to check the temperature of the cooling water. Further, a sensitive current relay is fitted into the tube current circuit to prevent failure of the tube by overloading.

The accuracy of measurement depends on the method used (CA or VA), the voltage applied to the X-ray tube and the type and thickness of the material measured. With the CA method hot

strip from 1 to 10 mm. can be measured with a constant accuracy of 0.0125 mm. This gives an accuracy of 0.08 per cent. on 1 mm. and of 0.01 per cent. on 10 mm. thickness. The percentage accuracy changes because the measurements are always carried out on the same point of the absorption curve. With the VA method the gauge has to be recalibrated for each change of section and the percentage accuracy will be approximately constant over a wide range of thicknesses.

## THE POST OFFICE ENGINEERING RESEARCH STATION

The Post Office Research Station houses the Research Branch and most of the Radio Experimental Branch of the General Post Office. Its main function is to improve the efficiency of the telecommunications services provided by the G.P.O. and the development of new experimental systems and apparatus. Recently the Station arranged a number of exhibits, typical of the work in progress, to which a representative of the Institution was invited.

To gain experience in the design, construction, operation and maintenance of electronic exchange apparatus, an electronic private automatic branch exchange has been constructed to provide an internal telephone service for the Research Station. The exchange has an ultimate capacity of 99 lines, and automatic telephone switching is by electronic means using thermionic valves and cold cathode tubes, thus eliminating moving parts and pressure-operated electrical contacts. This electronic exchange gives very much faster operation, and although it is only able to deal with one call at a time the operation is completed in 5 microseconds, waiting calls being held in a mercury delay line. The switches for the inter-connection of the extensions use time-division-multiplex transmission.

One section of the Post Office's work, which is continually expanding, is the provision of temporary and fixed television cable links. The television signals inevitably suffer some distortion in their passage over the cable and one of the equipments being demonstrated was a wave-form corrector. This improved model of the echo type wave-form corrector with calibrated controls has been designed to correct any distortion which might be introduced by the cable. Similar equipment is used where an outside broadcast signal is injected into a coaxial cable link at an intermediate point. This equipment simulates the distortion on the part of the main link not in circuit, such that overall equalization remains correct when the wave-form corrector is operated at the receiving end.

The Post Office is experimenting with transistors for use in line amplifiers, and a single-stage push-pull amplifier, giving 27 db gain over 150 to 5,000 c/s with  $600\Omega$  input and output impedances was demonstrated. For music circuits a three-stage amplifier with 20 db overall feedback giving an external gain of 50 db over 30 c/s-25 kc/s has been

constructed. The transistor has obvious attractions for this type of work as the power consumption is less than a tenth of a watt and the problems of highly reliable power supplies and heat dissipation are considerably reduced.

The reliability of telecommunications components is often questioned and it is, therefore, of interest to learn that the Post Office confidently expects a life of 20 years for their deep-sea submerged telephone repeaters. The repeater consists of hermetically sealed electrical units, housed in a streamlined cylinder, 9 ft long and 11 in. in diameter. This housing will withstand hydrostatic pressures of up to 4 tons per in.<sup>2</sup>, and the sea cable glands also have to withstand 2,500 V d.c., which constitutes the supply voltage. The amplifier consists of two forward paths in parallel so that a failure of any component in one path will not seriously affect the performance of the repeater. Valves, which have inherently presented the most serious component problem for a life of 20 years, have been manufactured in the Post Office laboratories and are expected to meet the onerous requirements.

It is interesting to note that the chassis on which the amplifiers are mounted are gold plated. The Bell Telephone Laboratories have recently found that tin, plated on iron or steel, is liable to produce whiskers of molecule thickness up to  $\frac{1}{2}$  in. in length. Gold does not exhibit this whisker formation.

It is often very desirable to obtain a source of fading signal, either frequency selective or Rayleigh fading, for the laboratory testing of receivers. A fading "machine" simulating these effects as encountered on long distance short wave radio circuits has been built by the Research Station.

Also demonstrated was the use of the aerial hut for investigating the performance of model aerials. Here, 1 : 200 scale models of aerial are used at a frequency of 3,000 Mc/s to test the effects of the presence of nearby buildings, masts and aerials. These effects are easily determined and structural re-arrangements can be made with a considerable saving of time and materials.

The work of the Post Office Research Station is not limited to Post Office problems. The Station is often consulted by other Government Departments and close contact is maintained with laboratories doing allied research and development.

## NEW BRITISH STANDARDS

The British Standards Institution has recently issued the following new and revised Standards, copies of which may be obtained from the British Standards Institution, Sales Branch, 2 Park Street, London, W.1.

**B.S. 89 : 1954. Electrical Indicating Instruments.** Price 7s. 6d.

Applies to indicating ammeters, voltmeters, wattmeters, frequency indicators and power-factor indicators, grouped into two classes according to their degree of accuracy and known, respectively, as precision and industrial instruments.

Details of methods of testing are given, including high voltage test values and damping times for different types of instruments. Tables are given for limits of error for precision instruments, industrial switchboard instruments, and industrial portable instruments. There is a section devoted to the variation in indication due to factors such as external magnetic fields and changes in the ambient temperature.

**B.S. 1991 : 1954. Letter Symbols, Signs and Abbreviations. Part 1: General.** Price 6s.

When it was decided to revise two well-established and partly overlapping British Standards, namely B.S. 560 : 1934, "Engineering Symbols and Abbreviations," and B.S. 813 : 1938, "Chemical Symbols and Abbreviations," it was thought desirable to take the opportunity of combining them to encourage the development of a consistent system for the whole field of science and technology.

As B.S. 560 covered such specialized subjects as "locomotive classification," "naval architecture" and "hydraulics and water engineering," it was decided that attention should be focused on the more fundamental quantities of common concern to all branches of pure and applied science, on conventions relating to their use, and on abbreviations for relevant words, especially the names of unit. Departures from well-established usages are recommended only where they are considered to be of serious importance, e.g. the abandonment by mechanical engineers (in particular) of the symbol  $\phi$  for entropy, which is commonly represented by  $S$  by physicists and chemists throughout the world, as well as by most engineers in other countries. There should be no departure from the consistent use of italic type for symbols for physical quantities (whether the letters are capitals or lower case), and of roman type for most other purposes, such as abbreviations for words, including the names of units.

**B.S. 2011 : 1954. Basic Climatic and Durability Tests for Components for Radio and Allied Electronic Equipment.** Price 5s.

This is the first of a series of British Standards dealing with radio components and forms the basis of the tests to be specified in the individual British Standards for the various types of components.

Some of the tests detailed are accelerated or exaggerated in order to secure quickly information regarding liability to failure, whilst others are in the nature of exposure to actual conditions likely to be experienced in service. One feature of the Standard is the introduction of a code indicating simply the working temperature, range and humidity classification of a component.

**B.S. 2478 : 1954. Tapes and Spools for Commercial and Domestic Magnetic Tape Sound-recording and Reproduction.** Price 2s.

The Standard specifies the dimensions and certain features for normal commercial and domestic purposes. Information on tape dimensions and tape speeds is given, together with certain requirements concerning recording and reproducing from dual track tape. Dimensions for spools are specified, and a table sets out the nominal length of tape that may be accommodated on standard size spools.

**B.S. 2488 : 1954. Preferred Values and Associated Tolerances for Resistors and Capacitors for Telecommunication Equipment.** Price 2s.

The Standard specifies a series of preferred values and associated tolerances for fixed wire-wound and fixed composition resistors and for fixed capacitors for telecommunication equipment. The series is based on the  $\sqrt[12]{10}$  system of preferred values with standard component tolerances of 5, 10 and 20 per cent.

**B.S. 2497 : 1954. Normal Threshold of Hearing for Pure Tones by Earphone Listening.** Price 2s. 6d.

The Standard specifies the values of sound pressure corresponding to the normal threshold of hearing of human subjects when listening by earphone with one ear to pure tones of various frequencies. It is of particular interest to those concerned with the evaluation of deafness.

The values at each frequency are expressed:

- (a) As the normal minimum audible pressure for human ears, measured at the entrance to the external auditory meatus, when the sound pressure is produced by an earphone applied to the ear.
- (b) In terms of the sound pressure set up in an artificial ear by an earphone of specific pattern when actuated by the voltage corresponding to the normal threshold referred to above.

**B.S. 2498 : 1954. Recommendations for Ascertaining and Expressing the Performance of Loudspeakers by Objective Measurements.** Price 3s.

The main aim of the Standard is not to lay down standards of excellence or figures of merit but to encourage among electro-acoustic laboratories a common approach and a common view-point. By defining, as closely as practicable, the methods of objective measurement to be followed in ascertaining loudspeaker performance it is hoped to promote interchange of information so that data collected in one laboratory may supplement data collected in another.

The kind of measurements envisaged are those which might be made when considering the approval of a production type; they are thus fairly extensive but it is not sought to make them exhaustive. In particular, only objective measurements are considered.

# DIRECT VOLTAGE STABILIZERS IN THE RANGE 10–100 kV WITH PARTICULAR REFERENCE TO DEGENERATIVE SYSTEMS\*

by

M. W. Jervis, M.Sc.Tech.†

## SUMMARY

Methods of stabilizing high direct voltages are described, and it is concluded that the degenerative arrangement gives the best stability. The residual fluctuations then depend on the loop gain and the stability of the reference elements. The maximum loop gain which can be applied depends on the frequency response of the system. In practice, loop gains of the order of 1,000 are possible, so reducing the effect of mains voltage and load current fluctuations by this factor. Reference elements are reviewed, and it is concluded that wirewound resistance potential dividers or energy-analysers are the most stable, stabilities of the order of 1 in  $10^5$  being obtained.

## 1. Introduction

Sources of stable high voltage are required for the acceleration of electrons to fixed energies in electron-optical instruments, and are necessary in the calibration of h.v. voltmeters.

Typical stability requirements are as follows:

Electron microscopes (40 kV and above)	1 part in $10^4$ – $10^5$
Electron diffraction cameras (40 kV and above)	1 part in $10^3$ – $10^4$
Projection television tubes (25–50 kV)	1 part in $10^2$ – $10^3$
H. V. voltmeter calibration	1 part in $10^2$ – $10^4$

Many different schemes can be envisaged for the stabilization of high voltages, but the following review is limited to arrangements which have been published.

## 2. Primary Batteries

Before considering the stabilization of high voltages derived from the mains supply, it is interesting to investigate the possibility of using a battery of Leclanché dry cells as a source of high voltage. Taking a 100-kV supply as an example, the cost would be in the range of £400 to £1,000, and the size 75 to 4 cubic feet, depending on the type of cell and its current rating. Their shelf life and life on small load would be in the region of 6 to 12 months. The

temperature coefficient of voltage of such dry cells is rather high (about 1 part in  $5,000/^\circ\text{C}$ ), and temperature control or compensation would have to be employed for high stability.<sup>1</sup>

Batteries have been used to supply a  $\pm 15$ -kV voltage stable to 1 part in  $10^4$  for an electrostatic analyser,<sup>2</sup> but they are clearly unsuitable for voltages much higher than this on account of their cost and inconvenience.

## 3. Stabilization of the Input Voltage to the H. V. Set

If load current changes or the internal resistance of a mains-driven h.v. set are small, the major source of variations of the output voltage will be mains supply voltage fluctuations. These can be reduced by a factor of 10–20 by arrangements which utilize the voltage stabilizing properties of chokes with their iron cores operating near saturation.<sup>3,4,5</sup> These devices are known as "constant voltage transformers." Some stabilizers of this type have an output voltage which depends on the supply frequency but, if the frequency changes are slow, this defect is not serious when relatively short period stability is required. By feeding the output of one stabilizer into the input of another, the attenuation factor can be increased to greater than 100. This arrangement is sufficient to give stability of 2 parts in  $10^4$ , and has been used by von Ardenne<sup>6</sup> for stabilizing supplies of 40-kV electron microscopes. Since the stabilizer cannot operate in a time shorter than one cycle of the supply, relatively large smoothing capacitors are necessary after rectification. Other types of mains voltage stabilizers are reviewed by Benson,<sup>4</sup> Maddock,<sup>3</sup> and others.<sup>5,7</sup>

\* Manuscript first received April 20th, 1954, and in final form July 9th, 1954. (Paper No. 295.)

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U.D.C. No. 621.316.7.027.7.

To reduce the size of smoothing capacitors for a given output ripple voltage, the h.v. set is often operated from a supply of frequency higher than that of the mains. When an h.f. alternator is used, its output can be stabilized by a suitable feedback loop, so keeping constant the input to the h.v. set.<sup>5,8,9</sup> If the h.f. supply is obtained from a valve oscillator, its output can be kept relatively constant by feeding it

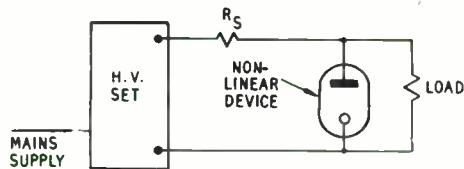


Fig. 1.—Stabilization of high voltages by means of a non-linear device.

from a stabilized d.c. source. Such an arrangement is used by Van Dorsten et al<sup>10</sup> for a 100-kV electron microscope supply operating from a 100-c/s oscillator, and a stability of the order of 1 part in  $10^4$  is obtained. Panzer,<sup>11</sup> with an oscillator of frequency 100 kc/s feeding a voltage multiplying arrangement to give +50 kV and -50 kV, obtains a stability of about 1 part in  $10^3$ . In this case, the d.c. supplies are stabilized with gas-discharge tubes. The oscillator output can also be stabilized by a feedback circuit from a diode rectifier connected to its output, or a winding on the transformer, and this system is used in a 25-kV h.v. set for a television projection system.<sup>12</sup>

#### 4. Non-linear Devices

Voltage stabilization can be obtained by using a non-linear device in which the current increases rapidly with increased voltage. If such a device is shunted across the load, and a resistor  $R_s$  connected in series with the h.v. supply as in Fig. 1, fluctuations in the voltage across the load will be reduced by the ratio of the series resistance to the incremental resistance of the device.

Gas discharge tubes are not obtainable for large voltages; they require relatively large currents for their operation, and so are not convenient for use with h.v. sets. The corona stabilizer tube is more suitable, and experimental tubes have been produced for voltages up to

40 kV and currents up to 1 mA.<sup>13</sup> Direct stabilization with the tube is rather inefficient but, in conjunction with valves, a simple stabilizer can be made. The stability of the corona tubes is rather poor, however, being about 0.1 per cent.<sup>14</sup>

#### 5. The Degenerative Feedback Method

In this method, fluctuations in the voltage output are measured by a device called the detecting element\*, amplified and fed back into the h.v. set so as to correct for the original fluctuations. The principle is identical to that used in low-voltage stabilizers, except that the detecting element and method of control have to be suitable for the high voltage.

Consider the arrangement shown in Fig. 2, the detecting element having a ratio  $\beta$ . For example, this may be a resistance potential divider of resistors  $R_1$  and  $R_2$  so that  $\beta = R_1/(R_1 + R_2)$ . The feedback amplifier is direct coupled and the difference in potential between divider tapping point and amplifier grid voltage is made up by a voltage  $E$ , known as the reference potential.

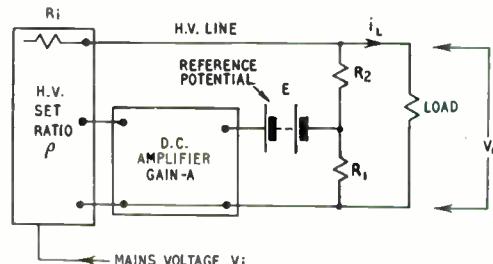


Fig. 2.—The degenerative feedback method of stabilization.

The h.v. set output voltage  $V_o$  will be given by:

$$V_o = \rho V_i - i_L R_i - Ae \dots \dots \dots (1)$$

where  $\rho$  = ratio of h.v. set output to mains supply voltage

$V_i$  = mains input supply voltage

$i_L$  = load current on h.v. set

$R_i$  = internal resistance of h.v. set

$A$  = feedback amplifier gain

$e$  = feedback amplifier input voltage

Now  $e = (\beta V_o - E)$

\* "detecting element" is the term accepted by the B.S.I.

and substituting in (1)

$$V_o = \rho V_i - i_L R_i - (\beta V_o - E) A$$

Therefore:

$$V_o = \frac{AE}{1+A\beta} + \frac{\rho V_i}{1+A\beta} - i_L \frac{R_i}{1+A\beta} \dots (2)$$

If  $A$  is large, it can be seen that

$$V_o = \frac{AE}{1+A\beta} \simeq E/\beta \dots (3)$$

$$\begin{aligned} \text{The stabilization ratio}^3 &= \frac{\delta V_i / V_i}{\delta V_o / V_o} \\ &= 1 + A\beta \dots (4) \end{aligned}$$

The internal resistance with feedback is

$$\frac{R_i}{1+A\beta} \dots (5)$$

The feedback reduces the effects of mains voltage and load current fluctuations by a factor  $(1 + A\beta)$ . The stabilized output voltage  $V_o$  is approximately  $E/\beta$ .

In practice, values of  $A\beta$  in the region of 1,000 are common. It can be seen that for a given value of  $A$ , it is desirable to make the fraction  $\beta$  as large as possible, as this gives a high loop gain.

## 6. Detecting Element

The detecting element for the fluctuations on the h.v. line is, in effect, a voltmeter which is required to measure the fluctuations without introducing any spurious signals. As the high voltage is to be stabilized, not measured, the voltmeter need only give relative indications, and its absolute calibration is not generally important.

As can be seen from equation (3), the stability of the high voltage depends on that of the detecting element, and this usually limits the ultimate stability obtainable. Fluctuations due to mains voltage and load current variations can always be made small by using a high loop gain, or by reducing the input voltage changes by pre-stabilization, such as by the means discussed in Section 3.

### 6.1. Resistance Potential Divider and Reference Potential

The most commonly used detecting element is a resistance potential divider, the voltage drop across one section being opposed by the reference

potential, as illustrated in Fig. 2. The problem then arises of obtaining a highly stable divider ratio while keeping the current drawn by the divider within the capabilities of the h.v. supply. The voltage and maximum allowable current drain from the h.v. supply fix the minimum resistance of the divider, and so influence the choice of materials used in its construction.

If the divider consists of resistors of the same temperature coefficient for both sections, their ratio will be independent of temperature. In practice, dividers are usually made from a number of resistor units and, as the temperature coefficient cannot always be guaranteed from one unit to another, the divider ratio varies with temperature.

The desirable properties of a material for the divider are, therefore:—

- (a) high resistivity to reduce the bulk for a given divider current;
- (b) low temperature coefficient and the same value for all resistor units.

#### 6.1.1. Metallic wire resistors

The resistance potential divider wound with metallic wire is probably the most stable detecting element for high voltages, provided sufficient care is taken in its design and construction. Manganin has the advantage of a low temperature coefficient of resistance (< 1 part in  $10^5/^\circ\text{C}$ ), and has been used for h.v. dividers,<sup>9,15</sup> but is inconvenient because of its relatively low resistivity ( $48 \mu\Omega/\text{cm}^3$ ). A reasonable compromise between resistivity and temperature coefficient is offered by nickel-chrome wire ( $100 \mu\Omega/\text{cm}^3$  and 1 part in  $10^4/^\circ\text{C}$ ). This was used in a resistor described by Waterton,<sup>16</sup> 0.002-in wire being wound into oil-filled 160-megohm units. A similar divider described by Van Dorsten<sup>17</sup> was used in a 150-kV stabilizer, a stability of 1 part in  $10^4$  being obtained. Here, wire of diameter 0.0006 in was used, but difficulty was experienced with breakages.

When the voltage is applied to a divider, variable corona and leakage can cause its ratio to fluctuate. These effects are most troublesome with air-insulated dividers, but can be greatly reduced by surrounding sections of the divider with screens maintained at potentials nearly equal to those of the sections within the screens.

These potentials are obtained from auxiliary divider which need not be very stable. With such an arrangement, Rymer and Wright<sup>18</sup> were able to stabilize voltages in the range 40–60 kV to 2 parts in  $10^5$ , and measure them to an accuracy of 1 part in  $10^4$ .

### 6.1.2. Carbon and metallic film type resistors

Carbon resistors are available in several forms, each having different properties. The most common, as used in the majority of radio circuits, is made from carbon mixed with a filler to give a suitable resistivity. The resistance material is then used as a solid body or as a filament deposited on an insulating tube. Such resistors are very unstable compared with metallic wire-wound types, as their resistance changes with voltage (apart from heating) and the temperature coefficient is high. Even under constant electrical and thermal conditions, their resistance fluctuates due to the imperfect contact between conducting particles of the resistor.

The "cracked carbon" type resistor is much more stable than the composition type, since the carbon is deposited as a continuous film on an insulating rod, no binder being used. The resistivity which can be obtained is limited, and high resistors are made by cutting a helical insulating track through the conducting film. The temperature and voltage coefficient increases with the resistivity of the film, for a 5-megohm unit the coefficients obtainable are  $0.04\%/\text{ }^\circ\text{C}$  and  $5 \times 10^{-6}/\text{volt}$ . The properties of these resistors have been reviewed by Coursey,<sup>19</sup> Fagan and Ehrenfried<sup>20</sup> and by Harris,<sup>21</sup> who report changes of 0.2–0.8 per cent. after 12 months and 0.3–1.5 per cent. after 22 months. Resistors of this type sealed in helium or nitrogen have been shown to have a stability of 1 part in  $10^4$  over a 1,000-hr period at full load.

Recently, a new resistor known as the boro-carbon type has become available. Work at the Bell System Laboratories<sup>22</sup> shows that these can be made with temperature coefficients comparing favourably with that of the nickel-chrome wire-wound types. Commercially available resistors have a temperature coefficient of  $0.016\%/\text{ }^\circ\text{C}$  for 100,000 ohm units, and should provide a useful compromise between the cracked-carbon and wire-wound types.

Conducting glass resistors have been developed

mainly in low resistance values and are not suitable in this application. Metallic film-type resistors are often used in high voltage work, the temperature coefficient depending on the metal used and the resistivity of the film.<sup>19, 20</sup> The stability is usually better than the carbon resistors, but is inferior to the metal in bulk as the film is not continuous, consisting of patches connected by rather imperfect contacts.

In commercial electron microscope supplies, carbon resistance dividers are almost invariably used on account of their small current drain,<sup>23, 24, 25</sup> a value of  $100 \mu\text{A}$  at 100 kV being common. The divider is usually oil-immersed so that rapid temperature changes and gradients are unlikely. An arrangement for ensuring good oil circulation is given by Waterton,<sup>26</sup> and Harris<sup>15</sup> while, in some cases, forced air circulation is used.<sup>27</sup> In the case of oil-immersed dividers, it has been found advantageous to enclose the divider in wax.<sup>23</sup>

### 6.1.3. Reference potential

With resistance potential dividers, their outputs are compared with a reference potential before amplification. It can be seen from equation (3) that the stabilized output voltage is proportional to this voltage, so that the h.v. stability will depend on that of the reference potential.

Gas discharge tubes have been used as a source of reference voltage<sup>17, 24</sup> but, as they exhibit fluctuations in their voltage, dry batteries are usually preferred, particularly in electron microscope stabilizers.<sup>23, 25</sup> If the battery is reasonably well-thermally insulated, its voltage will be sufficiently steady for the minute or so necessary to focus and make an exposure. When high stability is required over long periods, it is necessary to thermostat the battery as the temperature coefficient of voltage of Leclanché dry cells is considerable (200 parts in  $10^6/\text{ }^\circ\text{C}$ ).<sup>1</sup> Dry cells with temperature coefficients of voltage of 10–20 parts in  $10^6/\text{ }^\circ\text{C}$  are available<sup>28, 29</sup> and Weston standard cells (40 parts in  $10^6/\text{ }^\circ\text{C}$ ) have been used.<sup>30</sup>

## 6.2. Energy Analysers

A high voltage can be measured by using it to accelerate electrons and then measuring their energy in terms of magnetic or electric field required to deflect them through a known angle.

By fixing the deflecting field, movement of the electron beam can be used to detect fluctuations in the high voltage. This movement can then be converted into an error signal, which is then amplified and fed back to correct for the fluctuations. It will be seen that the analyser geometry and deflecting field strength take the place of the reference voltage and resistance potential divider. The stability of the high voltage then depends on the constancy of the analyser dimensions and the deflecting field.

In an analyser described by Haine and the author,<sup>31</sup> magnetic deflection through 180 deg. is used as shown in Fig. 3. One side of the

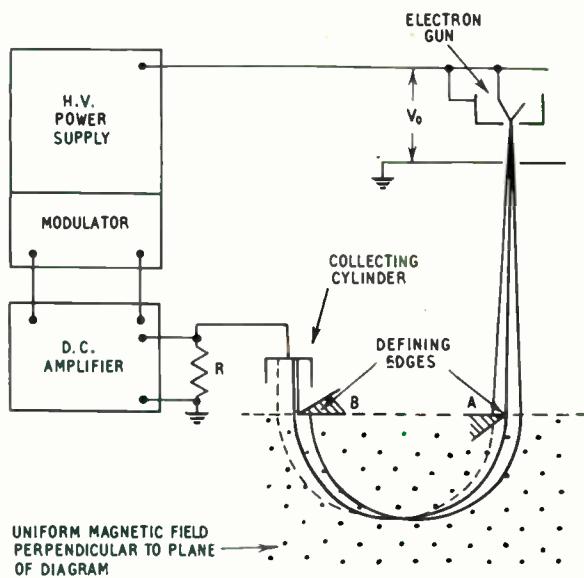


Fig. 3.—The electron velocity analyser method of stabilizing high voltages.

(Based on a diagram from a paper by Haine and Jervis in Proc.I.E.E.<sup>31</sup>).

electron beam is defined by edge A and, after deflection, movement of the beam is measured by the current collected on an electrode at the analyser exit. This current is then passed through the resistor R and the voltage drop across it fed into the feedback d.c. amplifier and h.v. set. By taking precautions to maintain constancy of the magnetic field and the distance between the defining edges A and B, a stability of better than 1 part in  $10^5$  is obtained in a voltage of 50 kV. Not only has this device a high internal stability,

but it also delivers a large signal to the d.c. amplifier, so that instability in the latter is negligible. For example, with  $R = 10$  megohms, the change in voltage at the d.c. amplifier for a 1-volt change in the 50-kV line is about 2 volts, in contrast to the case of a potential divider of ratio 200 : 1 when the corresponding signal would be 5 mV. The analyser requires about 100  $\mu$ A current drain from the h.v. set instead of 1 mA or more for a wire-wound potential divider of reasonable size.

Electrostatic analysers<sup>2, 9, 27</sup> are used mainly for high voltages (up to 4 MV), and are therefore out of the scope of this review. In the stabilization and measurement of these voltages, the electric field is required to be stable and is provided by positive and negative voltages of value up to about 50 kV applied to the analyser deflector bars. The negative feedback stabilizer system is almost invariably used with a wire or carbon resistance potential divider with amplifier and control system as described in the following sections. As the voltage has to be measured to 0.1 per cent. or better, a separate measuring divider is often provided.

## 7. Feedback Amplifier

Apart from supplying sufficient gain to make the total loop gain adequate, the feedback amplifier must be stable and may be required to have a good phase and frequency response (see Section 9). Any internal fluctuations within the amplifier can be considered as fluctuations of a voltage in series with its input, and therefore variations in the reference voltage. For example, if the effective input fluctuations are 2 mV, this corresponds to 1 part in  $10^5$  for a 200-V reference potential. In practice, due to variable contact potentials in the input stages of thermionic amplifiers, it is difficult to reduce the input fluctuations below 0.5 mV over one hour<sup>32</sup> and so reference potentials are usually made at least 100 volts. Thermionic feedback amplifiers are invariably used in electron microscope supply stabilizers, as their stability is adequate for the short times required in this case.

The amplifier works with high-source resistance so that grid current changes are important. For example, with a divider drawing 100  $\mu$ A, a grid current change of  $10^{-9}$  A corresponds to 1 part in  $10^5$  of the voltage. Amplifiers with low-grid current are reviewed elsewhere by the author.<sup>33</sup>

Galvanometer and contact modulator ("chopper") amplifiers<sup>32</sup> have the advantage of greater input stability ( $1 \mu\text{V}$  or better). Galvanometer amplifiers have been used in h.v. stabilizers,<sup>9,34</sup> giving a stability of 1 part in  $10^4$ . Using a chopper modulator and 60-megohm wire-wound divider temperature controlled to  $0.1^\circ\text{C}$ , one 40-kV stabilizer<sup>30</sup> gave a stability of 1 part in 20,000 over 240 hours. In this case, the stability quoted is that of the divider current, which is the same as the h.v. stability if the divider resistance is assumed constant.

## 8. H.V. Control Systems

The most suitable means of control of the h.v. set by the feedback amplifier depend on the type of set in question. Control systems for stabilizers have been reviewed by Benson<sup>4,35</sup> and Maddock,<sup>3</sup> and will not be discussed in detail. A few general observations will be made, however, and examples of their application to h.v. sets will be quoted.

Clearly, the control device must operate in a time short compared with the time taken for fluctuations to occur. Valve amplifiers are best, and are usually used as series controllers. The

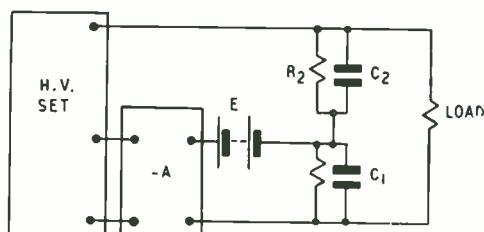


Fig. 4.—Method of compensating stray capacitances and so preventing oscillations in feedback loop.

valve can be used either at the earthy end of the h.v. set<sup>17,24</sup> or the amplifier and series valve can be at the h.v. potential.<sup>36</sup> When the amplifier is connected to the earthy end, electrostatic screening must be fitted to the h.v. transformer secondary to prevent capacitance currents passing through the amplifier. A series valve at h.v. potential can be controlled by a r.f. transformer, insulated for the high voltage.<sup>37</sup>

Often it is convenient to obtain the high voltage by rectifying the output of an alternator or oscillator-driven transformer. With an

alternator, control can be effected by the field excitation.<sup>9</sup> Valve oscillator-driven h.v. sets are often used in electron microscope supplies, the h.v. control being obtained by variation of the screen grid voltage of the pentode or tetrode oscillator valves.<sup>23,25</sup>

## 9. Oscillations in the Feedback Loop

In a feedback system, oscillations will occur when the phase shift round the loop is 360 deg., and the loop gain is greater than unity. In a typical h.v. stabilizer, phase shifts are present at a number of points and oscillations occur if the loop gain is made high.

Usually, a smoothing filter is used to reduce ripple output, and this causes some phase lag. At high frequencies thermionic feedback amplifiers cause a lag and, in the case of contact modulator and galvanometer amplifier types, this lag occurs at low frequencies. There is usually some stray capacitance from the resistance potential divider point to earth (C1 in Fig. 4), but its effect can be reduced by an appropriate capacitor C2 connected across the divider point to h.v. line. This capacitor can be made such that a relatively large capacitor can be connected across the earthy section, so making it insensitive to pick-up and interference. This arrangement has been used in electron microscope supplies,<sup>17,23,24</sup> and is particularly useful if the divider must be connected to an amplifier by a long-screened lead, and the divider is of high resistance.

The time constants can often be chosen so that they are of suitable relative length to avoid oscillations. If a large loop gain is required, or the comparable time constants are unavoidable, the phase shift can be reduced by suitable networks included in the loop<sup>9,34</sup> or by auxiliary a.c. amplifiers used to improve the phase response of parts of the feedback loop.<sup>31</sup>

## 10. Conclusions

Stabilization of the mains supply to an h.v. set can give a stability of 2 parts in  $10^4$  in the high voltage if load changes are small. The corona-type stabilizer across the h.v. set output has rather a poor performance and, even with valves, stabilities of better than 0.1 per cent. are unlikely.

The performance of the degenerative feedback stabilizer depends on the loop gain used and the

stability of the h.v. detecting element. The maximum loop gain which can be used without the onset of oscillations is related to the frequency response of the loop. By suitable design, gains of several thousand are possible, so enabling the effects of mains supply voltage and load current variations to be reduced by this factor. In practice, the residual fluctuations from these sources are often smaller than those introduced by the detecting element, especially if pre-stabilization is used. The wire-wound potential divider and battery reference source, suitably temperature controlled, is probably the most stable detecting element, and is capable of a stability of 1 part in  $10^5$  or better. The wire-wound potential divider implies considerable bulk and current drain on the h.v. set, however, and comparable stabilities are obtainable with energy analyser methods with a smaller current drain and bulk. For shorter term stabilization, for example, 1 part in  $10^4$  for a few minutes, carbon resistor dividers are adequate and have the advantage of small current drain for a given physical size and voltage. This is particularly important in the case of h.f. driven h.v. sets used in electron microscope supplies.

## 11. Acknowledgments

The author is indebted to Mr. M. E. Haine for helpful suggestions and criticism, and to Dr. T. E. Allibone, F.R.S., for permission to publish this paper.

## 12. References

1. A. Jacob and J. V. Holdam. "Electronic Instruments," Chap. 15. Radiation Lab. Series, Vol. 21. (McGraw-Hill, 1948.)
2. R. G. Herb, S. C. Snowden and O. Sala. "Absolute voltage determination of three nuclear reactions." *Phys. Rev.*, 75, Pt. I, 1949, p. 246.
3. A. J. Maddock. "Voltage stabilization, demands and methods." *J. Sci. Instrum.*, 28, November 1951, p. 325.
4. F. A. Benson. "Voltage Stabilizers." (Electronic Engineering Monograph, 1950.)
5. M. M. Hubbard. "Components Handbook," Chap. 12. Radiation Lab. Series, Vol 17. (McGraw-Hill, 1949.)
6. M. von Ardenne. "Elektronen Übermikroskopie." (Julius Springer, 1940.)
7. P. A. V. Thomas. "An alternating current stabilizer." *Electronic Engineering*, 25, December 1953, p. 522.
8. H. Bartel. "Über die Konstanthaltung von Hochspannungsanlagen." *Z. Tech. Phys.*, 19, 1938, p. 235.
9. R. L. Henkel and B. Petree. "Stabilized h.v. power supply for an electrostatic analyser." *Rev. Sci. Instrum.*, 20, October 1949, p. 729.
10. A. C. Van Dorsten, H. Nieuwdorp and A. Verhoeff. "The Philips 100-kV Electron microscope." *Philips Tech. Rev.*, 12, August 1950, p. 33.
11. S. Panzer. "Erzeugung hoher Gleichspannung mittels Hochfrequenz." *Optik*, 7, 1950, p. 290.
12. J. J. P. Valeton. "H.T. generators for large picture projection television." *Philips Tech. Rev.*, 14, July 1952, p. 21.  
Also, J. W. Crouch and B. R. Overton. "An improved generator for the e.h.t. supply to projection picture tube MW6-2." *Mullard Tech. Commun.*, 6, January 1954, p. 142.
13. I. H. Blifford, R. G. Arnold and H. Friedman. "Corona tube regulators for h.v." *Electronics*, 22, December 1949, p. 110.
14. F. A. Benson and J. P. Smith. "Variations in the characteristics of some corona stabilizer tubes." *J. Sci. Instrum.*, 30, June 1953, p. 192.
15. J. N. Harris. "A precision megohm ratio unit for h.v. measurements." *Rev. Sci. Instrum.*, 23, August 1952, p. 409.
16. F. W. Waterton. "A substandard d.c. voltmeter to read 300 kV." *J. Sci. Instrum.*, 19, July 1942, p. 105.
17. A. C. Van Dorsten. "Stabilization of the accelerating voltage of an electron microscope." *Philips Tech. Rev.*, 10, November 1948, p. 135.
18. T. B. Rymer and K. H. R. Wright. "A new determination of  $h/\sqrt{em_0}$  by electron diffraction." *Proc. Roy. Soc. A.*, 215, 1952, p. 550.
19. P. R. Coursey. "Fixed resistors for use in communication equipment." *Proc. Instn Elect. Engrs*, 96, Pt. III, May 1949, p. 169.
20. M. D. Fagan and G. Ehrenfried. "Components Handbook," Chap. 3, Radiation Lab. Series, Vol. 17. (McGraw-Hill, 1949.)

21. F. K. Harris. "Electrical Measurements," p. 207. (Wiley, 1951.)
22. R. O. Grisdale, A. C. Pfister and W. Van Roosebroeck. "Pyrolytic film resistors: carbon and borocarbon." *Bell Syst. Tech. J.* 30, April 1951, p. 271.
23. V. K. Zworykin, et al. "Electron Optics and the Electron Microscope," Chap. 6. (Wiley, 1945.)
24. M. E. Haine. "Design and construction of a new electron microscope." *J. Instn Elect. Engrs*, 94, Part I, October 1947, p. 447.
25. M. E. Haine, R. S. Page and R. G. Garfitt. "A three-stage electron microscope with stereographic dark field and electron diffraction capabilities." *J. Appl. Phys.*, 21, February 1950, p. 173.
26. F. W. Waterton. "A range of kilovoltmeters for high d.c. voltages." *J. Sci. Instrum.*, 25, 1948, p. 304.
27. A. O. Hanson. "Voltage measuring and control equipment for electrostatic generators." *Rev. Sci. Instrum.*, 15, March 1944, p. 57.
28. W. P. Senett and R. W. Pierce. "Exceptionally stable regulated power supply for electrometer tubes." *Rev. Sci. Instrum.*, 23, October 1952, p. 534.
29. M. W. Jervis. "The temperature coefficient of the e.m.f. of kalium cells." *J. Sci. Instrum.*, 30, February 1953, p. 60.
30. J. G. Cottingham, W. H. Moore, E. J. Rogers and C. M. Turner. "Cosmotron-injection system. Part II—Injection optics." *Rev. Sci. Instrum.*, 24, September 1953, p. 816.
31. M. E. Haine and M. W. Jervis. "The use of an electron velocity analyser to stabilize a 50-kV d.c. voltage source to a few parts per million." *Proc. Instn Elect. Engrs*, Paper No. 1729 M. (Proofs available to public since October 1954.)
32. K. Kandiah and D. E. Brown. "High-gain d.c. amplifiers." *Proc. Instn Elect. Engrs*, 99, Part II, August 1952, p. 314.
33. M. W. Jervis. "The measurement of very small direct currents." *Electronic Engineering*, 26, March 1954, p. 100.
34. C. J. Cook and W. A. Barrett. "Regulator for a 20-250-kV Cockcroft-Walton accelerator." *Rev. Sci. Instrum.*, 24, August 1953, p. 638.
35. F. A. Benson. "Voltage stabilization." *Electronic Engineering*, 25, May 1953, p. 202.
36. L. G. Parratt and J. W. Trischka. "An electronic voltage stabilizer for 1-50 kV 20-500 mA." *Rev. Sci. Instrum.*, 13, January 1942, p. 17.
37. R. Pepinsky and P. Jarmotz. "An inductively coupled series tube d.c. h.v. regulator." *Rev. Sci. Instrum.*, 19, April 1948, p. 247 and p. 273.

*Note added in proof.*—Information on h.v. resistors is given in the following recently published book by J. D. Craggs and J. M. Meek, "High Voltage Laboratory Technique" (Butterworths, 1954).

# APPLICATIONS OF HIGH-ENERGY ELECTRONS TO THE STERILIZATION OF PHARMACEUTICALS AND THE IRRADIATION OF PLASTICS\*

by

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

## SUMMARY

The paper describes the sterilization of pharmaceutical products and the variation of the physical properties of certain plastics by the action of ionizing radiations. It is shown that most efficient use of the available energy is made if electron bombardment is used in preference to X- or gamma-radiation. It is also shown that for the present time high-energy electrons are best obtained from some form of accelerator rather than from radio-active sources. In particular the linear accelerator forms a very convenient source. Experiments using a linear accelerator are described and the economics of the process shown to be attractive.

### 1. Introduction

The use of high energy electrons both in physical research and in the production of X-rays either for radiography or therapy is probably well known. The present paper is concerned with two other applications which, though at present in an experimental stage, are likely to be applied commercially in the near future.

The first depends on the effect of ionizing radiations on living organisms and leads to the sterilization of materials without appreciable rise of temperature; the process has therefore become known as cold sterilization. The possibility of such an effect is no new idea and indeed conjecture on the subject dates from the last century. Probably the first paper to appear on the subject was published in Germany in 1896, only a year after Roentgen's discovery of X-rays, and the title "On the question of the effect of Roentgen rays on bacteria and the possibility of their eventual application" clearly forecasts the present application.

The second application is of more recent date and has only become possible since powerful sources of radiation became available. It has been found that when certain plastics are subjected to relatively large doses of radiation

molecular changes take place and that in some cases this produces desirable changes in the physical properties of the material. In either process the effect of radiations of different types is much the same and experimental work has been performed with apparatus ranging from simple X-ray tubes to large nuclear reactors. Nevertheless since the energy absorption in the material will be different for the various types of radiation, and industrial application will require full utilization of the radiation available, it might be expected that one type would be found most applicable. This is in fact so and it will be shown that for many applications direct bombardment with an electron beam is the best method.

It is not the purpose of the present paper to consider the bacteriology or chemistry involved in the processes but certain experiments will be described. It will be shown that with one form of power source, the linear accelerator, the process could in many cases be applied in production on economically attractive terms and that with developments already envisaged the costs are likely to be considerably reduced during the next few years.

### 2. The Processes

#### 2.1. Sterilization

When a substance is irradiated either by X- or gamma-rays or bombarded by particles such as electrons or neutrons, energy is absorbed in the material largely as a result of ionization.

\*Manuscript received 16th June, 1954. (Paper No. 296.)

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U.D.C. No. 621.384.622.1 : 615.4 : 678.742.2.

Such ionization taking place in the structure of a living organism may be lethal and it is of course this action which makes possible the destruction of malignant growth in the X- or gamma-ray treatment of cancer. Exactly what happens to the organism is beyond the scope of this paper but an elementary consideration will be given later when considering quantitative effects. It might be expected that the more complex the organism the easier it would be to destroy and this is found to be so. For instance, a fatal dose for man is only a fraction of that for a small animal and is some hundreds of times less than that required to kill typical bacteria.

The field open to any method of sterilization is wide, and varies considerably in the treatment required. At one end of the scale might be considered the killing of relatively large organisms, for instance insects, an example being the ridding of weevil from grain or the treatment of wood for woodworm; this might be termed de-infesting. At the other extreme is the most stringent requirement in the rendering sterile of drugs, pharmaceutical products, and surgical dressings and sutures. As an intermediate case there is the problem of improving the keeping quality of foodstuffs, etc., this will involve killing many, but not necessarily all, of the organisms and in some cases may be satisfied by a surface treatment only.

It is found that in many cases the number of surviving organisms in a sample decreases logarithmically with increasing dose of radiation, that is to say repeated equal doses will reduce the number of organisms by a constant factor. This at first sight might seem to be contradictory to the desire for complete sterility. It is possible, however, to give a treatment after which the probability of finding even one surviving organism is small and increasing the dose will reduce this probability to any required value. Thus the dose required depends on the desired degree of sterility and partly because of this and also because of the large size of the organisms it is found that doses required in de-infesting are only some 2 per cent. of those for the treatment of drugs.<sup>2</sup> This is a point which is of considerable importance when the economics of a process are considered. In any form of treatment it is essential that the process should not be marred by any unwanted additional reactions and this is a point which must be investigated with great

care particularly in the case of foodstuffs or pharmaceutical products. In certain cases, if treatment were carried out using an atomic pile or if neutrons were used, radioactivity of the treated material might occur. When X-rays or electron bombardment are used, however, energy would normally be well below the level at which nuclear reactions occur and this effect may be discounted; chemical reactions on the other hand may take place. Should such reactions be found there are certain possibilities which might overcome the trouble. For instance, it is known that such reactions, in certain cases at least, are more active in dilute solutions than in concentrated ones.<sup>3</sup> It is suggested that much trouble can be avoided if, wherever possible, materials are treated in the dry state. Further, reduction of the effect has been reported by lowering the temperature<sup>4</sup> and it would appear that deep freezing of the product during treatment might be very useful in difficult cases.

In order that there should be a market for this form of sterilization, it has to be shown that it has advantages either in economy, convenience or effectiveness over other methods or that alternatively it can be used when no other method is available. At present the most usual method of sterilization is the application of heat, either as dry heat or as steam heating. Steam heating is sometimes accompanied by pressure. Such methods are economical and where no ill effects accompany the method they are the obvious choice. In some cases, however, the product is thermally unstable and heating cannot be used at all, whilst in other cases the method causes changes which, though not prohibitive, are undesirable. Mild examples of this latter are the change of taste of milk on pasteurization, and the fact that meat cannot be canned in the raw state. When no method of sterilization has been available, resource has been made to performing the whole preparation under aseptic conditions; a typical example of this is the production of penicillin and of course such a procedure adds enormously to the cost of the product. As will be shown later, sterilization by irradiation involves a temperature rise of at the most a few degrees and it can therefore be applied to cases which cannot be treated by the normal methods. Further, if the choice of radiation is made correctly, the process can be carried out with the product sealed in its final container and this has obvious advantages.

## 2.2. Irradiation of Plastics

During the last few years considerable attention has been given to the effect of comparatively large doses of radiation on polymeric substances. Considerable effort has been directed to the investigation of the effect upon polythene and, largely as a result of the work of Charlesby at A.E.R.E. Harwell, a good understanding of the process has been obtained. Normal polythene is, as is well known, soluble in certain organic solvents and has a melting point of about 115°C. On irradiation it becomes almost insoluble and the melting point has been removed, something akin to thermosetting having taken place. At temperatures above the normal melting point the irradiated material behaves as a soft rubber, deforming under strain but recovering on its removal and having a modulus which is a function of temperature.

It is reported that several other materials behave in a manner similar to polythene and amongst these may be quoted nylon, polystyrene, polychloroprene and natural rubber. In addition the co-polymers of butadiene and styrene, and of butadiene and acrylonitrile exhibit similar properties all showing reduced solubility and increased heat resistance. There are, however, other materials among which may be mentioned poly-isobutylene, butyl rubber, P.T.F.E., and methyl methacrylate which behave differently and here degradation takes place.

The main effect on polythene has been attributed to cross-linking. The action of irradiation is to break C-H bonds, producing free radicals and hydrogen atoms. Two free radicals on separate polymer chains combine to form a cross-link. It is considered that in a condensed system of this type the combination of two hydrogen atoms is energetically possible and therefore one hydrogen molecule is evolved for every cross-link formed. For large doses of irradiation many cross-links will be formed and the sample in effect becomes one large molecule having considerable resistance to solvents and, of course, having no crystalline melting point.

Degradation, on the other hand, may be attributed to the breaking of C-C bonds and consequent destruction of the polymer and the production of the lower hydrocarbons. In the case of methyl methacrylate Charlesby has suggested that the degradation may be turned to good account. Irradiation causes the liberation

of gases, probably methane, but these are retained in the specimen under considerable pressure. If now the specimen is heated to its softening point the gases expand and a foamed material is formed. An increase in volume of some 8 times is possible and the resultant material has a very low effective dielectric constant, high resistance and, of course, a low density. Charlesby's irradiations were carried out in an atomic pile at an ambient temperature of about 70°C and he reported that the foamed material was surrounded by a skin of unfoamed material of about 1 mm thickness. Experiments with electron bombardment at room temperature did not produce this skin but the effect could be obtained by irradiation at higher temperatures. It would seem therefore that the skin is formed due to the possibility of diffusion of gases out of the specimen in this region, provided the temperature is high enough.

Hitherto materials have been classified according to whether they cross-link or degrade, but recent work<sup>5,6</sup> has shown that, certainly in some cases, both processes take place. It would appear therefore that the difference is only one of degree determining which process predominates. In the case of polythene it has been shown that the probability of C-C breakage is only about 20 per cent. of that of cross-linking.<sup>6</sup>

## 2.3. Choice of Radiation

It has already been stated that the effects of various types of ionizing radiation are qualitatively much the same but that the efficiency of utilization may be widely different. It does not follow that the effects are identical even for the same energy absorption in the specimen and experiments are at present in progress to investigate some apparent differences.

Irradiation by placing specimens inside an atomic pile, although it has been used experimentally, is obviously not at present applicable to a commercial process and additionally there is the disadvantage of high ambient temperature and the possibility as in the case of polyvinyl chloride (P.V.C.) that the specimen will become radioactive. Alternative methods are to use the gamma-rays or electrons emitted from radioactive materials which may be either produced by irradiation in the pile themselves or may be produced as a fission product. Very large radioactive sources would be required and considerable protective arrangements would be

necessary. At present the cost of pile produced materials is completely prohibitive and although fission products might be available as by-products they would require concentrating and facilities for this are not, to the author's knowledge, yet available.

Similar radiations can, of course, be produced by machines, and electrons accelerated to high energies can either be applied directly or can produce X-rays by the bombardment of a target. It has been stated by Wild of A.E.R.E. Harwell<sup>7</sup> that for the next ten years or so the machine-made radiation will be the most attractive source, and there is in particular one type of machine, the linear accelerator, which, because of its high efficiency, appears an obvious choice.

The problem then devolves into deciding whether electrons should be used directly or whether they should be used to produce X-rays. There are certain special problems when surface sterilization is required, probably most important in the field of food preservation, where such a limitation prevents undesirable reactions inside the material. In such cases low-energy electrons or very soft X-rays will be used.

In general, however, it is essential that the specimen should be treated throughout its entire depth and this with some degree of uniformity. This, at first sight, might be thought to be a point decidedly in favour of using X-rays, since they have a much greater penetration than the electrons used to produce them. In fact, however, unless a very large bulk of material is being treated, their penetration is too great and very little energy is absorbed in the material. For instance, the X-rays produced by 8 MeV electrons are reduced to a 10 per cent. intensity only after passing through some 30 in. of water. If small thicknesses of material are used there is a large wastage of power and if thicknesses are made large to overcome this there is the problem of variation of dose rate throughout the material. Wastage would not be so bad if lower energies were used but then the efficiency of X-ray production would be very low, at best only a few per cent., and most of the power would be used in heating the X-ray target.

For these reasons it is preferable to make direct use of the electron beam and in order that specimens of adequate thickness can be treated energies of several MeV are required. The penetration of 8 MeV electrons into water

or other material of unity density is about 4 cm and for 4 MeV electrons about 2 cm, whilst for materials of other densities the range is inversely proportional to density. For many applications, for instance the sterilization of drugs in their ampoules, such penetrations are quite adequate, whilst in other cases it is possible to arrange the material in a suitable manner during irradiation, possibly giving treatment from both sides so as to double the thickness which it is possible to treat. Further, in the case of electrons, unlike that of X-rays, the absorption of energy can be considered to take place uniformly throughout most of the electron range.

### 3. The Linear Accelerator and its Capabilities

The travelling wave linear accelerator is a post-war development and has been described in several papers<sup>8-14</sup> and a short description has also been given in a paper read earlier in the present Convention.<sup>15</sup> It is sufficient here to state that in such a machine electrons may be accelerated to energies of several MeV and that efficiencies of 40 per cent. (ratio of electron beam power to r.f. input power) have already been attained and that considerably higher efficiencies are expected.<sup>16</sup> At present, outputs of some hundreds of watts are available and the electron beam is very easily extracted for the treatment of materials. The beam as it leaves the accelerator is of small cross-section and negligible divergence. In commercial application it would be a simple matter by means of magnetic fields to scan this beam over samples passing in front of the machine on a conveyor belt. Alternatively the beam may be scattered by means of foils. In experimental use the scattering technique has been used and a copper foil some 0.005 in. thick enables a large area of specimen to be covered at a distance of a foot or two from the end of the machine. In fact, over a diameter of 6 in. at 2 ft from the foil the intensity of irradiation is uniform within 5 per cent. This experimental technique is, of course, wasteful of power, but it makes easy the treatment of a wide variety of specimen.

The important quantity in any treatment is the energy absorbed in unit weight of material; this could be expressed in kW.sec/lb and indeed some papers have used this unit. It is more usual, however, to use one of the radiation units and until recently the r.e.p. (the roentgen equivalent physical) has been used. There has been some little confusion about this unit, as it

was originally defined as corresponding to an energy absorption of 83 ergs/gm, but more recently a value of 93 ergs/gm has been used to give closer correspondence to the roentgen. The situation has now been clarified by a new internationally agreed unit, the rad, and this corresponds to an absorbed dose of 100 ergs/gm. Conversion between units can be made on the basis of 1 kW.sec/lb being equivalent to  $2.2 \times 10^5$  rad. It can easily be shown that a machine with an output of 500 watts is, if the beam is fully utilized, capable of delivering a dose of  $10^6$  rad to material at the rate of approximately 400 lb/hour. Anticipating a later section of the paper it can be stated that doses of this order are required for sterilization whilst for the treatment of plastics  $10^7$  rad or more may be required.

It is interesting at this stage to consider the temperature rise which would be caused by the absorption of energy in a specimen. Physical tables indicate that the specific heat of common liquids cover the range of 0.2 to 0.6 and, excluding certain metals, solids fall largely in the region 0.15 to 0.8. Assuming, therefore, an average value of 0.5, it can be seen that the absorption of a  $10^3$  rad dose, i.e.  $10^3$  ergs/gm or 2.4 cals/gm causes a temperature rise of only  $4.8^\circ\text{C}$  even when all cooling is neglected.

#### 4. Experiments Using Linear Accelerators

During the development of linear accelerators for X-ray therapy it has been possible to carry out investigations on both sterilization and plastic irradiation. The experiments described below are those with which the author has been directly concerned. It is appreciated that these are a relatively small contribution to our present knowledge on the subject, but they are typical of many investigations performed by other workers and in addition illustrate the use of a particular type of machine. Reference to the already extensive literature is made by means of an appended bibliography.

##### 4.1. Arrangement of Apparatus and Dose Measurement

Two types of linear accelerator have been used, the first an 8 MeV equipment<sup>14</sup> and more recently a 4 MeV machine.<sup>12, 15</sup> In both cases the electron beam was scattered in a very wasteful manner in order to obtain uniform distribution over a large area. Under these conditions dose rates of the order of  $10^5$  rad/min

were available at a distance of 2 ft from the end of the machine. Measurement of dose rate has been carried out in terms of the incident electron current falling on the sample and the energy absorption inferred from this as follows.

Consider electrons of energy  $E$  MeV falling on the specimen with a current density of  $I \mu\text{A}/\text{cm}^2$  and further that the material is of unit density and in this the electrons have a range of  $R$  cm.

Then in  $R \text{ cm}^3$  there is an energy absorption rate of  $EI$  watts, that is  $EI/R$  watts per  $\text{cm}^3$ , or since density is unity,  $EI/R$  watts/gm. This is  $EI/R \times 10^7$  ergs/gm/sec and is obviously a dose rate of  $EI/R \times 10^7$  rad/sec.

Assuming that range is inversely proportional to density of material it can be seen that the same expression will give the dose rate for any material. In addition to the assumption just stated there are two others implicit in the above reasoning. They are:

- (a) That all the energy is lost by collision, i.e., in causing ionization. Thus energy lost by the emission of radiation is considered negligible. This assumption restricts the argument to energies less than, say, 10 MeV and the lighter elements.
- (b) That energy is lost uniformly throughout the range of the electron.

These assumptions are justified in an appendix and although there may be some small inaccuracy in dose defined in this manner the error is not large and the method provides an easily repeatable measurement for comparative purposes.

##### 4.2. Sterilization Experiments

Experiments on sterilization have been of two types. The first type has been with samples of controlled contamination and has been directed to the determination of the radiation resistance of various organisms. From the results of such work and a knowledge of the contamination to be expected in a particular product it is possible to estimate the dose which would be required for an adequate guarantee of sterility. The second type of experiment has been with the products themselves although in some cases these have been additionally contaminated. These experiments, whilst confirming the sterilizing action, have been performed so that any undesirable side reactions could be investigated. Examples of both types of work are given below.

#### 4.2.1. Radiation resistance of organisms

In this type of experiment some material is heavily contaminated with the organism under investigation and a number of samples produced. These are treated with various doses of radiation and afterwards an assessment of the number of surviving organisms is made. This is done by plating out in agar, after appropriate dilution, followed by incubation under controlled conditions. The number of colonies produced are then counted and taken as an indication of the surviving organisms. A control specimen which has not been treated is used to give the initial contamination.

As an example of this work Fig. 1 shows the results for *B. Megatherium*. In this case the material used was talc and this was very heavily contaminated. Very similar quantitative results are obtained for other organisms. It can be seen that a dosage of  $1.5 \times 10^5$  rad is required to reduce the number of organisms by a factor of 10. Under normal circumstances pharmaceutical products may contain 5-10 organisms/gm before sterilization and assuming these are packed in 1 gm ampoules it can be seen that if sterilization is arranged to give a reduction in the number of organisms by, say,  $10^6$  times the probability of finding a non-sterile ampoule will be less than 1 in 100,000.

On this basis of  $10^6$  reduction the dose required would be  $9 \times 10^5$  rad, say in round numbers  $10^6$  rad.

By making some considerably over-simplified assumptions concerning the mode of action of the radiation in the destruction of the organism it is possible to express the results outlined above in an alternative form. It can be shown by a simple application of probability theory that if we consider a single electron "hit" in a sensitive area of an organism is sufficient to kill it and if the area of this sensitive region is  $\alpha$  cm<sup>2</sup>, the number of surviving organisms per gm ( $m$ ) varies with dosage according to the following relationship

$$m = m_0 e^{-\alpha N}$$

where  $m_0$  is the number of organisms per gm before exposure and  $N$  is the dosage expressed in terms of the number of electrons which have passed through 1 cm<sup>2</sup> cross-section of the sample.  $N$  is easily determined from the current density since 1  $\mu$ A corresponds to a flow of  $6.25 \times 10^{12}$  electrons/sec.

From the results quoted for *B. Megatherium*  $\alpha$  is found to be  $5 \times 10^{-13}$  cm<sup>2</sup>.

This cross-section is a very useful measure of the ease or otherwise with which the particular organism may be killed. Whether the value has any significance in consideration of the structure of the organism depends on the validity of the assumption that a single hit is sufficient to kill.

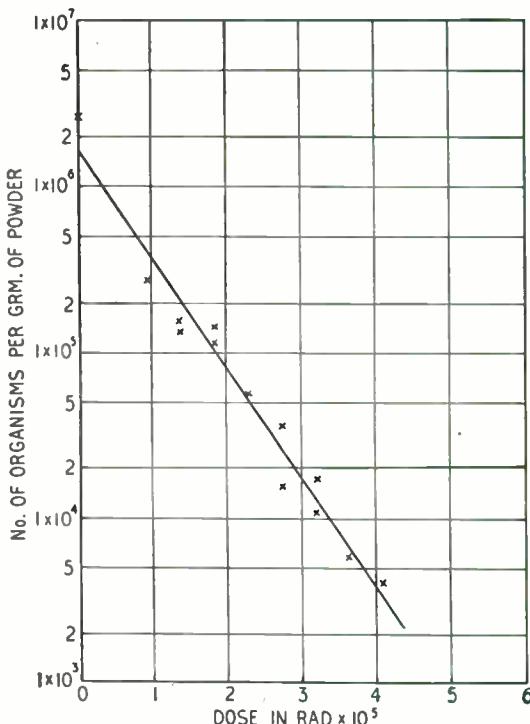


Fig. 1.—Effect of electron irradiation on talc contaminated with *B. Megatherium*. Number of surviving organisms plotted as a function of dose.

It has been suggested<sup>4, 17</sup> that bacteriological destruction is dependent on ionization in the genes and chromosomes of the organism and that this either gives lethal mutations or prevents reproduction. One might, therefore, expect that the effective cross-section derived above would be of the same order of magnitude as the relevant region of the organism. There are, however, other possibilities than the single target theory outlined and consideration of multiple hits either with or without the possibility of recovery is beyond the scope of the present paper. Many possibilities are, however,

considered by Lea<sup>17</sup> who also gives much of the biological background of the subject. Modern papers consider various energy transfer theories but for the case of bacteria, at any rate, target theories provide a reasonable working basis.

#### 4.2.2. Experiments on the final product

A wide variety of products have been treated in conditions simulating the treatment of the final product. In some cases a normal sample was used and in others heavier contamination was introduced. Two aspects of the process have received attention. In the first place it has been necessary to check that sterilization was effective and to determine the required dose. In addition, tests have been performed to determine that no harmful secondary reactions have occurred and that the properties of the product have not been damaged. In this second assessment it has been usual to examine specimens which have been given a dose considerably greater than that required for sterilization, so that even the slightest undesirable effect might be detected.

It is not possible to give details of all the products investigated but a few selected examples are described below. In most cases the assessment of the success or otherwise of the treatment was made by the makers of the product.

**Penicillin.**—This was an obvious material for the trial of the process and treatments have been performed under various conditions and with material from different sources. In all cases treatment has been made with the material in its final container, that is in some form of sealed glass ampoule. In one series of tests three types of sample were used as follows:

- (a) Sample containing  $10^6$  international units of sodic penicillin spontaneously polluted with various bacteria to a concentration of less than 1,000 organisms/gm. The material was in a dry state.
- (b) Sample of the same amount of material but mixed with water and contaminated with *Subtilis* to about  $1.5 \times 10^5$  organisms/gm.
- (c) Sample as (b) but using acetone instead of water.

A range of treatments were given to the various samples with doses ranging from 0.1 to 2.0 million rad. In all cases samples which received a dose of  $5 \times 10^5$  rad or greater were found to be sterile.

The biological activity of the material was also assessed after treatment by both iodometric and biological titration. It was shown that the activity of samples (a) and (c) had not been affected.

Sample (b), however, showed a reduced activity to a very marked degree and this was independent of the dosage given. This deterioration is attributed to storage in the moist condition.

**Other pharmaceuticals.**—A range of drugs, etc., have been treated and sterility has easily been obtained in every case. Examples which may be quoted are several types of oily suspension, streptomycin and insulin. Full investigation of activity after treatment has not been made in every case but the only material for which an adverse effect is reported is that of insulin in which activity is said to be reduced. This material was treated at room temperature and no effort has as yet been made to see if the effect can be avoided.

In the search for undesirable chemical reactions samples of two materials known to be relatively unstable were irradiated in the dry state and were given doses up to  $3 \times 10^6$  rad. They were examined for chemical decomposition using ultra violet spectrophotometry. The substances were kemithal sodium (a barbituric acid derivative) and paramino salicylic acid and in neither case could any decomposition be detected.

**Surgical sutures and dressings.**—It has been demonstrated that surgical sutures packed in an aqueous solution inside a glass tube can easily be sterilized and no apparent damage is done to the suture. It is already clear that the dosage required is of the order of  $2 \times 10^6$  rad and extensive tests are in progress to ensure that the properties of the suture are in no way spoiled. Dressings have been treated with complete success as regards sterility, the treatment being performed with the product in its package or box. In the case of adhesive dressings it is not yet known whether the keeping qualities of the adhesive are in any way affected.

**Foodstuffs.**—Experiments carried out on foodstuffs with the linear accelerator have so far been very elementary, but they have, however, confirmed the results of other workers to the extent that in almost every case change of taste takes place. This has been attributed to oxidative effects and in almost all cases is unpleasant. It

is, however, expected that by control of the irradiation conditions and possibly by the addition of certain materials the effect could be avoided or minimized. One material whose taste is not altered is sugar and this can be easily sterilized. Since, however, any contamination will be only a surface effect there are probably better ways of dealing with this case. An interesting effect is that for very large doses the white sugar becomes coloured pink. This effect is similar to the coloration of a number of materials, particularly the alkyl halides on irradiation and is attributed to lattice defects or colour centres. A similar effect takes place with glass and the ampoules in which materials are irradiated become "stained" brown to an extent depending on the dose and also on the composition of the glass. This effect may be regarded as undesirable in the packing of pharmaceutical products, but it is understood that it can be avoided by the inclusion of a small amount of cerium in the composition of the glass.

#### 4.3. Experiments with Plastics

Work on the irradiation of plastics by means of the linear accelerator has only just started and an extensive research programme is envisaged. It has proceeded far enough, however, to show that the effects of pile radiation reported by Charlesby and others can be repeated under more convenient and controllable conditions. Polythene has naturally been given greatest attention and not only has the decreased solubility and increased heat resistance been demonstrated but certain applications have been made. Thus diaphragms have been made for chemical apparatus containing liquids which would dissolve normal polythene and wave-guide components have been treated to give increased heat resistance. Dosages required for the treatment of plastics is an order of magnitude higher than that for sterilization, usually being of the order of  $10^7$  rad. It should be noted that during the irradiation solubility is gradually reduced but that the improved heat resistance depends on the dose being greater than a critical value. At this value the material has become cross-linked throughout its bulk. Further irradiation can, of course, add further cross-linkages but at the critical value there are sufficient linkages for every long chain molecule to be linked to every other and crystalline melting can no longer take place. Treated polythene can withstand high temperature without distortion

if there is no applied stress although it must be remembered that oxidation can still take place. A property of interest to the component designer is that treated material can withstand the application of a hot soldering iron and the use of such material in radio frequency plugs and sockets would appear obvious. Treatments are presently being given to a number of moulded items familiar to the radio engineer and it is hoped that these will find application under conditions where existing components have been found inadequate.

The application of the process is not, of course, confined to polythene and experiments are in progress on the setting of materials for the "potting" of components and the improvement of other polymers. One effect which was found almost accidentally is the treatment of gelatine. A "gel" which normally has a melting point of  $37^\circ\text{C}$  was found to remain unchanged at temperatures in excess of  $100^\circ\text{C}$ .

#### 5. Economic Assessment of the Process

Two types of linear accelerator have been used in the present work. The first was an 8 MeV equipment with an output of a little over 250 watts.<sup>14</sup> Later a machine producing a beam of 4 MeV electrons with a power output at design loading of 500 watts<sup>12, 15</sup> has been employed. In practice this equipment can produce an output of 800 watts at slightly reduced energy but in assessing the capabilities of the process the figure of 500 watts will be used.

On a basis of a 10 per cent. per annum capital depreciation and making allowance for replacements, power costs and operation and maintenance, it can be shown that for single shift working conditions the running cost of such a machine will be of the order of £2.5/hour.

Further, as has been stated in Section 3, such a machine assuming full utilization of the beam is capable of delivering a dose of  $10^8$  rad to 400 lb of material per hour. In many cases such a dose is adequate for sterilization and if material were treated in bulk, say on a conveyor belt passing in front of the machine, something approaching full utilization would be obtained. In this case the cost of sterilization would be of the order of 1½d/lb. In many cases, however, the shape of a final product would be such as to cause much of the beam power to be wasted and a utilization of, say, 25 per cent. is probably a reasonable estimate. It can be seen that even in this case cost is only 6d/lb and 100 lb can be

treated in an hour. In the case of materials such as drugs or sutures occupying a relatively small portion of a sealed ampoule, a better estimate of the economics of the process can be made by a study of the geometry of the sample to determine the rate at which they can be treated. The typical case of surgical sutures may be quoted. It has been estimated that, assuming a required dose of  $2 \times 10^5$  rad, tubes of sutures could be treated at the rate of 2,000/hour and at a cost of little more than 4d each.

Turning to the cost of irradiated plastics, it can be seen that the costs are higher since larger doses are needed. Treatment of polythene, for instance, requiring, say, a  $10^7$  rad dose and assuming 25 per cent. utilization, would cost about 5s per pound, that is, it would just about double the cost of the raw material.

On the estimates made above it can be seen that the application to the sterilization of expensive drugs and pharmaceutical products is economically attractive, the costs being small compared with original cost of the product. The application to low-priced foodstuffs would seem at present to be ruled out as being too expensive even if the technical difficulties concerned with change of taste are overcome. The treatment of plastics, although relatively expensive, is still of the same order as the cost of the raw material in certain cases and is probably attractive for specialized applications.

It should be noted that the costs quoted above could be considerably reduced by more intensive use of the equipment, for instance, by double shift working. At present the output of the linear accelerator is limited by the output of the radio frequency power source which is used. With valves at present in development, it is expected that powers an order of magnitude greater will become available. Further, some increase in efficiency can be made in the accelerator itself. Such improvements will only fractionally increase the cost of the equipment whilst the amount of material which can be treated will be increased by an appreciable factor. It can thus be confidently expected that during the next few years treatment costs will be reduced by a factor of between 5 and 10 times and the process would become applicable to a very much larger range of products.

## 6. Conclusion

It has been shown that the irradiation of materials leads to new processes in connection

both with sterilization and with the plastics industry. In the case of sterilization of drugs and foodstuffs it should be emphasized that although sterility can be guaranteed each case will have to be carefully examined to ensure that no unwanted effect takes place. By the employment of the linear accelerator as the irradiating source it has been shown that in many cases the processes could already be employed on economically attractive terms and that, with expected developments, application to a much wider field seems certain.

## 7. Acknowledgments

In the assessment of products treated with the linear accelerator the author has had the collaboration of a large number of organizations. It is impossible to give individual acknowledgement, but thanks are expressed collectively to all who have co-operated in this work. Contributions have also been made by the author's colleagues, G. Saxon and M. C. Crowley-Milling. The author also expresses thanks to Dr. Willis Jackson, F.R.S., M.I.E.E., Director of Research and Education, and to Mr. B. G. Churcher, M.Sc., M.I.E.E., Manager of the Research Department, Metropolitan-Vickers Electrical Co. Ltd., for permission to publish this paper.

## 8. References

1. F. Minck, *Münch. med. Wochschr.*, **5**, 1896, p. 101.
2. High Voltage Engineering Corporation. Bulletin D.
3. B. E. Proctor and J. P. O'Meara, *Ind. Eng. Chem.*, **43**, 1951, p. 718.
4. I. A. Meeker and R. E. Cross, *Science*, **114**, 1951, pp. 283-5.
5. A. Charlesby, *J. Poly. Sci.*, **11**, No. 6, 1953, p. 513.
6. A. C. Baskett and C. W. Miller, *Nature*, **174**, No. 4425, 1954, p. 364.
7. W. Wild, *Agric. and Food Chem.*, **2**, 1954, p. 224.
8. D. W. Fry and W. Walkinshaw, *Reports on Progress in Physics*, **12**, 1948-49.
9. D. W. Fry, *De Ingenieur*, **64**, 1952, p. 51.
10. C. W. Miller, *Nature*, **171**, 1953, p. 297.
11. C. F. Bareford and M. G. Kelliher, *Philips Tech. Rev.*, **15**, 1953, p. 1.
12. C. W. Miller and P. H. Flanders, *M-V Gazette*, **25**, 1953, p. 119.

13. P. H. Flanders and A. W. Haslett, *Science News*, 1954, No. 32, p. 33 (Penguin Books).
14. C. W. Miller, *Proc. Instn Elect. Engrs*, **101**, Part I, 1954, p. 207.
15. C. W. Miller, *J. Brit. I.R.E.*, **14**, August 1954, p. 361.
16. G. Saxon, *Proc. Phys. Soc.*, B, **67**, 1954, p. 705.
17. D. E. Lea, "Action of Radiation on Living Cells." (New York, Macmillan, 1947.)

### 9. Appendix 1: The Energy Loss of a Particle in Passing through Matter

This note is intended to show how the energy lost by a particle in passing through matter may be calculated and to justify the assumptions made in Section 4.1. The argument used is taken from Heitler ("The Quantum Theory of Radiation," O.U.P.) and we shall as a demonstration calculate the losses for water.

There are two processes by which a fast particle may lose energy:

- Energy may be transferred directly to an atom causing ionization or excitation, this being a process of inelastic collision.
- The particle may undergo deflection by the field of an atom and there will be a consequent emission of radiation ("Bremsstrahlung").

As a cause of energy loss the processes are additive and may be considered separately.

#### 9.1. Average Energy Loss by Inelastic Collisions

Heitler quotes the work of Bloch and gives a general expression which reduces in the two cases of non-relativistic, and extreme relativistic particles to the expressions given below.

$$-\left(\frac{dE}{dx}\right)_{\text{coll}} = NZ\phi_0\mu \frac{3}{4} \cdot \frac{\mu}{T} \left[ \log \frac{T}{IZ} + \frac{1}{2} \right] \quad \dots \dots \dots \text{N.R.}$$

$$-\left(\frac{dE}{dx}\right)_{\text{coll}} = NZ\phi_0\mu \frac{3}{4} \cdot \log \cdot \frac{E^3}{2\mu I^2 Z^2} \quad \dots \dots \dots \text{E.R.}$$

In these expressions

$Z$  is the atomic number of the absorbing material;

$N$  is the number of atoms/cm<sup>3</sup>;

$\phi_0$  is the cross-section for Thomson scattering;

$\mu$  is the rest energy of the electron;

$T$  is the kinetic energy of the electron;  
 $IZ$  is an average ionization energy of the atom, and

$I$  has been determined experimentally as 13.5 electron volts;

$E$  is total electron energy, i.e.  $E = \mu + T$ ;

$\frac{dE}{dx}$  gives energy loss per unit path length.

From the expressions given it can be seen that the energy loss decreases rapidly with increasing energy for small energies. At high energies there is, however, a very slow increase with energy. From the general relationship it can be shown that there is a minimum at energies of the order of  $mc^2$ . We shall confine our attention to the relativistic region.

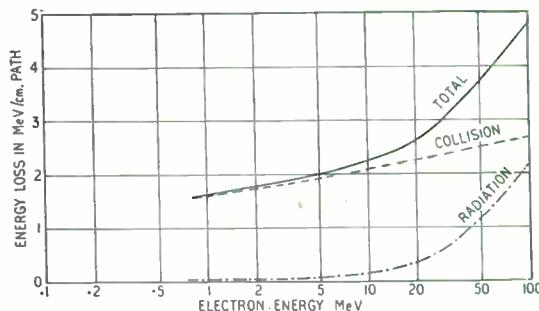


Fig. 2.—Theoretical values for electron loss in water.

For water, values of the various constants can be found to give

$$NZ\phi_0 = 0.22$$

and the relativistic expression then reduces to

$$\left(-\frac{dE}{dx}\right)_{\text{coll}} = 0.38 \log_{10}(7.15 \times 10^6 E^3)$$

Where  $E$  is measured in units of  $mc^2$  and  $x$  in cm. Several values have been computed and with the modification of energy unit are shown in Fig. 2.

#### 9.2. Average Energy Loss by Radiation

Heitler gives

$$\left(-\frac{dE}{dx}\right)_{\text{rad}} = NE\phi_{\text{rad}}$$

and shows that  $\phi_{\text{rad}}$  is given by the following

expressions for non-relativistic and extreme relativistic particles.

$$\phi_{\text{rad}} = \frac{16}{3} \bar{\phi} \dots \dots \dots \text{N.R.}$$

$$\phi_{\text{rad}} = 4 \left( \log \frac{2E}{\mu} - \frac{1}{3} \right) \bar{\phi} \dots \dots \text{E.R.}$$

where  $\bar{\phi} = Z^2 \times 5.71 \times 10^{-28} \text{ cm}^2 = \frac{Z^2 r_0^2}{137}$

$r_0$  being the classical electronic radius  $e^2/mc^2$ . Computation shows that in the non-relativistic region the radiation loss is small compared with the collision loss and so we are only interested in the relativistic expression which can be written

$$\left( -\frac{dE}{dx} \right)_{\text{rad}} = 4 \frac{NZ^2 r_0^2}{137} E \left( \log \frac{2E}{\mu} - \frac{1}{3} \right) \dots \dots \text{E.R.}$$

The value of  $\frac{NZ^2 r_0^2}{137}$  is given by Heitler for water as being  $1.27 \times 10^{-3}$ .

Several values have been computed and are plotted using energy units of MeV in Fig. 2.

### 9.3. Total Energy Loss and Particle Range

The total loss is given by the addition of that due to collision and that due to radiation and Fig. 2 shows this in the case of water.

The range of a particle of initial energy  $E_0$  is given by

$$R = \int_0^{E_0} \frac{dE}{\left( -\frac{dE}{dx} \right)_{\text{total}}}$$

In general this integration has to be performed numerically.

### 9.4. Justification of Assumptions used in the Paper

#### (1) That all energy is lost by collision

For an initial energy of 8 MeV integration of energy loss as given in the curves of Fig. 2 shows that only 2.3 per cent. of the energy is lost in radiation and this can be regarded as negligible.

Since, however, the radiation term depends on  $Z^2$  whilst the collision term varies with  $Z$  we expect the radiation loss to be more serious for heavy elements. In fact a rough calculation shows that an 8 MeV electron loses about 24 per

cent. of its energy by radiation when absorbed in gold.

Further, since the collision loss increases only logarithmically with energy whilst the radiation loss varies directly with energy in addition to a logarithmic term, it is obvious that even for water, radiation cannot be neglected at energies much over 10 MeV.

In our field of interest, however, that is, for energies less than 10 MeV and for the lighter elements, we see the assumption is justified.

#### (2) That energy is lost uniformly throughout the range of the electron

Figure 2 shows that energy loss varies only from 1.6 to 2.1 MeV/cm for energies from 1 to 10 MeV. Thus, taking an average value of 1.85, we see that the percentage variation is only  $\pm 13$  per cent. This is regarded as being sufficiently accurate.

There will be an increased loss at low energies, but the total amount of energy to be lost in that range is so small that we may neglect the effect.

#### (3) That range (measured in cm) is inversely proportional to density

We have justified the assumption that in the region of our interest radiation loss can be neglected and have taken the relativistic expression for  $\left( -\frac{dE}{dx} \right)_{\text{coll}}$  as representing the total loss of energy. Further, we have shown that this value remains constant to a first approximation over our range of energies. Now  $Z$  the atomic number, appears in the expression directly and in the denominator of the log term, we can neglect the effect of the latter term since over all practical values of  $Z$  it cannot make more than a few per cent. change.

We can then take

$$\frac{dE}{dx} \propto NZ$$

For most elements  $Z$  is very nearly equal to one-half of the atomic weight and in no case except hydrogen is the departure from this rule very great.

Thus, to a close approximation we can say that

$$\frac{dE}{dx} \propto NA$$

and obviously  $NA$  is the mass of 1 cm<sup>3</sup> of material in appropriate units, i.e. the density of the material ( $\rho$ ).

Thus,

$$\frac{dE}{dx} \propto \rho$$

But we have also shown that  $dE/dx$  is virtually constant throughout the range and therefore we can take

$$\text{Range } (R) = \frac{E_0}{\left(\frac{dE}{dx}\right)} \propto \frac{E_0}{\rho}$$

That is range (measured in cm) is inversely proportional to the density of the material.

A consequence of this relationship is that to a first approximation the energy absorbed by a specimen when irradiated with electrons expressed in ergs/gm will be independent of the density of the material.

In our experiments we have used in certain cases talc, and it is interesting to see what errors might be expected from our assumption.

Talc is stated to be  $H_2O \cdot 3MgO \cdot 4SiO_2$ , and from this we can derive a molecular weight of 378 and number of electrons per molecule as 190. Similar figures for water are 18 and 10 respectively.

Now collision loss depends on  $NZ$ , which in the case of compounds is to be taken as the total number of electrons per cubic centimetre, whilst density depends on  $N \times$  molecular weight. We thus see that energy lost per unit path in collisions in talc will differ from the figure calculated using the value obtained from water and assuming a straight dependence on density by a factor given by  $18/10 \times 190/378 = 0.9$ .

Thus our assumption has introduced an error of approximately 10 per cent. in this case and it should be noted that talc is a relatively bad case. Since, further, this error is in a direction to make our deductions conservative, it would appear justifiable to neglect it.

#### (4) Values for range

We have in the work with linear accelerators been interested in two values of initial energy, namely, 7.5 MeV and 4 MeV. The figures of range used for these energies were respectively 3.9 and 2.0 cm of water.

The values are based on an empirical formula given by Glendenin (*Nucleonics*, January 1948)

which states

$$R = 0.542E_0 - 0.133$$

where  $R$  is in gm/cm<sup>2</sup>. (This is, of course, numerically the same as range in cm for water.)  $E_0$  is in MeV and the formula is only valid for  $E_0 > 0.8$  MeV.

As a check we can obtain from Fig. 2 an average value of  $(dE/dx)$  for energies up to the relevant  $E_0$  and then  $E_0/(dE/dx)_{av}$  gives range. Values obtained in this manner agree with the formula within 4 per cent. for both values of  $E_0$ .

A further check can be obtained at 5 MeV since Heitler quotes 2.6 cm which is also within 4 per cent. of Glendenin's value.

### 10. Appendix 2: A Note on Some Radiation Units

Radiation measurements present many problems and although the quantities involved are always expressible in fundamental units it is natural that measurements should have been largely based on the more obvious manifestations of radiation. For instance, the measurement of the ionization caused by X-rays is much more attractive than a calorimetric measurement of the energy absorbed in some specimen and such forms of measurement lead to their own units. As may well be expected, certain units, devised for a specific purpose, have on the extension of energy and types of radiation been found inadequate and other related units have had to be introduced.

It is not intended to enter the discussion on the adequacy of existing units, nor are the notes given below intended to be rigid definitions. Not all of these units are used in the present paper, they have, however, been included since they are likely to be found in the papers quoted in the bibliography (Section 11).

#### 10.1. Units of Energy

The fundamental unit of energy in the c.g.s. system of units is the erg. In radiation measurements it is often convenient to have other units more closely related to the quantities under investigation. Such units are the electron volt (eV) and its multiple the mega electron volt (MeV). The electron volt can be defined as the energy attained by an electron, or particle with one electronic charge, when accelerated through 1 volt.

These units can easily be converted to the fundamental unit since 1 MeV is equivalent to  $1.6 \times 10^{-6}$  ergs. Energy is also expressed sometimes in units of  $mc^2$ , that is, in terms of the rest energy of an electron. Conversion can again be readily performed since  $mc^2$  is equivalent to 0.511 MeV or  $8.2 \times 10^{-5}$  ergs. It should be noted that these units of energy are used to express either the energy of a particle, say an electron or alternatively the energy of radiation, say X-rays, in which case it represents the energy of one quantum of the radiation. The energy ( $E$ ) of one quantum of radiation is related to the frequency ( $\nu$ ) expressed in cycles per sec by the relation  $E = h\nu$ , where  $h$  is Planck's constant and has a value of  $6.624 \times 10^{-27}$  erg. sec.

## 10.2. Dose Units or Units of Energy Absorption

The fundamental unit is ergs/gm, but a number of other units are in use as follows:—

### 10.2.1. The roentgen

The roentgen unit (r) is defined as "that quantity of X- or gamma-radiation such that the associated corpuscular emission per 0.001293 gm of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign."

0.001293 gm is the mass of 1 cm<sup>3</sup> of dry air at N.T.P. It should be noted that the roentgen is essentially a measure of quantity of ionization and is only related to the quantity of radiation under carefully defined conditions. It does not involve the quality (photon energy) or intensity (energy flow per unit time per unit area). Further, since the processes of ionization are a function of photon energy and absorbing material, the roentgen is, particularly for high energy radiation, a somewhat unsatisfactory unit. Nevertheless, since biological effects are closely allied with the ionization produced in tissue, the roentgen has found much use in biological investigations and of course it has been in use for a considerable time.

Equivalence between the roentgen and other units can be expressed as follows:—

$$\begin{aligned} 1 \text{ r} &= 1 \text{ E.S.U./cm}^3 \text{ of air at N.T.P.} \\ &= 2.083 \times 10^9 \text{ ion pairs/cm}^3 \text{ of air at N.T.P.} \\ &= 1.61 \times 10^{12} \text{ ion pairs/gm of air.} \\ &= 83.8 \text{ ergs/gm of air.} \end{aligned}$$

### 10.2.2. The roentgen equivalent physical (r.e.p.)

When ionization is produced in tissue by radiation other than photons (for example, electrons or neutrons) the doses may not be expressed in roentgens. Then if the energy lost by ionization in the tissues is the same as the energy loss for 1 roentgen of X- or gamma-radiation absorbed in air, the dose is defined by H. M. Parker as 1 roentgen equivalent physical. Thus, it can be seen that a dose of 1 r.e.p. is equivalent to an energy absorption of 83.8 erg/gm of tissue. Further, as we have shown in Appendix I that for electrons the energy absorbed per gram is to a first approximation independent of the nature of the material, we can loosely use the r.e.p. as meaning an energy absorption of 83.8 erg/gm of material. Since, however, when 1 roentgen of X- or gamma-radiation is absorbed in tissue (as opposed to air) the energy absorption is approximately 93 ergs/gm, it can be seen that a closer relationship between the units can be obtained if 1 r.e.p. is defined as an energy absorption of 93 ergs/gm. Recently, many papers have adopted this definition and care is required in interpreting results expressed in r.e.p. Some authors have avoided uncertainty by reference to r.e.p.<sub>83</sub> or r.e.p.<sub>93</sub>.

### 10.2.3. Roentgen equivalent man (r.e.m.)

Some types of radiation are more effective in causing biological effects than others, for the same energy absorption, and the relation is expressed by their relative biological effectiveness (R.B.E.). As an example, fast neutrons are considered about five times as effective as gamma-rays, i.e. their R.B.E. = 5. The r.e.m. is then "the estimated amount of energy absorbed in tissue which is biologically equivalent in man to 1 roentgen of gamma- or X-rays." From this definition

$$1 \text{ r.e.m.} = \frac{83.8}{\text{R.B.E.}} \text{ erg/gm of tissue.}$$

Thus for fast neutrons

$$\begin{aligned} 1 \text{ r.e.m.} &= \frac{83.8}{5} \text{ erg/gm of tissue} \\ &= 0.2 \text{ r.e.p.} \end{aligned}$$

### 10.2.4. The "energy unit"

This is not a unit of energy but of energy absorption which like the r.e.p. may be used for any type of ionizing radiation, and a dose of 1 energy unit is said to have been given when the

energy absorbed per unit mass of tissue is the same as would be absorbed per unit mass of water exposed to 1 roentgen of gamma-rays. It thus follows that 1 energy unit is approximately 93 erg/gm of tissue.

#### 10.2.5. The "n" unit

This is a unit which was originally used for fast neutrons which were measured by the ionization caused in a normal ionization chamber.

Thus 1 n unit of fast neutrons produces the same ionization in the Victoreen 100-r thimble chamber as would 1 r of gamma-rays. It is now known that the ionization produced in tissue is some 2 to 2.5 times the ionization in the chamber and therefore,

$$1 \text{ n} = 2 \text{ to } 2.5 \text{ r.e.p.} = 190 \text{ ergs per gm of tissue.}$$

#### 10.2.6. The rad

Since January 1954 a new internationally-agreed unit has taken the place of the units defined above as a measure of absorbed dose and it is defined as 100 ergs/gm. It should be noted that the roentgen remains the unit of X- and gamma-dose, although some difficulties in measurement are noted at high energy.

#### 10.3. Dose Rate

Dose rate can be specified in terms of the time derivative of any of the units of dose, for instance rad/min, etc. The fundamental unit is erg/gm/sec.

#### 10.4. Intensity

The unit of r/min is often loosely used as an expression of X-ray intensity; this is incorrect since it only specifies ionization intensity and that in a specified material (dry air) under definite conditions. True X-ray intensity can be specified only in fundamental units since it is the rate of flow of energy. The appropriate unit is the erg/cm<sup>2</sup>/sec. This unit can of course be applied to irradiation by electrons, etc., and since 10<sup>7</sup> erg/sec is equal to 1 W, the W/cm<sup>2</sup> is a very convenient alternative unit.

#### 10.5. Activity

Under this heading we consider what is effectively the strength of the source of the radiation. No matter what the type of source its strength may be expressed fundamentally in erg/sec or watts and further qualified, if radiation is emitted directly, by a statement of the directional characteristics.

In practice the performance of X-ray equipment is often specified in terms of the roentgen/min at some specified distance in some specified direction. Radioactive sources have their own units, for instance the curie is defined as the quantity of radon (0.66 mm<sup>3</sup> at 0°C and 760 mm) in radioactive equilibrium with 1 gm of radium.

The definition was extended in 1930 to include the equilibrium of any decay product of radium, especially polonium. Thus "1 curie Po" is  $2.24 \times 10^{-4}$  gm of Po, or the amount which has the same rate of emission of alpha particles as 1 gm of radium.

The number of atoms in 1 gm of radium disintegrating per sec is  $3.7 \times 10^{10}$ , and this leads to the use of the curie as that amount of any radioactive substance which has  $3.7 \times 10^{10}$  atoms disintegrate per sec. The energy associated with disintegration varies from one substance to another and the curie is not in any sense a measure of power or energy.

Much of the information in this Appendix has been taken from R. D. Evans (*Nucleonics*, October 1947) and W. V. Mayneord ("Some Applications of Nuclear Physics to Medicine"—*Brit. J. Radiol.*, Supplement No. 2) and for further information reference should be made to these papers. A glossary of terms used in biophysics and radiobiology is to be found in *Nucleonics*, April 1950.

### 11. Appendix 3: Bibliography

There is already a very extensive literature concerned with the biological effect of radiation and a rapidly growing one dealing with the irradiation of plastics. Many of the papers deal with specific actions in some detail. The bibliography given below illustrates the extent of the field covered.

#### 11.1. Papers concerned chiefly with sterilization or biological effects

1. B. E. Proctor and D. S. Bhatia, "Effect of high voltage cathode rays on amino acids in fish muscle." *Food Technology*, 4, September 1950, p. 357.
2. B. E. Proctor, J. T. R. Nickerson and S. A. Goldblith, "Storage of haddock." *Refrigerating Engng.*, 58, April 1950, p. 375.
3. J. T. R. Nickerson, S. A. Goldblith and B. E. Proctor, "A comparison of chemical changes in mackerel tissues treated by ionizing radiations." *Food Technology*, 4, March 1950, p. 84.

4. S. A. Goldblith, B. E. Proctor, *et al.*, "Effect of cathode rays produced at 3,000 kilovolts on niacin tagged with C<sup>14</sup>." *J. Biol. Chem.*, **179**, 1949, p. 1163.
5. S. A. Goldblith, B. E. Proctor, "Effect of high voltage X-rays and cathode rays on vitamins (riboflavin and carotene)." *Nucleonics*, **5**, February 1949, p. 50.
6. B. E. Proctor and S. A. Goldblith, "Effect of soft X-rays on vitamins (niacin, riboflavin and ascorbic acid)." *Nucleonics*, **5**, March 1949, p. 56.
7. B. E. Proctor and S. A. Goldblith, "Effect of supervoltage cathode rays on the non-enzymatic browning reaction of dried fruits and chemical compounds pertaining thereto." *Science*, **109**, 1949, p. 519.
8. K. G. Stern, A. Brasch and W. Huber, Abstracts of 115th Meeting of American Chemical Society, 1949.
9. U. Friedman, F. B. Traub and W. Huber, "High-intensity electrons as a tool for preparation of vaccines: 1, Preparation of rabies vaccine." *Fed. Proc.*, **9**, 1950, p. 382.
10. W. Huber, *et al.*, "Action of High Energy Electrons on Bacteria, Viruses and Desoxy-pentose Nucleic Acid." 7th Internat. Cong. of Cell Biology, 1950.
11. W. Huber, F. B. Traub, U. Friedman and A. Brasch, "Action of Ionizing Radiation on Biological Systems," p. 36c. 118th Meeting of Amer. Chem. Soc., 1950.
12. W. Huber, A. Brasch and A. Astrack, "Effect of Ionizing Radiation on Ascorbic Acid and Other Vitamins," p. 40c. 117th Meeting of Amer. Chem. Soc., 1950.
13. A. J. Ede, "The electronic sterilization of foods." *Food Sci. Abstr.*, **22**, 1950, p. 73.
14. E. J. Lawton, "Effect of cathode rays on various materials." *Science*, **112**, 1950, p. 420. (Abstract of a paper presented at Meeting of Nat. Acad. Sci.)
15. C. Dieckmann, W. Dittrich, H. Reich and G. Schubert, "Killing of *B. coli* by fast moving electrons from 6-MeV betatron." *Naturwissenschaften*, **37**, 1950, p. 140.
16. B. E. Proctor, S. A. Goldblith and H. Fram, "Effect of supervoltage cathode rays on bacterial flora of spices and other dry food products." *Food Res.*, **15**, 1950, p. 490.
17. B. S. Bhatia and B. E. Proctor, "Effects of high voltage cathode rays on aqueous solutions of histidine monohydrochloride." *Biochem. J.*, **49**, 1951, p. 550.
18. B. E. Proctor and S. A. Goldblith, "Electromagnetic radiation fundamentals and their applications in food technology." *Advances in Food Res.*, **3**, 1951, p. 119.
19. "The Effect of Supervoltage Cathode Rays on Para-aminobenzoic Acid and Anthranilic Acid Labelled with C<sup>14</sup>." Abstracts of the Boston Meeting of the Amer. Chem. Soc., April 1951.
20. W. Huber, "Results and analysis of various methods of irradiation of biological systems." *Naturwissenschaften*, **38**, 1951, p. 21.
21. G. W. A. Dick, C. E. Schwerdt, W. Huber, G. R. Sharples and H. A. Howe, "Immunization of cotton rats with inactivated poliomyelitis virus: II, Inactivation by physical methods." *Amer. J. Hyg.*, **53**, 1951, p. 131.
22. E. J. Lawton, M. P. Bryant, W. D. Bellamy, R. E. Hungate and E. Hall, "Some effects of high velocity electrons on wood." *Science*, **113**, 1951, p. 380.
23. E. L. Gaden, E. J. Henley and V. P. Collins, "Preservation of milk by radiations." *Food Technol.*, **5**, May 1951. (Abstract of paper presented at Institute of Food Technologists' Congress.)
24. Amer. Chem. Soc., "Death rays for bacteria." *Industr. & Engng Chem.*, **43**, March 1951, p. 17-A.
25. "Death ray kills insects." *Sci. News Letter*, March 25th, 1950.
26. "Sterilization by electronic bombardment." *The Canner*, September 16th, 1950.
27. "Electronic sterilization seen changing packaging of drugs." *Drug Tr. News*, February 5th, 1951, p. 36
28. E. S. G. Barron, "The effect of ionizing radiation on the activity of enzymes." Brookhaven Conf. Rep., "Biological Application of Nuclear Physics," 1948, pp. 10-16.
29. A. Brasch and W. Huber, "Ultrashort application time of penetrating electrons, a tool for sterilization and preserving of food in the raw state." *Science*, **105**, January 31st, 1947, pp. 112-117.
30. A. Brasch and W. Huber, "Reduction of undesirable by-effects in products treated by radiation." *Science*, **108**, November 12th, 1948, pp. 536-537.
31. W. M. Dale, "Effect of X-rays on aqueous solutions of biologically active compounds." *Brit. J. Radiol.*, **16**, 1943, pp. 338-339.
32. C. G. Dunn, W. L. Campbell, H. Fram and A. Hutchins, "Biological and photo-chemical effects of high energy, electrostatically produced roentgen rays and cathode rays." *J. Appl. Phys.*, **19**, July 1948, pp. 605-616.
33. E. Ephrati, "The mechanism of the effect of X-rays on bacterial toxins." *J. Biochem.*, **42**, 1948, pp. 383-389.
34. H. Fram, B. E. Proctor and C. G. Dunn, "Effects of X-rays produced at 50 kilovolts on different species of bacteria." *J. Bacteriol.*, **60**, September 1950, pp. 273-277.
35. W. Huber, F. B. Traub, U. Friedman and A. Brasch, "Action of Ionizing Radiation on Biological Systems: Effect of High Energy Electron Bursts on Antibodies." Paper of Amer. Chem. Soc., September 6th, 1950.
36. J. Loiseleur, R. Lataret and T. Caillot, "The radio-biological importance of the activation of oxygen." *C. R. Acad. Sci., Paris*, **213**, 1941, pp. 730-732.
37. D. Mazia, "Effects of radiation of enzyme systems." Brookhaven Conf. Rep., "Biological Applications of Modern Physics," 1948, pp. 7-9.
38. R. J. Norris, "Increased bactericidal effect of inorganic compounds in the presence of X-rays." *Bull. Basic Sci. Res.*, **3**, 1931, pp. 21-36.

39. G. F. Pfalz, "The immuno-biologic meaning of weak roentgen ray irradiation on the bactericidal power of the blood." *Archiv für Gynaekologie*, 138, 1929, pp. 93-110.
40. K. G. Stern, A. Brasch and W. Huber, "Effect of High-Intensity Electron Bursts of Ultrashort Duration on Serum Albumin and Desoxy-ribonucleic." Paper of Amer. Chem. Soc., March 29th, 1949.
41. J. G. Trump and R. J. Van der Graaff, "Irradiation of biological materials by high energy Roentgen rays and cathode rays." *J. Appl. Phys.*, 19, July 1948, pp. 599-604.
42. "The Industrial Use of Fission Products." Project 361, Stanford Research Institute.
43. L. H. Gray, "Actions of radiations on living cells: 1946 and after." *Brit. J. Radiology*, 25, No. 293, 1952, p. 235.
44. L. H. Gray, "The initiation and development of cellular damage by ionizing radiations." *Brit. J. Radiology*, 26, No. 312, 1953, p. 609.
45. R. S. Hannan, "Electronic sterilization." *Proc. Soc. Appl. Bacteriology*, 16, No. 1, 1953, p. 88.
46. A. Brasch and W. Huber, "Reduction of undesirable by-effects in products treated by radiation." *Science*, 108, 1948, p. 536.
47. R. S. Hannan, "Electronic sterilization of foods." *Research*, 49, 1953, p. 326.
48. R. S. Hannan and J. W. Boag, "Effects of electronic irradiation on fats." *Nature*, 169, 1952, p. 152.
49. R. S. Hannan, "The preservation of food with ionizing radiations." *Food Sci. Abstracts*, 26, No. 2, 1954, p. 121.
50. R. S. Hannan and H. J. Shepherd, "Some after-effects in fats irradiated with high energy electrons and X-rays." *Brit. J. Radiology*, 27, No. 313, 1954, p. 36.
- 11.2. *Papers concerned chiefly with the effects of irradiation on plastics, etc.*
1. K. Little, "Irradiation of linear high polymers." *Nature*, 170, 1952, p. 1075.
  2. A. Charlesby, "Effect of high-energy radiation on long-chain polymers." *Nature*, 171, 1953, p. 167.
  3. A. Charlesby and M. Ross, "Breakdown of methyl methacrylate polymer by high-energy radiation." *Nature*, 171, 1953, p. 1153.
  4. A. Charlesby, "The effect of high-energy radiation on some long-chain polymers." *Plastics*, 18, No. 190, 1953, p. 142.
  5. A. Charlesby, "Solubility and molecular size distribution of cross-linked polystyrene." *J. Polymer Sci.*, 11, No. 6, 1953, p. 513.
  6. A. Charlesby, "Swelling properties of polystyrene cross-linked by high-energy radiation." *J. Polymer Sci.*, 11, No. 6, 1953, p. 521.
  7. A. Charlesby, "The cross-linking of rubber by pile radiation." *Atoms*, 5, No. 1, 1954, p. 12.
  8. J. W. Ryan, "Effect of pile radiation on electrical insulation." *Modern Plastics*, 31, No. 8, 1954, p. 148.

In addition to the above papers there is a growing number of patent specifications, chiefly American, dealing with the practical exploitation of the process.

## DISCUSSION

In reply to questions by Mr. E. N. Shaw on the reliability of linear accelerators, Mr. Miller stated that there were not enough equipments in operation to give satisfactory statistics. He continued:

"Nevertheless, remarkably little trouble has been experienced and I would refer Mr. Shaw to the discussion on an 8-MeV equipment<sup>14</sup> in which the user gives a statement on the first year's operation. It might have been expected that the magnetron would have been the most vulnerable component and since it is the most expensive valve in the equipment, it was at one time thought that this would largely determine the maintenance costs. In fact the magnetrons have had surprisingly good lives and after 18 months the equipment at Hammersmith Hospital is still using the original valves."

"The life of ignitrons as modulator switches has proved to be short and at present this causes the major replacement charge. It is expected that the

eventual replacement of ignitrons by hydrogen thyratrons will remove this difficulty. Other electronic failures have been few and minor in character usually involving the replacement of a small valve at a rate consistent with experience of other electronic equipment. The vacuum arrangements are extremely reliable and, as would be expected from experience with other continuously evacuated equipment, will require very little maintenance. The general reliability of the equipment is perhaps illustrated by the fact that in my laboratory which is below the drainage level, more trouble has been experienced in a simple pumping system for the removal of the waste water than has been caused by the accelerator equipment itself."

"As regards effects of the beam on the output window, we have used a copper beryllium window 5/1000 in. thick over a period of 12 months and have noticed no ill effects."



