JOURNAL OF

The British Institution of Radio Engineers

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

Vol. 16 No. 8 AUGUST, 1956

NOTICE OF THE THIRTY-FIRST ANNUAL GENERAL MEETING

NOTICE IS HEREBY GIVEN that the THIRTY-FIRST ANNUAL GENERAL MEETING (the twenty-third since Incorporation) of the Institution will be held on WEDNESDAY, OCTOBER 31st, 1956, at 6 p.m., at the London School of Hygiene and Tropical Medicine, Keppel Street, Gower Street, London, W.C.1.

AGENDA

1. **To confirm the Minutes of the 30th Annual General Meeting held on October 26th, 1955.** (Reported on pages 533-36 of Volume 15 of *Journal* dated November 1955.)
2. **To receive the Annual Report of the General Council.** (To be published in September 1956 *Journal.*)
3. **To elect the President.**
   The Council is unanimous in recommending the election of George A. Marriott, B.A.(CANTAB.), as President of the Institution for the year 1956-57.
4. **To elect the Vice-Presidents of the Institution.**
   The Council unanimously recommends:
   The re-election of Leslie H. Paddle, John L. Thompson and Professor E. E. Zepler, PH.D.
   The election of Professor Emrys Williams, PH.D., B.ENG.
5. **To elect the Ordinary Members of the General Council.**
   The retiring members of the Council are:
   D. R. Chick, M.SC. (*Member*).
   F. G. Diver, M.B.E. (*Member*).
   H. J. Leak (*Member*).
   F. T. Lett (*Associate Member*).
   Captain A. J. B. Naish, R.N., M.A. (*Member*).
   E. W. Pulsford, B.SC. (*Associate Member*).
   In addition Professor E. Williams, PH.D., B.ENG. (*Member*) retires on being nominated for election as a Vice-President.
   Consequently, under Article 29, vacancies arise for ordinary members of Council as follows:—
   A maximum of five members, and two Associate Members.
   In accordance with Article 32, the Council nominates:—
   (*a*) Members for re-election: F. G. Diver, M.B.E.; H. J. Leak; Captain A. J. B. Naish, R.N., M.A.
   (*b*) Members for election: A. D. Booth, D.SC., PH.D.; E. M. Eldred.
   (*c*) Associate Member for re-election: E. W. Pulsford, B.SC.
   (*d*) Associate Member for election: R. H. Garner, B.SC. (ENG.).
   Any member who wishes to nominate a member or members for election must deliver such nomination in writing to the Secretary, together with the written consent of such person or persons to accept office if elected, not later than September 21st, 1956. Such nomination must be supported by not less than 10 corporate members.
6. **To elect the Honorary Treasurer.**
   The Council unanimously recommends the re-election of G. A. Taylor (*Member*).
7. **To receive the Auditors' Report, Accounts and Balance Sheets for the year ended March 31st, 1956.**
   The Accounts for the General and other Funds of the Institution will be published in the September *Journal*.
8. **To appoint Auditors.**
   Council recommends the reappointment of Gladstone, Jenkins & Co., 42 Bedford Avenue, London, W.C.1.
9. **To appoint Solicitors.**
   Council recommends the reappointment of Braund & Hill, of 6 Grays Inn Square, London, W.C.1.
10. **Awards to Premium and Prize Winners.**
11. **Any other business.** (*Notice of any other business must reach the Secretary 40 days before the meeting.*)

(*Members unable to attend the Annual General Meeting are urged to appoint a proxy.*)

THE ELECTRIC FIELD OF A DIELECTRIC HEATING WORK CIRCUIT *

by

N. H. Langton, Ph.D. (Associate Member)† and E. E. Gunn, A.N.C.R.T.†

SUMMARY

The electric field of the simplest type of work circuit of a dielectric heater is considered, in which the lower capacitor plate is larger than the upper. For a given frequency, the rate of heating at any point is proportional to the square of the electrical intensity at that point. It is desirable to know the extent of the fringing effect and the relation between size of specimen and size of capacitor plate for uniform heating. The paper describes the theoretical investigation of this type of field, and some experiments on field plotting using an electrolytic analogue.

1. Introductiou

In this paper the electric field of the simplest type of dielectric heater is considered. The high frequency electric field is produced between the plates of a plane parallel plate capacitor, the lower plate being larger than the upper. This type of heater is used for heating rectangular prisms of rubber or plastic material.

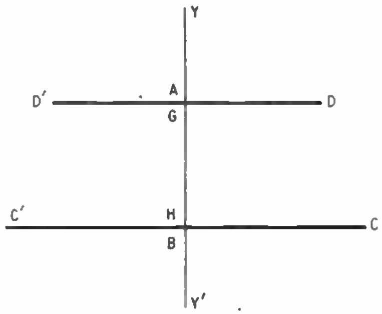

Fig. 1.—The capacitor system.

The plates will be assumed square or rectangular in plan, and Fig. 1 shows a vertical section through the capacitor, the plane of section being parallel to the edges of the plates. The trace of the upper plate is D′AD, A being the mid point, and that of the lower plate being C′BC, the midpoints A and B being vertically opposite each other. In the apparatus available to the writers, CC′ was 11 in. (27·9 cm) and DD′ was 6·5 in. (16·5 cm). Since the plates extend a reasonable distance above and below the plane of the paper in Fig. 1, we can treat the field as being two-dimensional.

The power dissipated in a specimen placed between the plates is given by the expression,

$$P = 1{\cdot}41.R^2.\omega.k.\cos\theta.10^{-12}\ \text{watts/in.}^3 \quad \ldots(1)$$

where the units are volts and inches, these being usual in practice. R is the electrical intensity (field strength), ω is the pulsatance ($=2\pi \times$ frequency), k is the dielectric constant of the material being heated, and $\cos\theta$ is its power factor. For a given frequency, therefore, the rate of heating at any point is proportional to the square of the electrical intensity at that point. Hence the heating of the specimen will only be uniform if the electric field in the region occupied by the specimen is uniform. Although the electric field between the plates of a parallel plate capacitor is uniform in the central region, as we approach the edges of the capacitor we get the well-known "fringing" effect where the lines of force between the plates start to bulge outwards. If the dimensions of the specimen are such that its edges lie too close to the edges of the capacitor plates, the outer regions of the specimens will lie in the fringing field where R is non-uniform and decreasing. Thus the outer portions of the specimen will be heated to a

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lesser extent than the central portion. Since rubber and plastics are poor thermal conductors, and the dielectric heating is completed in a fairly short period of time, there will be little equalization of temperature due to thermal conduction. Thus if the heating is such that the main body of the specimen is cured, the outer portions will be undercured. For this reason it would be useful to know the extent of the fringing effect, and the relation between the size of specimen and size of capacitor plate, to ensure fairly uniform heating throughout the whole of the specimen. The maximum length of specimen for uniform heating will also depend upon the height of the specimen, that is, upon the vertical distance apart of the capacitor plates.

The object of this paper is to describe the theoretical investigation of this type of electric field, and also some experiments on field plotting which can be used if less accurate results are sufficient. The theory described here assumes that the dielectric between the plates is uniform and isotropic and that it extends to infinity in all directions. The case of a capacitor with a slab of dielectric material between the plates is too difficult to attempt. This limitation is not serious, however, because the introduction of a parallel sided slab of dielectric would have little effect upon the main field. Most of the field distortion would take place at the ends if they happen to be in a non-uniform field, and this is what we are trying to avoid in any case. Also we are not interested, from the practical point of view, in a high degree of accuracy.

2. Theoretical

To investigate the two-dimensional electric field of Fig. 1, we use the method of conformal transformations, which is valid as long as the dimensions of the capacitor are small compared to the wavelength of the high frequency oscillations used. The capacitor shown in Fig. 1 is therefore assumed to be drawn in the complex z-plane, where $z=x+j.y$. Since the field is symmetrical about BA, we need only consider the region to the right of YADGHCBY′ which is shown in Fig. 2, where YA, GH and BY′ are lines of force, and ADG, HCB are equipotentials. The system has been rotated through $\pi/2$ for mathematical convenience. The method of solution entails obtaining a geometrical and then an electrical transformation. The required geometrical transformation has been given by Love,* and the electrical case was completed by Langton.† It was shown by Langton that the electrical intensity R at any point between the plates is given by the expression

$$R=\frac{2\pi e_0}{A}\left|\frac{(t+v)^2}{K'(t-c_1)(t-c_2)}\right| \quad \text{.......(2)}$$

where e_0 = the charge density on either plate, $t=\text{sn}\, w$ where w is the complex electrical potential, K' = the elliptic integral of the second kind, and v, c_1 and c_2 are constants whose values can be determined from the geometry of the system. The position at which we find any particular value of R for a given value of t is given by the equation,

$$z=\frac{2hK'}{\pi}\left\{\zeta(w)+\frac{\pi w}{2KK'}+\frac{\text{cn}\, w.\text{dn}\, w}{\text{sn}\, w+v}\right\} \quad \text{.......(3)}$$

where $\zeta(w)$ is the Jacobian zeta function, and sn w, cn w, dn w are the Jacobian elliptic functions as usual.

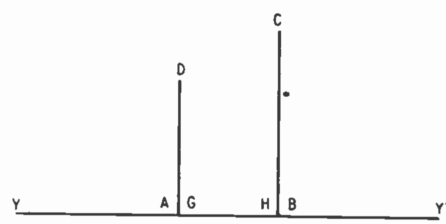


Fig. 2.—The Z-plane polygon.

It can be seen that these expressions are rather complicated, and it would be very difficult, though not impossible, to obtain numerical values for R at known positions between the capacitor plates. In this particular problem, however, we are interested mainly in the field near the edges of the capacitor plates, rather than the whole field. For this reason we can simplify the problem without flattering the conditions too much. The first simplification is to imagine that the lower plate HC extends to infinity, so that the point C becomes the point at infinity in the z-plane. This is not

* A. E. Love, "Some electrostatic distributions in two dimensions," *Proc. Lond. Math. Soc.* (Series 2), **22**, pp. 337-369, 1923.

† N. H. Langton, Unpublished work.

a good simplification from our point of view, but is of interest in that it leads to the accurate expression for the field of a parallel plate capacitor with equal plates, as shown by Love.*

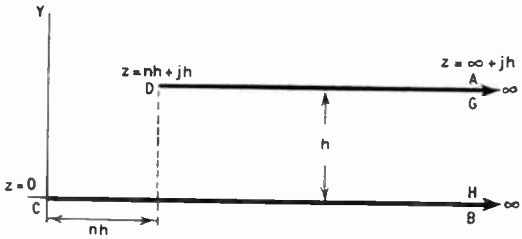


Fig. 3.—The simplified capacitor system in the Z-plane.

A better and more convenient simplification arises from the fact that, in the central region of the capacitor system, the equipotentials are all horizontal straight lines cutting the central line of force GH at right angles. If we imagine the points AG and HB to move to the point at infinity on the left of the axis of symmetry in Fig. 1 so that the capacitor plates become semi-infinite, the field near the ends D and C will not be altered very much. The capacitor system we shall investigate is therefore the one shown in Fig. 3, and consists of two unequal plates DA and CB, the points AG and BH being at infinity. We shall take C to be the z-origin, and h to be the vertical distance between the two plates. The point D is given the co-ordinates $(nh+\mathrm{j}h)$, where n is a constant for any particular solution, so that the amount of overlap of the lower plate beyond the top plate can be adjusted by varying the value of n. To obtain the geometrical transformation we require, from the Schwarz-Christoffel equation, a transformation which

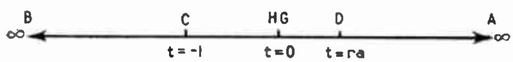


Fig. 4.—The T-plane.

will set up a one-to-one correspondence between the z-plane and an intermediate complex t-plane, so that the polygon BCHGDA becomes the real axis of the t-plane and the area external to the polygon becomes the upper half of this t-plane. At C and D the angles of the polygon are 2π, and at the corner GH the angle is zero.

The values of t at the corners are as shown in Fig. 4, which is the t-plane. Hence we obtain as the required transformation,

$$\mathrm{d}z/\mathrm{d}t = A.(t-a)(t+1)/t \qquad \ldots\ldots\ldots(4)$$

where A is a constant.

On integration this gives

$$z/A = t^2/2 + t(1-a) - a.\log t + B \qquad \ldots\ldots(5)$$

where B is the constant of integration.

At the corner D, $t=+a$ and $z=h(n+j)$. Substitution in eq. (5) leads to

$$B = \{h(n+\mathrm{j})/A\} - a + a^2/2 + a\log a \qquad \ldots\ldots(6)$$

giving B in terms of A.

At the corner C, $t=-1$ and $z=0$, hence we obtain

$$B = \tfrac{1}{2} - a + \mathrm{j}a\pi \qquad \ldots\ldots\ldots(7)$$

From eqs. (6) and 7), by eliminating B we obtain

$$A = \frac{h(\mathrm{j}+n)}{+\frac{1}{2} - a\log(a) - a^2/2 + \pi\mathrm{j}a} \qquad \ldots\ldots\ldots(8)$$

There is another method for obtaining a value for the constant A which leads to an interesting result when combined with eq. (8). Let $t=R.\exp\mathrm{j}\theta$, so that $\mathrm{d}t = R\mathrm{j}\exp.\mathrm{j}\theta.\mathrm{d}\theta$. Hence, from eq. (4),

$$\mathrm{d}z = A\mathrm{j}(R\exp\mathrm{j}\theta+1)(R\exp\mathrm{j}\theta - a).\mathrm{d}\theta \ \ldots(9)$$

If R approaches zero and $\mathrm{d}\theta$ becomes π, we are moving round the origin of the t-plane along the perimeter of a semi-circle whose radius is infinitely small. Crossing the t-plane origin from left to right corresponds to moving from H to G in the z-plane so that the corresponding change in z is $-\mathrm{j}h$. Therefore eq. (9) becomes

$$-\mathrm{j}h = \underset{R\to 0}{\mathrm{Lt}}\,(Re^{\mathrm{j}\theta}+1)(Re^{\mathrm{j}\theta}-a).A\mathrm{j}.\pi$$

Hence

$$-\mathrm{j}h = \mathrm{j}A.1 - a.\pi$$

so that

$$A = \frac{h}{a\pi} \qquad \ldots\ldots\ldots(10)$$

Equating this value of A with that given by eq. (8) gives the equation connecting a and n, which is,

$$a\log a + na\,\pi + \tfrac{1}{2}a^2 = \tfrac{1}{2} \qquad \ldots\ldots\ldots(11)$$

Substituting A in eq. (6) gives,

$$B = \tfrac{1}{2} - a(1-\mathrm{j}\pi) \qquad \ldots\ldots\ldots(12)$$

which is correct and checks the algebra.

Thus the completed equation for z in terms of t is

$$z=(h/a\pi).(t^2/2-at+t-a\log t+B) \quad \ldots(13)$$

the value of B being given by eq. (12).

Eq. (13) gives z in terms of a and n as well as t. The quantities a and n are constants for any one capacitor system, and depend only upon the geometry of the system. They are related by eq. (11). The value of n is given by the relative sizes of the two capacitor plates, and n may be of either sign depending upon which of the two plates is the larger. If the top plate is smaller, then n is positive, but if the top plate overlaps the lower, then n is negative. If $a=1$, then eq. (11) shows that $n=0$, and this corresponds to the case when both plates are of equal length. For such equal plates we obtain $A=h/\pi$, $B=\mathrm{j}\pi-\frac{1}{2}$ and

$$z=(h/\pi).(t^2/2-\log t-\tfrac{1}{2}+\mathrm{j}\pi) \quad \ldots\ldots(14)$$

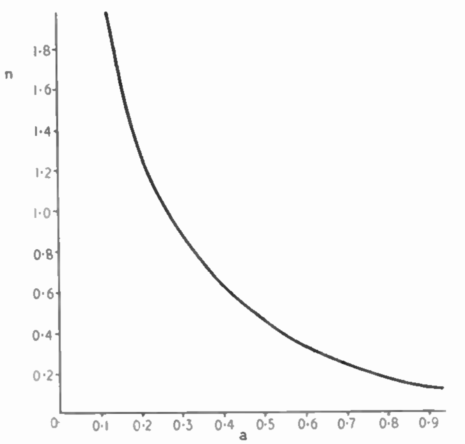


Fig. 5.—Graph of $na\pi=\frac{1}{2}-\frac{a^2}{2}-a\log a$.

That this is the correct transformation for two equal parallel plates can be seen by obtaining the transformation equation from first principles. Once a value of n has been chosen, and the corresponding value of "a" derived, values of z for corresponding values of t can be calculated from eq. (14). The relationship between a and n is shown graphically in Fig. 5.

Eq. (14) transforms the z-plane diagram so that the capacitor plates become the whole of the real t-axis and the rest of the z-plane, which contains the field we are investigating, corresponds to the upper portion of the t-plane. We now have to set up the required potential conditions, and this is done, as usual, by introducing a third plane which represents a complex potential. This is the W-plane, where $W=U+\mathrm{j}.V$ and U and V are generally the stream function and the potential function respectively. This plane must be linked by a one-to-one correspondence with the intermediate t plane so that the portions of the real t-axis are given the potentials required by the problem, and the upper half of the t-plane is made to correspond to the electric field between the capacitor plates. Since the transformations used are conformal, the field pattern in the z-plane, which will be some orthogonal grid of equipotentials and lines of force, will have transformed via eq. (13) into an orthogonal pattern in the upper half of the t-plane. When the electrical conditions are set up, the t-plane will represent the electric field between two differently charged plates in the same plane, separated by an infinitesimal gap at the t-origin HG. The equipotentials will obviously be radial lines through the point HG, and the equipotentials will be a series of concentric circles having a common centre at the t-origin. The electrical transformation must link this orthogonal system with the W-plane so that the radial lines are given their required potential values, the stream function values will then follow automatically.

3. The Electrical Transformation

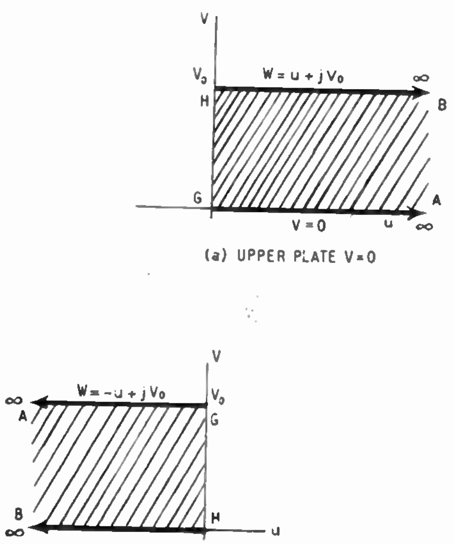
We imagine one of the capacitor plates to be at zero potential, and the other to have a potential of $+V_0$. The W-plane will then consist of two semi-infinite straight lines parallel to the horizontal axis. There are two possible transformations, depending upon which of the two capacitor plates is to have zero potential. The field diagram we will obtain will, of course, be the same in either case. These two electrical planes are shown in Fig. 6a and Fig. 6b. In both cases, the line HB or AG has the equation $W=\pm U+\mathrm{j}V_0$ and represents a potential value of $+V_0$ units, whilst the real axis has an equation $W=\pm U$ and so corresponds to a zero equipotential. The corners of the electrical plane diagram are lettered the same way as the t-plane shown in Fig. 4, and it will be seen that in both Figs. 6a and b the internal area of the rectangle, shown shaded, corresponds to the upper half of the t-plane as we traverse the perimeters in the same sense. We require to transform either W-plane rectangle so that the sides BH and AG become linked by a one-to-one correspondence with the two halves of the t-plane, and the line GH becomes the infinitesimal line of force between the two conductors at the point of infinity in the z-plane.

The required transformation in both cases is obtained from the Schwarz-Christoffel equation. The interior corner angles at G and H are both $\pi/2$, whilst the other corner is at infinity. Thus we obtain

$$dW = A(t-0)^{-\frac{1}{2}} \,.\, (t-0)^{-\frac{1}{2}} \,.\, dt \quad ......(15)$$

$$\text{or} \quad W = A \log t + B \quad ......(16)$$

where A and B are constants to be found.



(a) UPPER PLATE V=0

(b) UPPER PLATE V=0

Fig. 6.—The W-plane.

Consider Fig. 6a, which is the diagram to use when we wish to make the upper plate have zero potential. To find the value of the constant A in this case, let $t = r.\exp.\, j\theta$, so that $dt = rj.\exp\, j\theta.d\theta$, then,

$$dW = A.j.d\theta$$

from eq. (15). Suppose we move across the real t-axis origin from left to right, passing round the discontinuity at $t = 0$ along the perimeter of a semi-circle of infinitely small radius. Then $d\theta = \pi$, and $dW = +jV_0$ because this corresponds to moving from the lower plate to the upper plate of the capacitor system. Hence we have

$$j.V_0 = A.j\pi$$

$$\text{so that} \quad A = V_0/\pi \quad ....(17)$$

We can apply the same argument to Fig. 5b, the only difference being that in this case as we pass the t-origin we are moving from the plate at zero potential to that at $+V_0$ and we obtain

$$A = -V_0/\pi \quad ....(18)$$

Hence eq. (16) becomes,

$$W = \pm(V_0/\pi) \,.\, \log t + B \quad ....(19)$$

the sign depending upon which of the capacitor plates has zero potential. Since the field is not affected by this, either form of eq. (19) may be used. Since the lower plate is generally earthed in practice, we shall assume that the upper plate has an instantaneous potential of $+V_0$ and use the equation

$$W = \frac{-V_0}{\pi} \,.\, \log t + B \quad ....(20)$$

To determine the value of B, let $t = +a$, which is a point on the upper plate and corresponds to $V = +V_0$.

$$U + jV_0 = \frac{-V_0}{\pi} \log a + B$$

Hence, equating real and imaginary parts, $B = jV_0$, so that the completed electrical transformation is

$$W = \frac{-V_0}{\pi} \log t + jV_0 \quad ....(21)$$

The final transformation is obtained by eliminating t between equations (13) and (21), when we obtain

$$z = \frac{h}{a\pi}\left\{ e^{-2\pi W/V_0} - e^{-W/V_0} \,.\, (1-a) - ja\pi + \frac{a\pi W}{V_0} + B \right\}$$

$$\text{where } B = \tfrac{1}{2} - a(1 - j\pi). \quad ....(22)$$

To obtain the equation of an equipotential in the z-plane we must hold V at some constant value, and find the values of x and y for various convenient values of U. To simplify the arithmetic, we will fix the dimensions of the capacitor and pick a convenient value for V_0.

Eq. (11) connects the "variables" a and n. Taking $a=0{\cdot}2$ for convenience, we obtain $n=1{\cdot}276$ which means that the lower plate projects $1{\cdot}276h$ beyond the upper plate, where h is the distance between the plates. These values give

$$\frac{\pi z}{5h}=\frac{t^2}{2}+t-0{\cdot}2t-0{\cdot}2\log t+0{\cdot}3+0{\cdot}2\mathrm{j}\pi \quad \ldots(23\mathrm{A})$$

for z in terms of t, which will be required later, and

$$\frac{\pi z}{5h}=\tfrac{1}{2}\mathrm{e}^{\frac{-2\pi W}{V_0}}-0{\cdot}8\mathrm{e}^{\frac{-\pi W}{V_0}}+\frac{0{\cdot}2\pi W}{V_0}+0{\cdot}3 \quad \ldots(23)$$

The most convenient value for V_0 is π, which gives

$$\frac{\pi z}{5h}=\tfrac{1}{2}\mathrm{e}^{-2W}-0{\cdot}8\mathrm{e}^{-W}+0{\cdot}2W+0{\cdot}3 \quad \ldots(24)$$

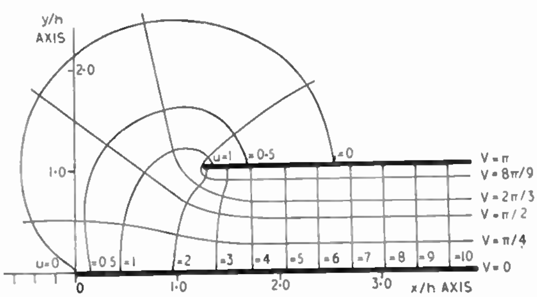


Fig. 7.—Theoretical plot of field for small h.

Taking $V_0=\pi$ does not restrict the solution, as any other value of V_0 can always be expressed as some multiple of π. Since $W=U+\mathrm{j}V$, we can equate real and imaginary parts from eq. (24), leading to the equation:—

$$\frac{x\pi}{5h}=\tfrac{1}{2}\mathrm{e}^{-2U}.\cos 2V-0{\cdot}8\mathrm{e}^{-U}.\cos V+0{\cdot}2U+0{\cdot}3 \quad \ldots\ldots\ldots(25)$$

$$\frac{y\pi}{5h}=-\tfrac{1}{2}\mathrm{e}^{-2U}.\sin 2V+0{\cdot}8^{-U}.\sin V+0{\cdot}2V \quad \ldots\ldots\ldots(26)$$

By giving V any convenient constant value, the x and y co-ordinates of the corresponding equipotential can be found from eqs. (25) and (26). The field diagram, Fig. 7, shows the results of these calculations. Once sufficient equipotentials have been drawn, the lines of force can be drawn in free-hand, or, if higher accuracy is required, they could be plotted by giving U a series of constant values and proceeding in a similar manner to that described above. The diagram shows the fringing effect near the end of the capacitor systems, and the electric field starts becoming seriously non-uniform to the left of the line of force $U=5$ approximately. It should be remembered that the diagram represents a capacitor stretching to infinity along the positive x-axis, so that the field will not be the same as that of a practical finite capacitor of the dielectric heater. Comparison of Fig. 7 however with the results of experiments described in the next section show that the differences between theory and experiment are small, and the theory given above is sufficiently accurate for dielectric heating purposes.

4. Slope of the Equipotentials

In the type of problem we are considering here, the electric field will be uniform where the equipotential lines are horizontal, and the lines of force are vertical, the lines being equally spaced for equal increments of potential or flux. This we can see is true in the central region of the capacitor. Since we are mainly interested in the field variation as we move along between the plates in the x-direction, we can take the inclination of the lines of equipotential to the horizontal as a measure of the non-uniformity of the field. This inclination is $\mathrm{d}y/\mathrm{d}x=f(U)$, V being constant. We can obtain an expression for the slope of the equipotential as follows, putting $t=r\exp \mathrm{j}\theta$, we then have

$$W=-\log R-\mathrm{j}\theta-\mathrm{j}\pi \quad \ldots\ldots\ldots(27)$$

when $V_0=\pi$.

Hence
$$U=-\log r \quad \ldots\ldots\ldots(28)$$
$$V=\pi-\theta$$

Substituting for t in eq. (13) gives, with $a=0{\cdot}2$,

$$\frac{\pi z}{5h}=\frac{r^2\mathrm{e}^{2\mathrm{j}\theta}}{2}+0{\cdot}8r\mathrm{e}^{\mathrm{j}\theta}-0{\cdot}2\log r-0{\cdot}2\mathrm{j}\theta+ +0{\cdot}3+0{\cdot}2\mathrm{j}\pi$$

Equating real and imaginary parts gives

$$\frac{\pi x}{5h}=\frac{r^2}{2}\cos 2\theta+0{\cdot}8\,r\cos\theta-0{\cdot}2\log r+0{\cdot}3$$

$$\frac{\pi y}{5h}=\frac{r^2}{2}\sin 2\theta+0{\cdot}8\,r\sin\theta-0{\cdot}2\theta+0{\cdot}2\pi$$

For constant V, θ is constant, hence

$$\frac{dy}{dx}=\frac{r^2\sin 2\theta+0{\cdot}8\,r\sin\theta}{r^2\cos 2\theta+0{\cdot}8\,r\cos\theta-0{\cdot}2} \qquad \text{.........(30)}$$

Eq. (30) will give the slope of any equipotential in the z-plane. The equipotential value is fixed by giving θ the appropriate value using eq. (29), and the distance along the equipotential is determined by the value of U, from which r is found using eq. (28).

For example, if we take the central equipotential $V=V_0/2=\pi/2$, therefore $\theta=\pi/2$.

Hence $$\frac{dy}{dx}=\frac{-4{\cdot}0}{5e^{-U}+e^{U}} \qquad \text{.........(31)}$$

Thus the slope of the $\pi/2$ equipotential is only zero when $U=\pm\infty$ that is, when $x=\pm\infty$. Thus the line is only horizontal at the points at infinity. This is to be expected, since the theory refers to plates infinitely long. A comparison of the theoretical field with that found by experiment however shows that there is little difference between the two as long as the plates of the actual capacitor are close together compared with their length. Since, in practice, we would use the plates in such a way to avoid placing the ends of the specimens in the fringing field, the theory is applicable within the limits of accuracy we require. Table 1 shows how dy/dx alters as we move along the $\pi/2$ equipotential.

The table shows that for values of U greater than $U=5{\cdot}0$ the slope differs from the horizontal by less than 2 degrees. In a practical capacitor where the plates are not infinitely long the equipotential slopes will become zero more quickly than shown above. Thus any conclusion based on this theory will tend to have an error on the safe side. The above calculations could be repeated for other equipotentials, but using the equipotential $V=\pi/2$, which is central, will give us all the information we require to a sufficient degree of accuracy in most practical cases.

Now $t=p+jq=r\exp j\theta$ where U and V are connected with r and θ through eqs. (28) and (29). If $V=\pi/2$ so that $\theta=\pi/2$ we have $t=r.j$. Thus the t-plane locus corresponding to the equipotential $V=\pi/2$ is $p=jq$ and is a straight line passing through the t-origin inclined at 45 deg. to the real axis.

We can also show that the maximum slope of the $\pi/2$ equipotential is at U equal to $\frac{1}{2}\log 5$ so that $U=0{\cdot}8047$.

If $t=jr$ and $\theta=\pi/2$ we get

$$\frac{\pi x}{5h}=\frac{-e^{-2U}}{2}+0{\cdot}2U+0{\cdot}3 \qquad \text{......(32)}$$

$$\frac{\pi y}{5h}=0{\cdot}8e^{-U}+\frac{\pi}{10} \qquad \text{......(33)}$$

These equations give us the co-ordinates on the equipotential $V=\pi/2$ of any point having a particular slope, the U-value being obtained from eq. (31).

As an approximation to be used in practice, we can take the non-uniformity of the field to commence where the equipotentials begin to slope appreciably. This gives an error on the safe side, because it will be shown later that the field remains uniform a little beyond the point where the equipotential begins to curve. For example, if we take $U=5$ as representing the limit of the uniform field, we have

$$\frac{\pi x}{5h}=1{\cdot}3$$

so that $$x=2{\cdot}07h \qquad \text{.........(34)}$$

Now the corner of the upper plate has an abscissa of $x=1{\cdot}276h$, so that the horizontal distance s, of the point calculated above from the edge of the upper capacitor plate is approximately $0{\cdot}8h$. This is the distance measured inwards from the edge of the upper plate along the $\pi/2$ equipotential. If we repeated these calculations for other equi-

Table 1

Variation of slope of $\pi/2$ equipotential calculated from equation (31) $[\theta=\tan^{-1}dy/dx]$

U	=	0	0·5	1·0	2·0	3·0	4·0	5·0	6·0	7·0	8·0
dy/dx	=	−0·6667	−0·6246	−0·8812	−0·4958	−0·1967	−0·0732	−0·0269	−0·00972	−0·0037	−0·0013
θ	=	148°18′	148°1′	138°77′	153°58′	168°49′	175°49′	178°28′	179°47′	179°72′	179°79′
x/h	=	0·3186	0·344	0·688	1·100	1·432	1·750	2·07	2·39	2·708	3·25

potentials we could finally draw a line from the upper plate to the lower which would give the limit of the uniform portion of the field. It is near enough for our purposes, however, to draw a vertical line joining the two plates through the point $x=2{\cdot}07h$ and take that as the effective limit of the uniform field. If then we ensure that any parallel sided block of dielectric placed between the plates does not approach the edge of the upper capacitor plate nearer than $0{\cdot}8h$ we will know that the block will be almost entirely uniformly heated. There will be a small degree of non-uniformity along the vertical edge, because the limit of the uniform field, as determined above, is not quite vertical and straight, but this would not be very important in practice since a small amount of non-uniform heating near the edges would be eliminated by thermal conductivity. If the block of dielectric is made smaller than the above limits imply, then of course the heating will be uniform throughout.

Thus for any distance apart h of the capacitor plates, the edge of a rectangular block of dielectric must not approach the edge of the upper plate by less than about $0{\cdot}8h$. This conclusion only applies when h is small in comparison with the horizontal length of the smaller plate, since the theory assumed semi-infinite plates. The relationship $S=0{\cdot}8h$, where S is the minimum safe distance for uniform heating, is linear. We may also obtain the required relationship by experimentally plotting a number of field diagrams for the actual capacitor plates, and finding the value of S for each value of h graphically. This is done below, where it will be seen that the experimental relationship is also linear for relatively small values of h, but for higher values of h, the distance S is less than that predicted above. Thus the theory gives an error on the safe side. The relationship has also been checked by drawing field diagrams for different values of h using eqs. (25) and (26) though only one such diagram is shown here, Fig. 7. By finding the point on the $\pi/2$ equipotential where the line is just horizontal in each case, a relation between S and h can also be found. Fig. 12 shows that the results obtained this way agree with the equation $S=0{\cdot}8h$ very closely. The process could, of course, be repeated for different amounts of overlap, i.e. different values of a, but this is not done here.

5. The Electrical Intensity R

The electrical intensity (field strength) R at any point in the field can be found from the defining equation

$$R=|dW/dz|=|dW/dt\,.\,dt/dz|$$

We have already obtained expressions for dW/dt and dz/dt so we therefore obtain,

$$R=(V_0a/h)\,.\,|1/\{(t+1)(t-a)\}| \quad \ldots(35)$$

We can easily obtain numerical values for R from this equation once we have decided upon the value for a, that is, upon the amount of overlap of the original capacitor plates. It is easier to work in terms of t than directly in terms of z, and to calculate the values of z for the values of t used in the above equation from eq. (13) which gives z in terms of t. These calculations have been performed for certain regions of the field and the variation of R along the edges of the capacitor plates has been calculated. The results are shown graphically in Fig. 8, the z-values being obtained from eq. (13), and values of $R.5h/\pi$ are plotted against the real part of z/h.

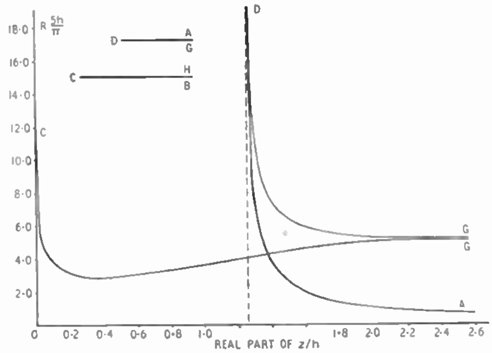


Fig. 8.—Variation of R along the edges of the capacitor system.

Figure 8 shows that the value of $R.5h/\pi$ approaches the value 5·0 as we move along the inner surface of either plate towards the right. There is little further variation in R once we are about $0{\cdot}7h$ from the corner D. The field along the upper surface of the upper plate falls more quickly than that along the inner surface as would be expected. The field strength approaches infinity at the corners D and C, since these are sharp corners. The variation of R

along the lower surface of the bottom plate is not shown.

We are mainly interested in the variation of R as we move along a horizontal line between the two plates. The value of R at any point can be found by making t complex in eq. (36), and then finding the corresponding value of z from eq. (13). We will illustrate this by finding the variation of R as we move along the $V=\pi/2$ equipotential.

Putting $t=r\exp j\theta$ we have shown that, for $V=\pi/2$

$$\frac{\pi x}{5h}=\frac{-e^{-2U}}{2}+0{\cdot}2U+0{\cdot}3 \qquad \ldots\ldots\ldots(37)$$

$$\frac{\pi y}{5h}=0{\cdot}8e^{-U}+\frac{\pi}{10} \qquad \ldots\ldots(38)$$

Now $\quad W=U+jV=-\log t+j\pi$

so that $\quad U+jV=-\log r-j\theta+j\pi$

Hence $\quad U=-\log r \qquad \ldots\ldots\ldots(39)$

$$V=-\theta+\pi \qquad \ldots\ldots\ldots(40)$$

If $V=\pi/2$, $\theta=\pi/2$ and $e^{j\theta}=j$.

Hence, along the $\pi/2$ equipotential $t=jr$ and $r=e^{-U}$. Hence the x and y co-ordinates of any point on this equipotential can be found from eqs. (37) and (38) for any value of t, and the value of R for the same t-value found from eq. (36). Fig. 9 shows how R varies as we move along the $V=\dfrac{V_0}{2}=\dfrac{\pi}{2}$ equipotential.

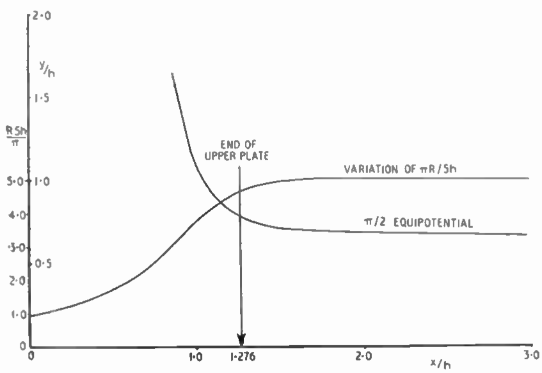


Fig. 9.—Showing the $\pi/2$ equipotential and the variation of R along $\pi/2$ equipotential.

$R.5h/\pi$ is plotted against x/h as we are more interested in the variation in the horizontal direction than that in the vertical. A similar procedure could be used to obtain the variation of R along any other equipotential.

The graph of Fig. 9 shows that R is constant between the plates until the point $x=1{\cdot}65h$ (approximately) is reached. This point is a distance of $0{\cdot}374h$ from the edge of the upper plate. Beyond this point, the value of R decreases as we move out from between the plates. This means that the dielectric will be uniformly heated as its edge is not nearer than the distance $0{\cdot}374h$ to the edge of the upper plate. This is only true for the $\pi/2$ equipotential; equipotentials nearer the lower plate will be associated with a uniform value of R a little nearer to the edge of the upper plate than $0{\cdot}374h$, and the reverse will be true for equipotentials above the $\pi/2$ line. The differences are small, and it is sufficiently accurate in practice to take the point on the $\pi/2$ line as indicating the limit of the uniform field.

If we compare this graph with that of the $\pi/2$ equipotential, we see that the latter begins to turn from the horizontal before the variation of R becomes noticeable. Thus if we take the change of slope of the equipotential as a rough indication of when the field becomes non-uniform, the error will be on the safe side. Eq. (1) shows that the percentage change in P is twice the percentage change in R. Fig. 9 shows that if we exceed the limit of uniform field by $0{\cdot}1h$, the corresponding change in $R.5h/\pi$ is about $0{\cdot}1$ giving a percentage variation in R of 2 per cent. Hence an error of $0{\cdot}1h$ in the placing of the dielectric with respect to the boundary of the uniform field causes a 4 per cent. drop in the rate of heating.

6. Experimental

To investigate experimentally the two-dimensional field of the parallel plate capacitor shown in Fig. 1, a method of field plotting was adopted which involved the use of an electrolytic analogue.

The apparatus consists of two representative electrodes in the form of metal strips which are connected to a suitable source of supply. In these experiments a fixed frequency oscillator, operating at 1,000 c/s, was used. The electrodes are placed edge on to make contact with a sheet of absorbent paper, such as blotting paper, which had previously been immersed in a dilute solution of copper sulphate. Good contact between the electrodes and the electrolytic pad is necessary, otherwise the field is affected. Alternatively, the dilute electrolyte can be applied with a cotton-wool pad. This second method was found to be more practicable since the absorbent paper tends to break after being immersed in the electrolyte. Also, repeated damping of the electrolytic pad is facilitated. This is necessary, since drying out of the pad occurs giving rise to centres of higher resistivity causing local changes in electrical intensity.

Beneath the absorbent pad are placed sheets of carbon and plain drawing paper; the carbon paper forms the centre layer, with the duplicating surface in contact with the drawing paper.

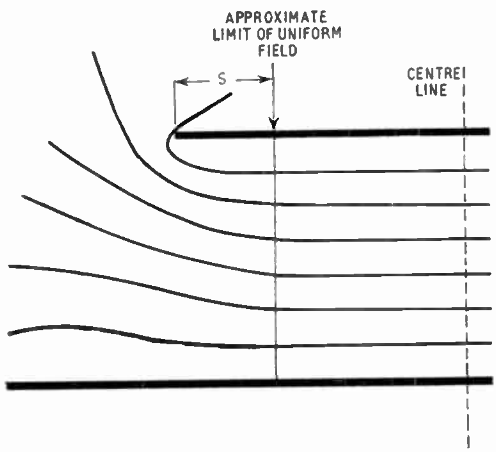


Fig. 10.—Experimental plot for medium h.

Plots of the equipotentials are made by using two thin brass probes connected to a suitable detector such as a head phone. The equipotentials are found by placing one probe in contact with the electrolytic pad at any point in the field of the two representative electrodes. The line of equal potential is found by moving the second probe back and forth across the field, at a suitable distance from the first stationary probe. Zero reading is obtained on the detector when both probes are at equal potentials. At this point in the electric field, pressure is applied to the probes, duplicating onto the drawing paper points along the equipotential. When sufficient points have been marked, and the edges of the electrodes traced, the drawing paper is removed and the equipotentials drawn in through the points.

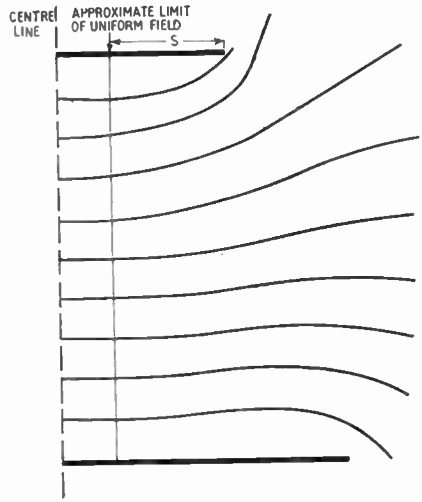


Fig. 11.—Experimental plot for large h.

The lines of force, which must be orthogonal to the equipotentials, and also to the traces of the capacitor plates, can generally be drawn in freehand. Figs. 10 and 11 show the fields obtained in this way. The field for small h, which was also obtained experimentally, is not shown as it was identical with that obtained theoretically, shown in Fig. 7. Quantitative results may be obtained by using a d.c. potential across the capacitor system and a galvanometer connected to the probes, the potential of any line being found with a voltmeter, but this was not done here as it was unnecessary.

7. Conclusions

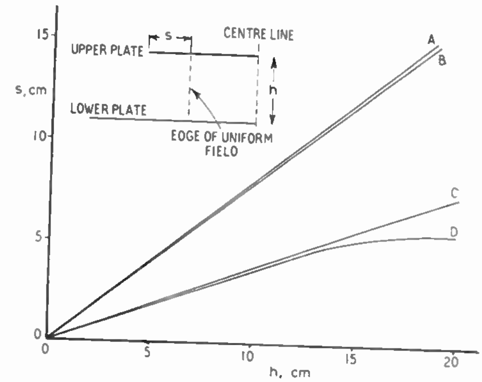
Figure 12 shows the results of the various methods used to find the limit of the uniform held between the plates of the parallel plate capacitor, the upper plate being $1{\cdot}276h$ shorter than the lower, where h is the distance between the plates.

The straight lines OA and OB were obtained from the theoretical results. OA refers to the point on the $\pi/2$ equipotential where the slope is less than 2 deg., whilst OB was obtained by drawing a number of fields from eqs. (25) and (26) and estimating the distance S from the diagrams, as indicated in Figs. 10 and 11. The two methods lead to very nearly the same results, as would be expected. We obtain the equation $S=0{\cdot}8h$.

The line OC was obtained by finding the variation of R along the equipotential, as shown in Fig. 9. The field strength R starts to drop at a value of S given by $S = 0{\cdot}374h$. From Fig. 9 it is seen that the $\pi/2$ equipotential starts to curve appreciably before R alters, giving $S = 0{\cdot}8h$ as already mentioned. Thus if we estimate S from the field diagrams, which are easy to obtain, we have an error on the safe side of about 100 per cent. in S. It should be remembered however that this conclusion is only true for the parallel plate capacitor here, where the overlap is $1{\cdot}276h$, and that it only refers to a capacitor whose plates are very long in comparison with h, the distance between them.

The curve OD represents the results obtained from the experimental field plots using a capacitor the same size as that on an actual dielectric heater with a fixed overlap. It can be seen from Fig. 12 that the curve OD is linear until $h = 13$ cm approximately. The length of the upper plate is 16·7 cm, so that in practice it appears that the plates can be comparatively widely spaced before the relationship between S and h becomes non-linear. The straight line OC is very close to the linear portion of OD, showing that the approximations made in order to simplify the theory did not invalidate the argument. As h becomes large compared with the length of the plates, the deviation of experiment from theory becomes noticeable, as is expected. Experiment gives almost the same value for S as the value calculated from the variation of R along the $\pi/2$ equipotential.

It appears, therefore, that we can find S for a parallel plate capacitor by plotting the theoretical field for the required value of h, finding the point along the central equipotential where it starts to slope appreciably, and dividing the value of S thus found by two. Alternatively, we can find S directly by experimental field plotting.



OA by calculation from slope of $\frac{\pi}{2}$ equipotential.
OB from theoretical field plots.
OC from theoretical variation of R.
OD from experimental field plots.

Fig. 12.—The safe distance S in terms of h.

The experimental method can be used similarly for other types of capacitors, and it is also possible to simulate the effects on the field of non-homogeneous dielectrics and inserted thermocouples, but this will form the topic of a further paper.

THE USE OF EPOXIDE AND POLYESTER RESINS IN THE ELECTRONICS INDUSTRY*

by

R. Q. Marris†

SUMMARY

The chemistry, electrical and physical properties of polyester and epoxide resins are discussed briefly. Some advantages and disadvantages of the two classes are described. Some practical considerations involved in encapsulation and the general use of resins are mentioned.

1. Introduction

Throughout the history of radio and electronics, many attempts have been made to seal satisfactorily and to reinforce electronic components and, in latter years, complete circuits and sub-assemblies. In the early years it was the fashion to impregnate with waxes and pitches, and dip seal, or alternatively to encapsulate the components in these materials by placing them in a small container and filling. The main object was of course to make the component resistant to changes in temperature and humidity, as well as to increase the mechanical strength and electrical insulation. In general, these early attempts at impregnation and encapsulation were only partially successful, the main faults being lack of adhesion to outcoming leads, terminals and inserts etc., as well as the unfortunate fact that the materials used were liable to melt or soften at the upper temperature limits required for the better types of equipment.

With the advent of the second World War, equipment designers found themselves faced with extreme ranges of temperature and humidity requirements, with high voltages, small dimensions and the ever increasing speeds of aircraft and projectiles. Thus we found ourselves transported in rapid succession from normal equipment to miniature equipment, and then to sub-miniature equipment.

During the last war various electronic and electrical components and assemblies were moulded in such materials as polythene and polystyrene, and this technique went a long way towards providing a robust component or assembly with a fair degree of sealing in good insulating compound. However, in view of the fact that such components as resistors, capacitors, inductors and even thermionic valves were likely to be involved in these moulding techniques, it will be realized that the high temperatures and pressures required during the processing produced an extremely high reject rate; and of course once again there was no real adhesion to outcoming terminals and fixings, as a result of which there was still a path for the entry of moisture under certain conditions. However, polythene was an extremely good insulating material, and provided a robust finished component, and in spite of the other imperfections, was used in very considerable quantities.

Towards the end of the second World War, the first polyester resins became available in the United States of America for the moulding and encapsulation of electronic components, sub-assemblies and units. With these materials processing could be carried out without pressure, and at room or not particularly high temperatures, and within the normal working temperatures of the components being encapsulated.

Shortly after the end of the war, the first epoxide resins were tried experimentally in Switzerland, and subsequently became available in this country. In these resins a material had finally been found which would adhere to metals and many other materials, and provide complete sealing. Once again the processing temperatures could be kept within reasonable limits, pressure not being required. With the arrival of these polyester and epoxide resins,

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the art of electronic component and circuit moulding and encapsulation has progressed with ever increasing speed, and at the present time "potted" items are being introduced into more and more new equipments.

As this paper is only concerned with epoxide and polyester resins, it may be mentioned in passing that there are other types of synthetic casting resins available, which at the moment do not offer the advantages of the resins under discussion, and which are still in the development or small production stage as far as the electronic field of application is concerned.

Polyester and epoxide resins are now being manufactured or distributed by quite a number of firms in this country. Each firm stresses the advantages of its own particular product, and bearing this in mind it is proposed to consider only the average properties of the two particular groups of resin under discussion.

Individual resins are available for processing into a solid or flexible form. The various manufacturers supply resins for casting, moulding and encapsulation, for laminating and as adhesives, and in addition resin-based paints are now available from several sources. Resins are available for hot or room-temperature curing.

2. Chemistry of the Resins

2.1. *Epoxide resins*

The epoxide resins are produced by the reaction of epichlorohydrin with a polyhydric phenol. By the addition of curing agents, the epoxide resins may be converted into infusible solids by processing and curing at temperatures from normal room temperature upwards. During this process heat is evolved, and this is generally referred to as the exotherm. By selecting particular curing agents, the epoxide resins may be cured over a wide range of temperatures, and various specific physical and electrical properties accentuated.

In appearance the unprocessed resins are a straw coloured syrup or yellow solid lumps. The curing agents are of a variety of colours, and are supplied in liquid or powder form.

2.2. *Polyester resins*

Polyester resins are formed by mixing unsaturated alkyds with a reactive monomer. Normally a catalyst is required for polymerization, and the processing can be accelerated by the use of heat or an accelerator, or both. The resins are supplied in the form of colourless to light brown liquids, depending on the type and manufacturer concerned. The catalysts are available in liquid, paste and powder forms, and many different types can be used.

Once again heat is generated during the processing, and this exotherm can be adjusted by the selection of the catalyst, and by controlling the amounts of catalyst and accelerator used, as well as the processing temperature.

3. Electrical and Physical Properties

Table 1 illustrates the electrical and physical properties which can be expected in fully-cured resins of the epoxide and polyester types. It is stressed that these are typical figures, and that quite wide variations exist between the various resins available, and that the results can be changed considerably by the addition of various chemicals and fillers.

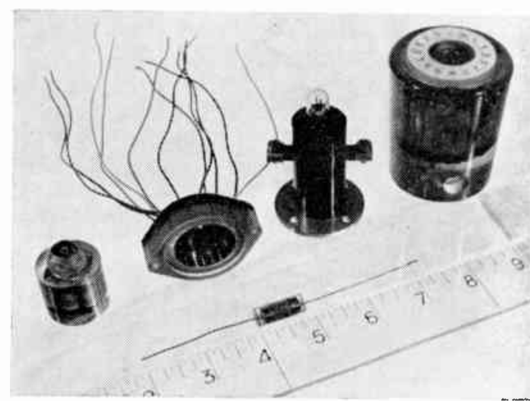

Fig. 1.—Typical resin encapsulated electronic circuits and components. From left to right: An 80 ohm transmitter coaxial dummy load; moulded commutator; neon indicating circuit; typical "potted" circuit. In front, moulded germanium crystal rectifier.

4. The Industrial Uses of Resins

4.1. *Casting, Moulding and Encapsulation*

4.1.1. Advantages—general

The use of resins for moulding or for the encapsulation of electronic circuits and components provides protection against changes in temperature, humidity, and thermal shocks. The water absorption rate of most casting resins is low. Moulded items can be subjected to high acceleration forces. With regard to the construction of circuits and components to be moulded, a much cheaper and simplified form

Table 1

Electrical and Physical Properties of Resins

Type of Resin	Specific Gravity	Tensile Strength "Unfilled" (ASTM D638-49T) lb/in²	Water Absorption (ASTM D570-42) % in 24 hours	Dielectric Strength (ASTM D495-42) volts/mil	Volume Resistivity For 50% Rel. Hum. at 25°C ohm/cm	Dielectric Constant (ASTM D150-47T) 60 c/s	Dielectric Constant 1 Mc/s	Power Factor (ASTM D150-47T) 60 c/s	Power Factor 1 Mc/s
Typical Polyester	1·2	8,000	0·2	300–400		3·18	3·08	0·004	0·012
Room temperature cured Epoxide	1·19	8,000	0·113	400	6×10^{14}	3·9	3·59	0·18	0·02
Epoxide cured at approx. 60-70° C	1·19	8,500	0·07	400–500	$8{\cdot}7 \times 10^{14}$	3·8	3·7	0·0023	0·010
Epoxide cured at 140° C or above	1·23	12,000	0·05	450	10^{15}	3·9	3·62	0·004	0·019

of internal constructions can very often be used, including the elimination of many of the usual mechanical supports, and the resultant unit is usually of a more compact form.

Treated circuits and components are capable of withstanding the climatic cycling to specification K114, and under suitable conditions they can be designed to withstand temperatures as low as −100° C and as high as +100° C or more. It is stressed however that the limiting factors are likely to be the temperature ratings of the components used internally, or the permissible shape and size of the final moulded assembly. The result can be cracking at low temperatures, and humidity test breakdown, and in some cases deterioration of electrical properties at the higher temperature limits. By using moulded electronic sub-circuits and components, equipment production and servicing are made easier, as quite large parts of the circuit are bonded together.

4.1.2. Disadvantages—general

The disadvantages of the technique under discussion are not numerous. They are:—

(*a*) In general the circuit or component is no longer repairable. Thus if it breaks down in service or in the course of manufacture, it may well have to be scrapped. However it has been found possible to dissolve chemically the cured polyester resins, though some chemical damage may be done to the internal components. Recently a chemical technique has been evolved to strip off epoxide resins as well as polyesters. Once again damage to some of the internal components may result.

(*b*) The slight increase in capacitance in moulded circuits and components may cause some instability or other electrical troubles, but in general these can be counteracted by designing the unit specifically for encapsulation.

(*c*) Some loss of Q is experienced in inductors, but recent investigations into the chemical modifications of proprietary resins have indicated ways of eliminating this trouble, and the investigations are of course proceeding. The loss of Q is caused by dielectric loss, or by pressure on the magnetic core if this is present, or a combination of both.

(*d*) The process is quite expensive where small quantities are involved, but experience shows that the manufacturing costs fall sharply as the quantity to be made increases.

4.1.3. Advantages of using polyester resins

The chief advantage of polyester resins is that they are very considerably cheaper than epoxides. This point has to be carefully weighed against the relative technical advantages and disadvantages of the two types of resins.

4.1.4. Advantages of using epoxide resins

Here again we are met with an immediately obvious advantage, and that is the excellent adhesion of epoxide resins to metals and other materials. Epoxide resins have in general lower thermal expansion rates than their polyester counterparts, a feature which can of course be reduced considerably by the inclusion of fillers.

4.2. *Polyester and Epoxide Laminates*

Both polyester and epoxide resins are being extensively used for glass and other laminates. The laminates are either made in sheet form, or formed into quite complex shapes. The laminates provide a substitute to sheet metals in the aircraft and other industries, whilst in the electronic and electrical fields they are being used in increasing quantities as a robust insulation material.

The polyester and epoxide laminates provide a tough material which is resistant to heat, chemicals and water, and which at the same time has excellent electrical properties. In the case of the epoxide laminates, there is the advantage that these can be bonded to metals during processing and, as has been already pointed out, the use of polyesters provides a cheaper laminate.

Many different cloths are being used for resin laminating, among which are fibreglass, asbestos, linen, nylon and paper.

4.3. *Other Uses*

Epoxide resins are being used for several other purposes than those just discussed. They form an excellent adhesive for joining metals and other materials together, and epoxide based paints have recently been introduced which show particularly good adhesion to metals, etc., and which form a protective coating greatly superior to those obtained with the more conventional paints.

A most interesting recent discovery is the development of a conductive resin material for use with radioactive isotopes. The material is also available for electrical shielding, and for the production of special resistors. The conductivity is controlled and may be varied by manipulation of the chemical content.

Recently machine press tools and jigs have been moulded in various resins, and it is estimated that these will eventually provide a robust and economical form of tooling as the technique develops.

5. Survey of Practical Considerations when using Resins

5.1. *Health*

In common with other plastics and industrial processes, cases have occurred where the users of resins have been subject to skin complaints due to handling or fumes. The skin complaints have been placed in the dermatitis category, and are of course non-infectious. It has been proved beyond all reasonable doubt that if proper precautions are taken, and if operators can be persuaded to implement them, then the effects of using the resins can be almost completely eliminated. In general it has been found that adequate washing, the use of barrier creams and the dispersal of any fumes by ventilation, should prove adequate.

5.2. *Chemical Resistance*

Typical examples of the resistance to chemicals which may be expected with polyester and epoxide resin mouldings are shown in Table 2.

Table 2

Chemical Resistance of Resins

Reagent	Polyester resin	Epoxide resin
Acetone	Non-resistant	*
Benzene	Resistant	Resistant
Hydrochloric acid	Resistant	Resistant
Nitric acid	Non-resistant	Non-resistant
Distilled water	Resistant	Resistant

* Cold-cured epoxide resins are generally non-resistant to acetone, whereas the hot-cured epoxide resins are partially or almost completely resistant.

5.3. *Adhesion*

In general polyester and epoxide resins will not adhere to thermo-plastics such as polythene, etc.

The adhesion to metals is poor in the case of polyester resins, whereas with cold-cured epoxide resins fairly good adhesion can be expected. Experience shows that very reasonable adhesion to metals may be obtained with the hot-cured epoxide resins, and it is a common practice to seal the outcoming terminals in polyester mouldings with one of these resins painted on and baked.

Epoxide resins may be used for sticking pieces of metal together, and special adhesive epoxide resins are available for this purpose and are used by the aircraft and other industries.

5.4. *Exothermic Reaction*

The exotherm is the rise in temperature which takes place due to the chemical action which occurs when the curing agent or catalyst is added to epoxide or polyester resins. If left uncontrolled, the exothermic temperature may rise from a few degrees to as much as 150°C above the processing temperature, which, as has been seen, may be anything from room temperature to 140°C depending on the type of resin used and the application.

The exothermic reaction may be controlled in a number of different ways, the most usual methods being to arrange for a good heat transfer from the moulds, and by incorporating powdered fillers which assist the transference of heat from the centre of the moulding to the outside.

5.5. *Fillers*

Fillers, usually in powdered form, are mixed into both polyester and epoxide resin mixtures for a number of reasons which are enumerated below:—

(1) To reduce the cost of the moulded item, powdered fillers such as quartz, mica or alumina are very much cheaper than the resins used.

(2) To reduce the stresses which occur due to contraction as the resin mixture hardens.

(3) To assist the transference of heat from a resin encapsulated circuit or component.

(4) Some fillers increase the electrical breakdown strength of the material.

(5) To reduce the thermal expansion rate of the cured resin.

5.6. *Shrinkage and Moulding Stresses*

In all casting resins, including epoxides and polyesters, considerable volumetric shrinkage occurs during gelling and curing. The result appears in several ways, chiefly in the form of cracking, incorrect overall dimensions of the finished article, and the damaging of any parts which are encapsulated.

These moulding stresses may be relieved in many ways, including the use of fillers and the reduction of the exothermic action by heat transference as outlined above.

6. The Future

There is little doubt that the art of using epoxide and polyester resins is still in its infancy. At the moment electronic circuits, components, transformers and assemblies are all being encapsulated, where high voltages are found and as engineers realize the advantages of these materials in high voltage work.

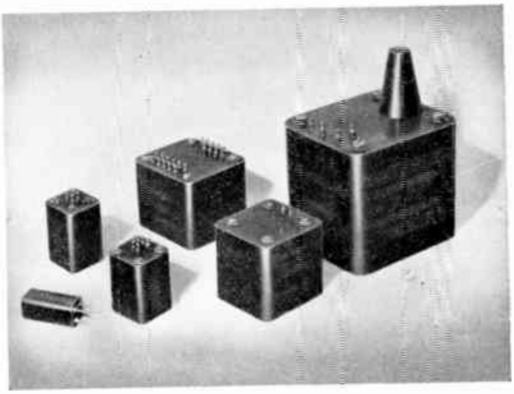

Fig. 2.—Typical resin encapsulated transformers.

Experimental work and limited production is now taking place in the aerial field, and aerial insulators, etc., are being moulded in these resins for use on ground aerial arrays and as aerial insulators and supports on the outside of aircraft. In military equipment resin mouldings and encapsulations are taking an increasing part, by virtue of their ability to protect circuits and components against rough handling, mechanical and thermal shock, and changes in climatic conditions. With higher speeds of aircraft and missiles, and the tightening of requirements for electronic components and circuits, epoxide and polyester resins will play an ever increasing part.

7. Acknowledgments

In conclusion the writer would like to thank the Directors of Lion Electronic Developments Limited of Feltham for permission to publish this paper, the majority of the technical contents of which have been verified in their laboratory and works.

D

NOTICES

Institution Meeting in Paris

Members of the Institution in Paris are arranging a meeting, to be followed by a dinner in the King George V Hotel in Paris on Friday evening 7th September next. This meeting will follow the lines of a conversazione arranged two years ago, which provided an admirable opportunity for members to meet during the course of the Foire de Paris. This year the meeting and dinner will take place during the course of the Paris Salon de la Radio et de la Télévision (September 5-15).

Members will also welcome the occasion to express thanks to the Institution's Honorary Local Secretary in Paris, Mr. A. V. J. Martin (*Associate Member*), before his departure to the United States to take up an appointment there. Mr. Martin's most recent contribution to the *J.Brit.I.R.E.* was a paper on "Apparatus for the Measurement of Physical Constants by the Elastic Vibrations Method," which was published in the March 1956 issue.

The President of the Institution, Rear Admiral Sir Philip Clarke, K.B.E., C.B., D.S.O., will preside at the dinner, and will be accompanied by Mr. W. E. Miller, Immediate Past President, and the General Secretary, Mr. Graham D. Clifford.

Further information may be obtained from the Institution in London, or preferably direct from Mr. A. V. J. Martin, 79 rue Duhesme, Paris 18e.

Circulation of the Journal

The Certificate of the Audit Bureau of Circulations for the period January-June 1956 shows that the *Journal* of the Institution has had an average monthly circulation of 6,342 copies.

This is the highest figure reached since Audit Bureau of Circulations Certificates have been issued in respect of the *Journal*, and does not, of course, take into account any journals purchased after the conclusion of the six-monthly period.

Library Requirement

The Institution's Library requires copies of Physics Abstracts, Section A of Science Abstracts for January, March, June, July and December with index for 1943; and March, June, September, November and December with index for 1944. These are to complete sets for binding, and as they are now out of print, the Librarian would be grateful for any offers of copies in good condition.

Science Abstracting

Scientific literature is now so vast that it is impossible for anyone even to see more than an insignificant fraction of all published information. Yet unless each specialist can count on becoming aware of information and data in collateral fields that might be useful to him, he cannot cultivate his own field efficiently. The development of abstracting and other bibliographical publications to deal with this situation and as aids to scientific progress formed the subject of an International Conference organized by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1949. One result of this Conference was the establishment of the International Advisory Committee for Documentation and Terminology in Pure and Applied Science.

This body gives information on some aspects of its work in a Report recently issued through the Secretariat of UNESCO. Among its publications are a monthly bulletin on scientific documentation and terminology which is circulated to give news of developments conducted under the Committee's advice, also a guide for the preparation and publication of synopses. The latter is a leaflet supplied on request in any of four languages (English, French, German and Spanish) for editors of scientific journals to pass on to contributors, with the aim of standardizing the synopses of papers so that the time-lag between the appearance of original articles and their referencing in abstract journals may be reduced.

The Committee recommends in the Report that it "would welcome any possible action being taken to encourage editors of scientific and technical abstracting and indexing services to include therein an increasing number of references to patents and unpublished technical reports." Further, it recommends that UNESCO should urge them "to indicate in their publications the principles whereby they select material for notice," with the expectation that such indications would assist in making the whole system more efficient. The importance is also stressed of the terminological and lexicographical work which UNESCO is encouraging in many fields of science and engineering; this work is described in a chapter of the report on Scientific and Technical Translation (and on other possible means for reducing language barriers) which has recently been completed and is due to appear shortly.

SILICON JUNCTION POWER DIODES*

by

D. E. Mason, Ph.D.†, A. A. Shepherd, Ph.D.† and W. M. Walbank, M.Sc.†

SUMMARY

A simplified description of the physical processes responsible for conduction in silicon is given which forms the basis for a description of the properties of *p–n* junctions and hence of silicon diodes. An account of the three main methods of making *p–n* junctions and of the properties of diodes made by these methods then follows. The limitations of the various methods of making diodes and the probable limits of performance which can be achieved using them are discussed. The characteristics of silicon junction diodes which are superior to those of other rectifiers are emphasized and some of the uses for which they possess notable advantages described.

1. Introduction

As the development of silicon junction rectifiers has been proceeding for only about four years, the possibilities of these devices have, as yet, only been touched upon. The small-scale production of silicon diodes has limited the uses to which they have been put to those for which no other diode is suitable. This limitation has been accentuated by the high cost which necessarily accompanies small scale production. However, experimental and theoretical investigations have suggested that silicon rectifiers much superior to those at present available can be developed and that there are many uses for silicon diodes besides rectification which have not yet been exploited. The characteristics of the improved silicon diodes which it is expected will be available after a few years of systematic development are emphasized rather than the characteristics of the few types at present commercially available.

2. Theoretical Characteristics

2.1. *Conduction in silicon and similar semi-conducting materials*

Each silicon atom in a crystal is bound to its four nearest neighbours by a bond resulting from the sharing of an electron between two adjacent atoms. In a perfect crystal at low temperatures no conduction will be possible as there are no electrons free to move. Pure silicon, at even such a high temperature as 300°K (27°C), would have a resistivity of 230,000 ohm-cm. If, however, the crystal contains atoms of Group V of the periodic table which have five valency electrons instead of the four of silicon, one electron will be loosely bound as only four are required to satisfy the four bonds to the adjacent silicon atoms. At normal temperatures this electron will be free to move under an applied electric field. Material showing such conduction due to electrons is known as "*n*-type." Similarly if atoms of Group III (with three valency electrons) are present in the crystal, one electron will be missing from a bond for each impurity atom present. The place from which the electron is missing will behave as a positive charge since, if an electron moves in from a neighbouring atom to fill this missing place or "hole" the hole will move in the opposite direction. Under an applied field these "holes" will behave rather like positive electrons. Materials of this type are said to "conduct by holes" and are known as "*p*-type." Only small proportions of impurities are necessary to modify the resistivity of the material considerably. For example, the addition of one part per million of arsenic to silicon will bring the resistivity into the one ohm-cm range.

Although a perfect silicon crystal at low temperatures is an insulator, as the temperature is raised some electrons receive enough thermal energy to break the bond and are then free to move through the crystal under an applied electric field. The places from which the electrons have escaped behave as "positive holes" in the way described above so there are

* Manuscript received 18th May, 1956 (Paper No. 362).

† Ferranti Ltd., Wythenshawe, Manchester 22.

U.D.C. No. 621.314.63.

a number of electrons and an equal number of holes free to move in the crystal. If n is the concentration of electrons and p of holes at any temperature T°K,

$$p = n = N_0 \exp(-E/2kT) \quad \ldots\ldots\ldots(1)$$

where N_0 is $2{\cdot}8 \times 10^{16}\, T^{3/2}$ for silicon and E is 1·1 eV so that the expression may be rewritten:

$$p = n = 2{\cdot}8 \times 10^{16}\, T^{3/2} \exp(-6450/T) \ldots(2)$$

Pure material which becomes conducting due to the freeing of electrons and holes by thermal energy is known as intrinsic.

When impurities are present, say in a concentration of N n-type (Group V) impurities per cubic centimetre, the electron concentration is increased so that some of the missing electrons from the bonds are replaced, that is the concentration of holes is decreased. The numbers of holes and electrons are then given by

$$np = N_0^2 \exp(-E/kT) \quad \ldots\ldots\ldots(3)$$

In the temperature range in which semi-conductors are used in devices the concentration of electrons is approximately equal to the concentration, N, of n-type impurity atoms present, so that

$$p = (N_0^2/N) \exp(-E/k\mathrm{T}) \quad \ldots\ldots\ldots(4)$$

that is, the number of holes in an *n-type* semiconductor in equilibrium at temperature T increases exponentially with T^{-1}. For convenience in referring generally to both n- and p-type materials, the carriers present in the greatest concentration are called majority carriers while carriers of the other type are called minority carriers. For the range of resistivities used in diode and transistor manufacture the resistivity is approximately inversely proportional to the concentration of impurity.

If holes are introduced by any means into an n-type semi-conductor so that the hole concentration exceeds the equilibrium concentration p, the excess concentration of holes Δp will decrease to zero due to recombination with electrons at a rate given by

$$\frac{\mathrm{d}(\Delta p)}{\mathrm{d}t} = -\frac{\Delta p}{\tau} \quad \ldots\ldots\ldots(5)$$

where τ is a constant known as the lifetime. Thus the excess concentration of holes decreases exponentially with time. The minority carrier lifetime in silicon decreases as the concentration of imperfections and impurities increases. The lifetime of silicon in devices may vary from a fraction of a microsecond to several hundred microseconds.

In p-type materials the electron concentration is given by exactly similar equations merely substituting "electron" for "hole" and "hole" for "electron."

When the concentration of holes in a n-type semi-conductor is not uniform, holes will flow in such a direction as to eliminate the concentration gradient, diffusing a characteristic distance L before recombining with electrons. The distance L is given by $L^2 = D\,\tau$, where D is 13 cm² per sec for holes and 38 cm² per sec for electrons in silicon. In transistors the flow of carriers across the base region is almost entirely due to this diffusion current.

2.2. *Rectifying action in semi-conducting diodes*

The rectification in a junction diode takes place at the junction of the n and p-type regions of the same crystal. Referring to Fig. 1, if there is initially a uniform concentration of holes in the p-type region and electrons in the n-type region, there will be a flow of electrons towards the p-region and holes towards the n-region with consequent recombination until a space-charge layer is set up creating an energy barrier sufficiently high to prevent the flow of further current.

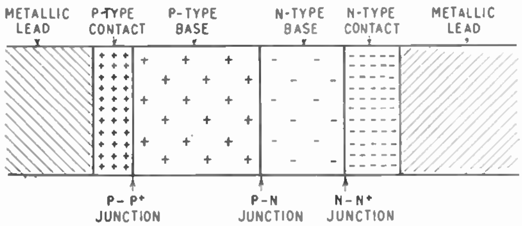

Fig. 1.—Schematic picture of the various parts of a junction diode and the impurity concentrations in those parts.

When the p-region is biased positively holes flow across the barrier from p- to n-regions until they recombine with electrons in the n-region after a time given by the lifetime τ. An electron current flows through the n-region to replace the electrons lost by recombination with holes. Electrons, similarly, will flow across the barrier from the n-region to the p-region until they recombine with holes in that region.

The ratio of the electron and hole currents flowing across the junction will be proportional to the electron and hole concentrations in the n and p-regions respectively. Thus if the p-region has a much greater impurity concentration than the n-region, the current across the barrier will consist mainly of holes.

When the p-region is biased negatively, only the few holes in the n-region and the few electrons in the p-region are attracted across the barrier. As these concentrations of minority carriers increase rapidly with temperature as described above, the reverse current will be very temperature sensitive. After a fraction of a volt is applied the reverse current will saturate at a value I_0 which depends on temperature.

At any temperature T the current across the barrier will be given by theoretical considerations as

$$I = I_0 [\exp (qV/kT) - 1] \quad \text{.........(6)}$$

where V is the *voltage across the barrier*. I_0 increases exponentially with the reciprocal of temperature.

When a reverse voltage is applied, electrons are removed from the n-type side of the barrier and holes from the p-type side so that a double layer is set up to oppose the applied potential. The region from which carriers are removed is known as the "depletion layer." The presence of this double layer results in the barrier having a capacitance per unit area which decreases with increasing reverse voltage and with increasing resistivities of n- and p-type regions. It is important to realize that the whole of the applied voltage appears across the barrier and that the n- and p-type regions are field-free except for the minute field due to a very small current flowing through material of low resistivity.

However, when current flows in the forward direction there will be a voltage drop across the p- and n-type regions on each side of the barrier. The voltage drop in these regions will be proportional to their resistivity. When holes flow across the barrier into the n-type region extra electrons are drawn in to neutralize the space charge set up by the *injected* holes. Thus the resistance of regions reached by the injected holes will be reduced due to the addition of a large concentration of injected holes and an equal number of electrons introduced to maintain electrical neutrality. This phenomenon is known as conductivity modulation. In this way the resistivity of the n- and p-regions may be reduced one hundredfold at quite moderate current densities.

Contacts have now to be made to the n- and p-regions which do not interfere with the action of the diode. Suitable contacts are obtained by making an n–n^+ junction to the n-region and a p–p^+ junction to the p-region (the $^+$ sign indicates a very high impurity content of the appropriate type). This junction creates a barrier which tends to prevent the flow of minority carriers from the base region to the contact. Also as the n^+ region has such a high electron concentration, the hole concentration there will be very small and the current density of holes crossing the barrier when the diode is biased in the reverse direction will be small. The barrier at the contact has the effect of *accumulating* minority carriers injected by the p–n junction when the diode is biased in the forward direction. This is important in reducing the resistivity near the contact where the conductivity modulation might otherwise be small especially if the lifetime in the base region is small.

It has been shown that in a fully modulated diode at moderate currents that the effect of the barrier at the contact is such that the relation between the current through the diode I and the *voltage across the complete diode* V' is

$$I = I_0 [\exp (qV'/2kT) - 1] \quad \text{.........(7)}$$

irrespective of the height of the contact barrier or the rate of recombination of holes and electrons at the contact.* Equation (7) should be compared with equation (6).

During the first few microseconds of the passage of forward current a large concentration of injected minority carriers is formed in the base region. If the diode is then open-circuited, the minority carrier concentration will redistribute itself gradually dying away due to recombination in the volume of the material and at the surfaces. If the voltage had merely been reduced to zero the concentration would

* J. Saby, "Junction rectifier theory." Read at Physical Society Spring Meeting on Semiconductors, April 1956. To be published in *Report of Semiconductor Conference*.

T. H. Kinman, G. A. Carrick, R. G. Hibberd and A. J. Blundell, "Germanium and silicon power rectifiers," *Proc. Instn Elect. Engrs*, **103**, Part A, April 1956. (I.E.E. Paper No. 1936U; October 1955.)

disappear due to recombination and diffusion back to the p–n junction where it is collected. (Minority carriers cannot diffuse out at the contact due to the barrier there.) If a reverse potential is applied, a field is set up in the base region which withdraws the injected charge more rapidly. The initial current on applying a reverse voltage is commonly of the same order of magnitude as the forward current before reversal.

2.3. *Reverse voltage limitations*

As the reverse voltage applied to a silicon diode is increased, carriers approaching the barrier from either side will be accelerated in the field in the depletion layer and at a sufficiently high field will ionize lattice atoms to give further carriers which can be accelerated in the field to give increased ionization. Hence, when a critical voltage is reached, a rapid increase of reverse current occurs. The process is somewhat analogous to the Townsend mechanism of current multiplication in gases. The most convincing evidence that a multiplication process of this type is occurring is given by the following experiment.† A light spot illuminates the silicon on one side of a p–n junction and the variation of current with voltage is measured. At low voltages there is a saturation current due to the minority carriers produced by the light spot being collected at the junction. However, at voltages approaching the breakdown voltage a photocurrent is observed which increases rapidly with increasing applied voltage as shown in Fig. 2.

The probability of current multiplication in diodes increases rapidly as the field in the junction approaches a value of about 250,000 volts per cm. Thus if a diode capable of withstanding a high reverse voltage is desired the field should be substantially constant at its maximum strength for a considerable thickness of the diode. With a diode which has an abrupt transition from n to strongly p-type material, the greatest voltage can be obtained by increasing the resistivity of the n-type material from which it is made and thus increasing the width of the depletion layer. With a graded junction the concentration of impurity is varied across the junction to produce a field substantially equal to the maximum over a greater thickness than with an abrupt junction. Very high voltage breakdowns could be obtained with a thick region of intrinsic material between the p and n regions. In the intrinsic region the field would have its greatest value and would remain constant. However conduction through the intrinsic region would depend entirely on current carriers injected from the n and p regions. Their lifetime in the intrinsic region would therefore have to be long enough to enable them to diffuse across to the other low resistivity region.

3. Methods of Diode Production

In order to produce semi-conductor devices having controlled properties it is essential that the basic material should be a perfect single crystal. The usual method of preparing single crystals of silicon is by growth from molten silicon on to an orientated seed crystal. The seed is dipped into the molten silicon (which is maintained just above its melting point of 1430°C) and slowly withdrawn, when a single crystal is formed on the end of the seed.

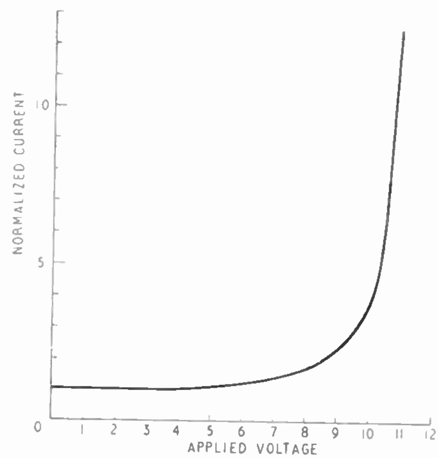

Fig. 2.—Variation of photocurrent with applied junction voltage for an illuminated silicon junction. The ordinate scales have been normalized by setting the photocurrent at low voltages equal to unity. (After McKay and McAfee†. By courtesy of the Editor of The Physical Review.)

Crystals up to an inch in diameter and several inches in length may be grown in this way. The purity of such crystals is usually such that the resistivity is greater than 20 ohm-cm and the lifetime greater than

† K. G. McKay and K. B. McAfee, "Electron multiplication in silicon and germanium," *Physical Review*, **91**, pp. 1079-84, 1st September, 1953.

100 microseconds over the bulk of the crystal. Crystals of lower resistivity are obtained by controlled doping with a suitable impurity.

The p–n junction responsible for the rectifying action in a semi-conducting diode may be formed in three main ways.

Firstly when a silicon crystal is grown by the above method, the first part of the crystal may be made n-type by adding a Group V element (such as arsenic) to the melt, then when the crystal is half grown adding enough of a p-type impurity to more than compensate for the n-type impurity already present, so that the second half of the crystal is p-type. The position of the junction can be located on the crystal and bars, each containing a p–n junction, cut from the crystal. Suitable contacts have then to be made to the p and n regions of the diode. This method of diode production enables the rate of transition from the n-type region to the p-type region to be controlled and gives a diode in which there is no abrupt change from n- to p-type material.

A second method of producing junctions is the alloy process. In one method a wafer of n-type silicon is heated in contact with aluminium. The aluminium may consist of a wire or foil held against the silicon surface or a film evaporated on the surface. On heating to a suitable temperature a molten alloy of silicon and aluminium is formed. When the unit is held at the melting point of the aluminium-silicon eutectic, aluminium probably diffuses into the original n-type crystal to convert it to heavily p-type material. Silicon doped with aluminium may recrystallize back on to this layer to thicken the layer of p^+ silicon. During subsequent slow cooling small crystals of aluminium and silicon form on the converted layer. The boundary between the converted silicon and the original n-type material forms the p–n junction, with the converted material as the p-type base while the aluminium-silicon alloy probably forms the contact. The remaining aluminium acts as an electrical lead. An n^+ contact is made to the n-region using gold containing antimony instead of the aluminium used for the p-region. The alloy method gives essentially an abrupt junction.

The third method of making diodes is by the diffusion of suitable n- and p-type impurities through the solid silicon slice at high temperatures without the formation of a liquid eutectic layer. A layer of boron is first deposited on the n-type slice from a suitable gas such as boron trichloride at a temperature above 1000°C. The boron then diffuses in over a period of many hours while the slice is maintained in an inert atmosphere in a furnace. The p-type layer is then lapped off one face of the slice and an n^+ contact made by diffusing in phosphorus also at a high temperature. The p- and n-type surface layers are of sufficiently low resistivity to plate satisfactorily for the attachment of metal leads.

4. The Choice of a Material for Semi-conducting Diodes

The range of materials which might be considered for junction diodes includes the elements of Group IV of the Periodic Table (germanium, silicon and diamond), the compound silicon carbide, and the compounds of members of Groups III and V. The most important physical properties of these materials for rectifier construction are the energy gap between filled and conduction bands, the mobilities of holes and electrons, and the lifetimes which can be obtained.

As a crystal with a larger energy gap is used, the reverse current at a given temperature will decrease but so also will the forward current at a given voltage. In a practical device this means that the threshold voltage for conduction in the forward direction will increase. For instance, the threshold for germanium with an energy gap of 0·74 eV is about 0·2 volts while for silicon with an energy gap of 1·12 eV it is 0·5 volts. In normal operation germanium can be used up to 80°C, while silicon can be used up to 250°C. Rectifiers made from materials with still larger energy gaps could be used at still higher temperatures, permitting the use of radiative cooling. They could also be used at much higher ambient temperatures. For high voltage rectification, the increase in threshold voltage does not greatly decrease the rectification efficiency. In a diode of the type we have been considering, the forward current is inversely proportional to the lifetime of minority carriers provided that the conductivity modulation is sufficient. As conductivity modulation requires a long lifetime, an optimum lifetime should exist for a diode of given construction.

A high minority carrier mobility (velocity for unit field) will result in a large modulation of the base conductivity for a small number of injected carriers. This may assist in minimizing hole storage. A high breakdown voltage will necessitate a low carrier concentration in the base region.

Ease of manufacture, both in the purification of the raw material and in device fabrication, has resulted in the present popularity of germanium. The fabrication of rectifiers by growing from a melt should be possible for all materials of which single crystals have been grown in this way. It is doubtful if alloying techniques would be successful with compounds due to the complex metallurgy involved. Diffusion methods should be possible with both simple elements and compounds, while depletion of one component of a compound should give similar results to diffusion.

A table of the relevant properties of some materials which might be considered for junction rectifiers is given in Table 1.

Table 1

Properties of Materials suitable for Semi-conducting Diodes

Substance	Energy Gap (eV)	Electron Mobility	Hole Mobility	Lifetime achieved (seconds)
Germanium	0·74	3600	1800	$>10^{-3}$
Silicon	1·12	1500	500	$>5 \times 10^{-4}$
Diamond	5·2	850		10^{-8}
SiC	2·8			
InP	1·25	3400	650	less than 10^{-6}
GaSb	0·67	4000	650	
GaAs	1·35	3500		
GaP	2·4			
AlSb	1·6		200	
AlAs	2·4			

5. The Characteristics of Junction Diodes

As the potentialities of alloyed diodes have, so far, been realised to a greater degree than those of grown junction or diffused junction diodes and as all silicon junction diodes at present on sale are of the alloyed type, these will be considered first.

5.1. *Alloy junction diodes*

5.1.1. Signal or low power diodes

Alloy signal or low power diodes may be divided into two classes, the first typified by the original Bell Telephone Laboratories and Texas Instrument units being non-modulated while the second class including the Ferranti ZS10 and Transitron diodes show considerable conductivity modulation. The performance of non-modulated diodes in the forward direction deteriorates steadily with increasing reverse breakdown voltage. The increasing resistivity of *n*-type base needed to give the higher reverse voltage produces a considerable increase in the forward resistance in series with the rectifying barrier. With modulated diodes the reduction in base resistance due to hole injection is sufficient to swamp any variation in the normal resistance of the base region when the diode is drawing forward current, so that the forward characteristic is practically independent of the breakdown voltage.

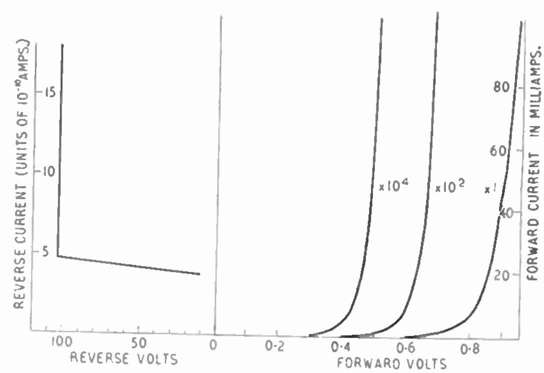

Fig. 3.—Current-voltage characteristic of a ZS10 small area silicon junction diode at room temperature.

The characteristics of a typical alloyed diode (Ferranti ZS10) are shown in Figs. 3 and 4 and the general construction in Fig. 5. This diode has a rectifying junction of less than 10^{-4} in^2 and as it is only intended for use in small power applications no special provision is made for conducting the heat away from the silicon die. The conduction of heat down the leads provides the main heat conducting path from the die. This diode has a permissible dissipation of 150 mW at 25°C.

From curve 4 it will be seen that the forward current is less than one microampere for voltages less than 0·4 volts but that it then increases rapidly so that 100 mA is passed at less than one volt. If the forward characteristic is explored further by using low duty ratio current pulses to decrease the average dissipation the current will be found to increase to 5 A at approximately 7 V. As the voltage drop across the rectifying barrier, which is represented by the exponential part of the forward characteristic shown in Fig. 4 (see equation 6), is only 0·7 V when 100 mA is passed and 0·9 V when 1 A is passed, it will be appreciated that the characteristics of the diode will depend greatly on the properties of the base layer between rectifying junction and n^+ contact. With reasonable manufacturing tolerances it is found that the voltage drop for 100 mA forward current lies between 0·8 and 1·2 V. As the temperature of the diode increases, at low voltages the current will increase due to the exponential increase of I_0 with temperature while at larger voltages the current will decrease

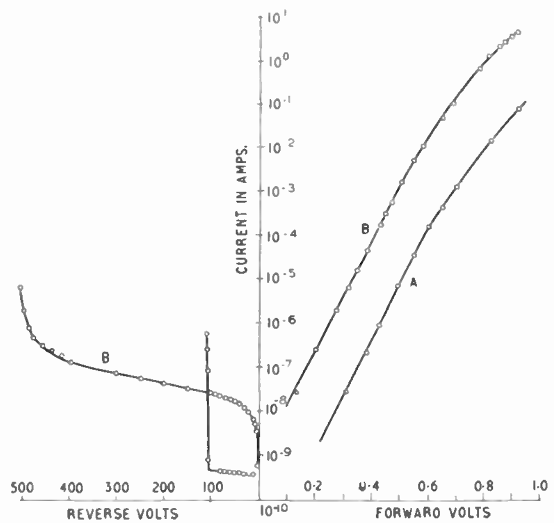

Fig. 4.—Current-voltage characteristics of silicon junction diodes at room temperature with a logarithmic current scale. A, ZS10 small area alloy diode. B, diffusion diode of 0·01 in² area.

due to the overriding effect of the term $\exp(qV/kT)$ in equation (6). With the ZS10 diode the latter decrease is only observed with low duty ratio current pulses. I_0 is usually found to be about 10^{-13} amperes at room temperature.

The reverse current, which in the simple theory presented above should saturate at I_0, actually is much larger and may not saturate. At room temperature the reverse current is never less than 10^{-10} A. The lack of saturation may be due to the presence of recombination centres generating minority carriers within the base layer. As the applied voltage is increased the width of the depletion layer increases and the generated minority carriers are swept out of an increasing volume of the base region. Another mechanism explaining the lack of saturation depends on the presence of a surface p-layer forming an extension of the p–n junction with the n-type base which is thin enough to have a high resistance. As the reverse voltage increases the reverse current drawn will cause a voltage drop in the layer such that larger and larger areas of surface draw their saturation reverse currents at increasing voltages. The "saturation" reverse current at moderately high temperatures increases approximately exponentially with temperature at a rate corresponding to an activation energy of 0·67 eV. Thus a diode passing a saturation reverse current of $1{\cdot}3 \times 10^{-9}$ A at 13°C will pass 6×10^{-8} at 60°C and 3×10^{-6}A at 127°C.

As reverse currents of less than 10^{-9} A may be obtained at a reverse voltage of 100 V at room temperature it will be appreciated that any surface leakage across the exposed part of the junction must be eliminated. This is done by a careful etching treatment after alloying which removes the imperfect material formed at the junction during alloying. Residual leakage after etching may be due to conduction by ions which have not been removed from the surface by an inadequate cleaning technique or by leakage through a protective film coating the diode.

The maximum reverse voltage at which the diode may be operated is determined by the onset of the avalanche process as described in Section 2.3. At the abrupt junction formed by the alloying process a very high field may extend for sufficient distance for corona to occur across the junction. This limits the abrupt junction diode to about 1000 V. In practice, breakdowns, probably in the surface layers at the junction, tend to occur at a lower voltage than the body breakdown and become more difficult to eliminate as the body breakdown of the diode increases. Using low resistivity material diodes can be made with stable breakdown voltages in the 1–20 V region. The slope impedance varies approximately as the square of the breakdown voltage between 4 and 40 V while the temperature coefficient is negative below about 7 V where it becomes zero, then increasingly positive. Typical values of slope resistance in the breakdown region for a diode of the same construction as a ZS10 diode are 7–10 Ω for a 7-V diode and 30–50 Ω for a 15-V diode. This part of the characteristic has been used as a voltage reference at low voltages. The main reason for desiring a true body breakdown in diodes used for rectification is that in this case the breakdown voltage depends only on the resistivity of the material used and on the configuration of the junction and will therefore be stable while surface breakdowns may depend on the surroundings of the diode and change with time.

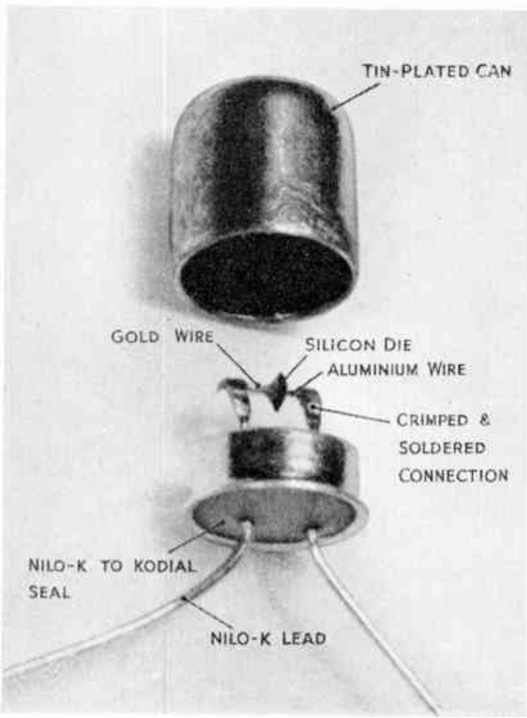

Fig. 5.—The construction of a ZS10 silicon junction diode. The external diameter of the can is 5·7 mm.

The hole storage characteristics of a ZS10 diode are illustrated in Fig. 6. The diode is made to pass a forward current of 150 mA for a sufficient time for equilibrium to be set up. The diode is then open-circuited for a variable time after which a reverse voltage of 100 V is applied through a 2,000-Ω resistor and the hole storage current measured. The decrease in the area under the curves for increasing times of delay shows the way in which the stored charge decays away in the open-circuited diode. Table 2 illustrates the dependence of the initial reverse current, decay time and stored charge on the forward current passing before reversal. The reverse pulse was of 50 volts amplitude, had a source impedance of 2,000 Ω, and was applied immediately the forward current ceased.

Table 2

Forward Current	Initial reverse current (mA)	Time to decay to 10% (μsec)	Stored charge in coulombs
100	23	2·0	$2{\cdot}45 \times 10^{-8}$
75	22	1·8	$2{\cdot}0 \times 10^{-8}$
50	20	1·5	$1{\cdot}5 \times 10^{-8}$
25	12	1·2	$1{\cdot}0 \times 10^{-8}$

Hole storage may limit the useful frequency range of such a diode as the storage current may take several microseconds to die away. Hole storage is also of importance in power applications. The main consideration here is the power dissipated in the diode when the frequency is high enough for a high reverse voltage to be applied before the hole storage current has ceased. It is important to realize that the hole storage of a non-modulated diode need not be any less than that of a modulated diode, the essential difference being that in the non-modulated diode the region of the base which is effectively modulated does not extend to the contact.

5.1.2. Higher current alloy junction diodes

Alloy junction diodes of greater current-carrying capacity can be made by increasing the area of the junction using either wire or foil or an evaporated layer of aluminium. The main difficulty in the production of such diodes is the considerable shrinkage of the aluminium–silicon eutectic on solidifying with consequent strain and possible fracture near the junction. Well modulated diodes capable of carrying 10 A have been made by these techniques.

5.2. *Grown junction diodes*

When a *p–n* junction is grown from the melt, the impurity concentration across the junction can be changed gradually. This impurity distribution produces a field substantially equal to the maximum field over a considerable width of the junction and would thus appear very suitable for diodes to withstand very high reverse voltages. However, if a high-voltage diode is to pass a reasonable forward current the *p*- and *n*-type base regions must be modulated by injected minority carriers so that the p^+ and n^+ contact regions must be sufficiently close to the *p–n* junction for the majority of injected minority carriers to reach them. This means that these regions must be alloyed to the diode fairly close to the junction without affecting the lifetime in the *p*- and *n*-base regions. As the junction is grown originally from the melt and consists entirely of silicon, the lifetime in the bar should be as high as that in a single crystal grown from the melt. This lifetime is much greater than the lifetime in devices made by the alloy process. As all processing of silicon at high temperatures after growth (especially unless subsequent cooling is very slow) tends to reduce the lifetime of minority carriers in silicon it is advantageous to use a process which involves the minimum of heating and strain close to the *p–n* junction. All grown junction diodes so far produced have been laboratory specimens but an indication of possible performance may be deduced from specimens in which the diode made from a bar of 2 mm square cross-section passed a current of 50 mA at 6 V and withstood a reverse voltage of 5 kV.

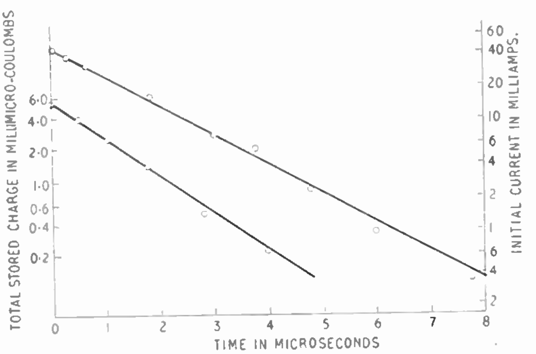

Fig. 6.—The variation of stored charge (lower curve) and the variation of the initial current (upper curve) with the time at which a constant reverse voltage is applied after the cessation of forward current.

The advantages of the grown junction diode may not be as definite as would be imagined from previous discussion, as we have assumed previously that in diodes made by the alloy process, avalanche breakdown occurred before the depletion layer reached the contact region. If, however, the resistivity of the die is great enough for this to be untrue, the solution of the equation for the field across the base region changes and at high voltages this field is practically uniform. This means that alloy (or diffusion) diodes withstanding high voltages could be made if the lifetime can be maintained great enough to permit modulation of the base resistivity.

5.3. *Diffusion diodes*

One of the main advantages of this method of production is the ease of manufacture of large area junctions. In the diffusion process no large mechanical strains are set up near the junction, whereas in the alloy process, the avoidance of strain presents a serious problem. Thus it should be possible to make diffusion diodes with an area as large as that of the largest slice which can be cut from a single crystal of silicon. Also the diffusion process produces a gradual change in impurity concentration at the junction which should make it possible to obtain higher reverse voltages than those obtainable with simple alloy diodes. The main disadvantages of the process appear to be the drastic decrease in lifetime of the slice during processing over 1,000°C and the changes in resisistivity which occur during this process. If these difficulties are surmountable it should be possible to produce a rectifying element 0·1 inches square which would have the same performance per unit area as the optimum alloy diode and would thus pass 25 A with a voltage drop of 1 V. Reverse voltages of 400–700 V might be expected with reverse currents at room temperature of less than 10 μA. Fig. 4 shows the characteristics of a diode which are approaching these values, the forward current at 1 V being 10 A. It will be appreciated that the removal of the energy dissipated at the junction (25 watts) is a problem of some importance and will determine the size of the completed diode.

6. The Applications of Silicon Junction Diodes

6.1. *Summary of important features of silicon junction diodes as circuit elements*

The applications for which silicon junction diodes are especially suitable, follow from their main advantages which are detailed below:—

(1) They are mechanically rugged and able to withstand shock and very severe vibration.

(2) Units are designed to operate with 1·0 V across them at their maximum continuous rating, the junction current density then being about 3,000 amperes per square inch of junction area. At this rating the unit can withstand severe overloads for times less than the thermal time constant of the unit.

(3) Junction temperatures of 150–200°C are normal while temperatures up to 300°C may be allowable in special applications. The high permissible junction temperature allows a considerable temperature drop in the arrangement for the dissipation of heat and permits the use as heat sinks of structural members of large thermal capacity at temperatures as high as 100°C.

(4) As the reverse current is so small, the power dissipation due to reverse current flow is negligible except at very high temperatures or at very high reverse voltages. The very small reverse current also makes the silicon diode a suitable replacement for the thermionic diode in circuits in which very small reverse currents are necessary.

(5) Silicon junction diodes are very small for the current rating and reverse voltage at which they will operate. For units capable of handling continuous currents of more than one ampere the size is determined by the arrangement necessary for heat dissipation.

(6) In many circuits semi-conducting diodes have advantages over thermionic diodes as no heater supply is necessary, no forward current flows at zero applied voltage and the capacitance is very small, while in addition silicon diodes have low reverse currents.

(7) The form of the reverse breakdown (avalanche) characteristic of silicon diodes makes them especially suitable for use in series to withstand high reverse voltages without a parallel chain of resistors to divide the voltage. Units capable of withstanding 100 V per unit have been connected in series to withstand 5 kV. As the reverse voltage across a chain of diodes is increased, practically all the voltage will appear across the diode with the lowest reverse current until the breakdown voltage of that diode is reached. The current will now increase very rapidly until the reverse current of the diode with the next lowest saturation current is reached, when the current will remain constant until the breakdown voltage of that diode is reached. This process will continue until all the diodes are operating in their avalanche breakdown regions when the current will increase rapidly with voltage. As it is quite permissible to operate these diodes in the avalanche region provided that the power dissipation is severely limited the use of silicon diodes in series without a voltage dividing chain is quite satisfactory.

For use in parallel to carry large currents some caution is necessary as the slope resistance of the diode in the conducting region is very small and manufacturing tolerances are such that the current carried in this region for a given applied voltage may vary by a factor of four. However, a low resistance in series with each diode is sufficient to equalize the current flow through each diode and to distribute the power dissipation. For the ZS10 diodes a series resistance of 4Ω would be quite sufficient while for the diffusion diode shown in Fig. 4 a resistance of 0·1Ω would be adequate.

6.2. *Typical applications as rectifiers*

(1) As the voltage drop across the rectifier is only 1 V at the full rated current, silicon junction diodes are very suitable for low voltage high current rectification at high efficiency. Only where forced-air or water cooling is suitable does the rather lower voltage drop of germanium junction rectifiers become of importance. Considerable savings in valuable factory space may be made by using silicon rectifiers instead of selenium rectifiers in power supplies for plating and electrolytic tanks. They are also useful for automobile charging systems, eliminating cut-outs and enabling the use of robust alternators instead of d.c. generators employing brushes.

(2) The small reverse current enables magnetic amplifiers with very small drift to be made. Only in the most sensitive types of amplifier designed to work at high temperatures is the reverse current of any consequence, making balanced pairs of rectifiers necessary.

(3) They are suitable for use in power supplies and control circuits of all types in parts of aircraft and other situations where extreme vibration and high temperatures occur.

(4) Very small well-protected units for high voltage rectification may be constructed.

(5) A rather unusual use for silicon diodes is as rectifiers in a silicon junction diode modulator for direct-current amplifiers employing

junction transistors. N. F. Moody* has described a unit, which when operated under correct conditions, can convert d.c. signals to an a.c. carrier over a range which extends from audio to at least 100 kc/s. A zero stability of 10^{-10} watts or better is achieved at room temperature. This corresponds to currents of the order of 10^{-8} amperes for units fed from a constant source. Operation at 80°C is still acceptable although degraded by about two orders of magnitude.

The stability of the unit using silicon diodes is due to the stable threshold (which varies comparatively little from diode to diode), the definite slope of the logarithmic forward current curve and the negligible reverse current at room temperature. It is interesting to compare this performance with that given by other types of rectifier. The thermionic diode yields an excellent semi-logarithmic relationship between forward current and voltage and furthermore may be designed to show reverse currents even smaller than the silicon diode. The performance is marred by contact and thermal emission velocity potentials which may introduce changes of a tenth of a volt in the threshold during life. In transistor circuits the need of heater power, with attendant problems of heater–cathode insulation and pick-up makes the device an undesirable ancillary.

The older multi-crystalline rectifiers, such as copper oxide and selenium units, do not follow any accurate theoretical law. Thus considerable errors due to resistive unbalance occur and reverse currents are usually many orders greater than those shown by silicon junctions. The germanium diode, while otherwise very suitable, has a reverse saturation current large enough to degrade the modulator performance by three orders of magnitude.

* N. F. Moody, "A silicon junction diode modulator for use in junction transistor direct-current amplifiers." *Electronic Engineering*, **28**, p. 94, March 1956.

This modulator provides an interesting use of silicon diodes where the forward current is only of the order of 10^{-7} amperes. The total size of the silicon junction diode ring modulator unit with transistor amplifier is only $1\frac{1}{4}$ in. × $\frac{1}{2}$ in. × $\frac{1}{2}$ in., a very compact piece of circuitry.

6.3. *Applications of silicon junction diodes other than as rectifiers*

(1) The comparatively low impedance of the avalanche breakdown region is useful as a voltage reference especially at low voltages. In large power diodes this characteristic can be used as a lightning protector.

(2) The very small forward current below 0·5 V combined with the low impedance above 0·7 V makes the silicon diode a valuable protective device effectively short-circuiting voltages above 0·7 V.

(3) As the current increases accurately in an exponential manner with voltage over four orders of magnitude of current, selected silicon diodes are useful as logarithmic elements giving a voltage output proportional to the logarithm of the current passing through them from a high impedance source.

7. Conclusion

It is evident that the applications of silicon junction diodes are very great indeed, especially in situations where high ambient temperatures are experienced. They are suitable for use when currents from microamperes to thousands of amperes and voltages from a few volts to tens of thousands are handled. From the general discussion it is evident that they will also be used as voltage references and logarithmic elements.

8. Acknowledgments

Our thanks are due to Dr. P. Ravenhill for the measurements of hole storage and to Dr. D. F. Taylor for measurements of diode characteristics.

GRADUATESHIP EXAMINATION—MAY 1956—PASS LISTS

These lists contain the results for *all* successful candidates in the May 1956 Graduateship Examination. A total of 761 candidates entered for the examination which was held at 70 centres. This number included 217 candidates attempting all or parts of the examination in order to complete qualification for election to Graduateship or Associate Membership of the Institution.

LIST 1—UNITED KINGDOM AND EUROPEAN CENTRES

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

ADAMS, Terrance George Frederick. (S) *London.*
ALLEN, George. (S) *Plymouth.*
ARDITTI, Joseph. (S) *London.*
ASHMAN, Roy John. (S) *London.*
ASHMAN, William George. (S) *London.*

BARRETT, Brendan. (S) *Birmingham.*
BELLIS, Frederick Victor. (S) *London.*
BUGEJA, Alban Anton. (S) *London.*

CHAPMAN, Maurice George. *London.*
COLE, Horace Albert George. (S) *London.*
COULBECK, Bryan. (S) *Birmingham.*

DAWES, James Peter. (S) *London.*

ELLIS, William Bernard Keble. *London.*

FISHER, Jack Edward. (S) *London.*

GOUTAMA, Mysore Ananthamurty. (S) *London.*
GRAY, Robert Frank. (S) *London.*

HANNIFAN, John Patrick. *Birmingham.*

KNITER, Edmund. (S) *London.*

LAKDAWALA, Homi Feroze. (S) *London.*
LISTER, Cyril. *London.*

McCARTHY, Kenneth John. (S) *London.*
McDONALD, Brenden Anthony. (S) *London.*
MAJUMDER, Amal Kumer. (S) *London.*
MASTERS, John Henry. *H.M.S. Dolphin.*
MILLS, Samuel John. (S) *London.*

PHILLIPS, Kenneth John. *Birmingham.*

RATCLIFFE, Norman. (S) *Manchester.*

SIBBALD, John Scott. (S) *Edinburgh.*
STRANGE, Norman Edward. (S) *London.*

WARD, Reginald Havelock. *London.*
WEEDON, Antony John. (S) *London.*
WILLIAMS, Laurence *London.*

The following candidates were successful in the Parts indicated

ABBOTT, Michael Ronald. (IIIa) (S) *London.*
ABRAHAM, Arefe Aine. (II) (S) *London.*
AINSCOUGH, Kenneth. (IIIb) (S) *London.*
AYLWARD, Patrick. (IIIb) (S) *Dublin.*

BAKHSHI, Manohar Singh. (IIIb) (S) *London.*
BALFRE, Paul Victor. (I) (S) *London.*
BELL, Duncan. (I) (S) *London.*

BENNETT, Arthur John. (II) (S) *London.*
BINKS, John Kenneth (I) (S) *Birmingham,*
BRENNAN, James Joseph. (II) *Dublin.*
BURR, Albert Edward. (I) *London.*

CAMPBELL, Malcolm. (IV) (S) *London.*
CHANNING, Ronald Francis. (II & IV) (S) *London.*
CHEUNG, Shiu Hung William. (II, IIIb & IV) (S) *London.*
COOPER, John Derek. (II & IIIb) *London.*
CRANE, Patrick Herbert (I) *London.*
CUTLER, George Donald. (I) (S) *London.*

DALZELL, Thomas Derek. (I) *Manchester.*
DAVIS, Michael John. (I) (S) *London.*
DOBBIN, Robert George. (I) (S) *London.*
DORMAND, Keith. (II & IIIb) (S) *Jersey.*
DOUBELL, Lionel Joseph. (II) *London.*
DOUGLAS, Walter Harry Brookes. (IIIb) (S) *London.*
DU BARRY, James Joseph. (II & IIIb) (S) *Dublin.*

ELLERINGTON, William. (I) (S) *London.*

FLANAGAN, Robert Gerald Patrick. (IIIa) (S) *Dublin*
FLOREK, Casimirus. (IIIb) (S) *London.*
FULTON, Edward Ian Whittenham. (I) *Glasgow.*

GEORGE, Julian. (II) (S) *London.*
GREEN, Kenneth Henry. (II & IIIa) (S) *London.*
GREY, John. (I) (S) *Belfast.*

HALTON, Dennis Lewin (I & II) (S) *Manchester.*
HEYS, Harry. (IIIa) *London.*
HOLDEN, Dennis George. (IIIb) (S) *London.*
HORGAN, Francis. (I) (S) *London.*
HYDER, Thomas William. (II) (S) *London.*

JACKSON, Michael Clifford. (II) (S) *Bristol.*
JAEGER, Eric. (II & IIIa) (S) *London.*

KENNY, Gerald. (II) (S) *London*
KERSH, Cyril. (II (S) *Birmingham.*
KHAN, Mohammed Salim. (II) (S) *London.*

KING, John (I) (S) *Dagenham.*
KIVITY, Nissim Joseph. (I) (S) *London.*
KLIKOWICZ Eugeniusz. (I) (S) *London.*
KOUREAS, Varnavas Demetri. (IIIb) (S) *London.*
KYI, Maung Aung. (II) (S) *London.*

LANGTON, Charles Hazelhurst. (IIIa) *Manchester.*
LE WARNE, John Arthur. (I) *London.*
LOUCH, Terence George Henry. (I) *London.*

MARTLEW, Alan. (I) (S) *Manchester.*
MENZIES, Duncan Alexander John. (I) (S) *Glasgow.*
MOORE, Ernest Henry. (II & IIIa) (S) *London.*
MOSS, Geoffrey. (IIIb) (S) *London.*
MULDOWNEY, Gerald Charles. (IIIb) *London.*
MURPHY, Joseph William (IIIb) (S) *Manchester.*

OLSEN, George Henry. (II) (S) *Newcastle.*
ORZECHOWSKI, Janus Stanisław. (I) (S) *London.*
OSBORN, James Phillip. (I) (S) *London.*
OXBOROUGH, Derek Mervyn. (I) *London.*

PIATEK, Tadeusz-Ludwik. (II) (S) *London.*
PODLASKI, Jan. (II) (S) *Manchester.*

RAI, Thakral H. B. (II) (S) *Birmingham.*
RICE, Matthew Joseph (I) (S) *Belfast.*
ROBSON, Alan. (IIIa) (S) *Newcastle.*
RYNKIEWICZ, Arthur Edward. (II & IIIb) (S) *London.*

SANDYS, Maurice Arthur. (I, II & IIIa) (S) *London.*
SCHOFIELD, Paul. (IIIb) (S) *London.*
SEXTON, Brian Leslie. (II) (S) *London*
SHARP, Gerald Louis. (I) (S) *London.*
SLOOTS, Arnoldus H. J. (IIIb) (S) *Delft.*
SMITH, John Douglas. (IIIb) (S) *London*
SPACKMAN, Charles Bradwell. (II & IIIa) (S) *London.*
SPARKES, Joseph Thomas. (IIIa) (S) *Manchester.*
SPENCER, Godfrey Stanley Gibson. (IIIa) (S) *London.*
STEPHEN, Sidney George. (I) (S) *Cardiff*
STORNEBRINK, Petrus Jacobus. (I & II) (S) *Delft.*

TAYLOR, William John. (II) (S) *London.*
TSANG, Hin-Wa Albert. (I) (S) *London.*
TURNER, Dennis John. (II & IIIb) (S) *London.*
TYE, Alfred Henry. (I) (S) *Birmingham*

WALES, Sidney Alfred. (IIIa) (S) *H.M.S. Saintes.*
WHITE, Nigel John. (I) (S) *Bristol.*
WHITEMAN, John. (II) (S) *Birmingham.*
WILKINSON, George Arthur. (I) (S) *Hull.*
WOOLFORD, Alan John. (IIIb) (S) *London*

LIST 2—OVERSEAS CENTRES

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

BHATIA, Madan Mohan Sugnomal. (S) *Bombay.*
BHOWMICK, Saurendra Nath. (S) *Bangalore.*
BRADLEY, Robert Oswald. *Karachi.*
BUEHLER, Walter. (S) *Montreal.*

FISHMAN, David H. *Tel-Aviv.*

GITTINS, Leonard. (S) *Cairo.*

JAIN, Mahendra Kumar. (S) Bombay.

KANWAR, Randhir Singh. (S) *Delhi.*

KAR, Sarjot Kumar. (S) *Bangalore.*

NEUMARK, Nathan. (S) *Tel-Aviv.*

RANGARAJAN, K. S. (S) *Madras.*
ROTHNEY, Alex Castel. *Accra.*

SHARP, Gregor Hugh. (S) *Sydney.*
SHINDE, Yeshwantrao R. (S) *Bombay.*

THOMAS, Edison Symonds. (S) *Bangalore.*

VENKATESWARAN, Vadakanthara Venkatachalan. (S) *Bangalore.*

The following candidates were successful in the Parts indicated

AGHARKAR, Ratnakar Vinayak. (IIIa) (S) *Bombay.*
ANTONY, O. A. (IIIb) (S) *Trichnopoly.*
ARAVINDAKSHA, Menon T. M. (II) *Bombay.*
ASLAM, Mohammad. (II) *Karachi.*
AZAR, Yoram. (II) (S) *Tel-Aviv.*

BANSAL, Vijai Kant. (IV) (S) *Delhi.*
BERLING, George Paul. (IIIa) (S) *Toronto.*
BHAGAT, Shiv Raj Huria. (IIIa) (S) *Agra*
BHATTACHARYA, Dilip Kumas. (II) (S) *Delhi.*
BOWLER, John Ralph Williams. (I) (S) *Dunedin.*

CHABRIA, Bihari. (II) (S) *Madras.*
CHATTERJEE, Akhil Kumar. (I) *Agra.*
CHEW, Bak Khoon. (IIIb) (S) *Singapore.*

DANDEKAR, Shridhar Kashinath. (IIIa) *Bombay.*
DHALL, Raj Kumar. (IIIa) (S) *Calcuuta.*
DIAS, Cyril Francis. (IIIa) (S) *Delhi.*
DOGRA, Yash Pal. (IIIa) (S) *Calcutta.*
D'SOUZA, Denis. (II) (S) *Bombay.*

FIRLOTTE, Joseph Leander. (I, II, IIIa & IIIb) (S) *Montre..*
FRAMPTON, Peter Guy. (I, II & IIIa) (S) *Hong Kong.*

GABOR, Reuben Peter. (IIIb) (S) *Tel-Aviv.*
GILBERT, Garvin Robert. (II) (S) *Wellington.*
GODSI, Mayer. (I, II & IIIa) (S) *Tel-Aviv.*
GOSWAMI, Joginder Pal. (I) *Agra.*
GRAMOPADHYE, Balkrishna Dhondo. (II) (S) *Bombay.*
GURCHARAN, Singh Surie. (IIIa) (S) *Bangalore.*
GURDIAL, Singh. (II & IIIa) (S) *Kuala Lumpur.*

HALTOVSKY, Efrain David. (I) (S) *Tel-Aviv.*
HANS, Raj Singh Siwach. (I, II & IIIa) (S) *Delhi.*
HARBANS, Singh Sarna. (I) (S) *Lucknow.*
HATTANGADI, Vasant Annaji. (IIIb) (S) *Bombay.*
HOLTZHAUSEN, Petrus Johannes. (IIIa) (S) *Johannesburg.*

ISLAM, Sayed Sultan-ul. (IIIb) (S) *Rawalpindi.*
ISLAM, Nazrul. (IIIa) (S) *Lahore.*
IZZARD, Malcom Ian. (IIIb) (S) *Durban.*

JAGGI, Inder Singh. (IIIa) (S) *Delhi.*
JAGJIT, Rai. (I & II) *I.N.S. Valsura.*
JAIN, Ajit Pershad. (IIIb) (S) *Delhi.*
JAIN, Naim Chand. (II) (S) *Delhi.*
JANGRA, Ram Narayan. (I) (S) *Lucknow*
JATHAR, Neelkanth Balakrishna. (IIIb) (S) *Bombay.*
JAYARAM, Thumala Varadharajulu. (I) (S) *Madras.*

KARKHANIS, Bhalchandra Balkrishna. (IV) *Delhi.*
KHADILKAR, Narayan Shankar. (I, IIIa & IV) (S) *Bombay*
KHARKAR, Shripad Viswanath. (IV) (S) *Bombay.*
KING, Gordon Henry. (II) (S) *Sydney.*
KOTWAL, Jogdish Prashad. (I, II & IIIa) (S) *Trichinopoly*
KRISHNASWAMY, Rao M. S. (IIIa) (S) *Bangalore.*
KUMAR DEVA, Shanti. (IIIa) (S) *Agra.*
KUNDU, Sati Nandan. (IIIb) (S) *Lucknow.*
KUNDU, Sushyamal. (IIIb) (S) *Bangalore.*

LAKSHMANA, Rao Motamarry. (IIIa) (S) *Bombay.*
LAKSHMANAN, Krishna. (IIIb) *Delhi.*
LEVI-MINZI, Gad. (I) *Tel-Aviv.*

MACKINNON, Terance Charles Flynn. (IIIa) (S) *Kuala Lumpur.*
MADAN, Amrit Lal. (IIIa) (S) *Calcutta*
MADAN, Kaikhushru Rustomji. (IIIb) (S) *Bombay.*
MADAN, Rusi Sorabji. (IIIb) (S) *Bombay.*
MAHAJAN, Prabhakar Shankar. (IIIa) (S) *Bombay.*
MAHMUD, Mohd Hanif. (I, II & IIIa) *Karachi.*
MAITRA, Pranab Kumar. (I) *Calcutta*
MANJE, Gowda N.S. (II) (S) *Bangalore.*
MARATHE, Yashvant. (I & II) *Bombay.*
MATHEWS, Abraham. (II) (S) *Agra.*
MEHTA, Dinshaw M. (IIIa) (S) *Bombay.*
MEYER, Leighton Francis. (II) (S) *Wellington.*
MIRCHANDANI, Chandurbhan Fatehchand. (IIIb)) (S) *Delhi.*
MITTAL, Rajesh Chandra. (II, IIIa & IIIb) (S) *Aga.*
MUTHURAGHAVAN, Navaneethan. (IIIa) (S) *Bangalore.*

NAIR, Bala Krishna Shreekumar. (IIIb) *Bombay.*
NARASIMHAN, K. Srinivasachary L. (IIIa) (S) *Calcutta.*
NARASINHACHAR, Mandayan K. (IIIa & IIIb) (S) *Calcutta.*
NARULA, Bhagwan Dass. (II) *Bangalore.*

OM PRAKASH, Chopra. (II & IIIb) (S) *Delhi.*

PRAHARAJ, Arakhita. (IIIb & IV) (S) *Bombay.*

RAHEJA, Udhavlal Topandas. (II) (S) *Bombay.*
RAMA, Chandra Warrier K.G. (I) *Madras.*
REICH, Paul. (IIIb) (S) *Tel-Aviv.*
RODDY, Dennis. (IIIb (S) *Toronto.*
ROY, Arun Kumar. (IIIa) (S) *Calcutta.*
ROY, George. (II) (S) *Calcutta.*
RUPRIA, Balwant Singh. (I) (S) *Bombay.*

SANKARANARAYANAN, S. (IIIa) (S) *Hyderabad.*
SAPRU, Kanhaiya Lal. (IIIb) (S) *Delhi.*
SARMA, D. Parameswara Prasad. (IV) *Bangalore.*
SATHYANARAYAYANAN, N. (I) (S) *Madras.*
SEKHRI, Guatan Dev. (IIIa) (S) *Delhi*
SHAMSHER, Singh Jawahar. (IIIa) (S) *Hyderabad.*
SHARMA, Gulzari Lal. (IIIb) (S) *Hyderabad.*
SHEMY, Kalman. (IIIa) (S) *Tel-Aviv.*
SHUKLA, Rajan Prakash. (IIIa) *Agra.*
SOHAL, Joginder Singh. (IV) (S) *Bombay.*
SUBRAMONYAN, S. Harihari. (IIIb) (S) *Calcutta.*

TALMACIU, Joseph. (IIIa) (S) *Tel-Aviv.*
TARLOCHAN, Singh. (II) (S) *Agra.*
THADANI, Hiro K. (II) *Delhi.*

USMAN, Mirza Mohd. (I) (S) *Dhahran.*

VASUDEVAN, V. (I, II & IIIa) *Delhi*

(S) denotes a registered Student.

THE CLOSING DATE FOR ENTRIES FOR THE NOVEMBER 1956 EXAMINATION IN GREAT BRITAIN IS OCTOBER 1ST.

RADIO AND TELEVISION INTERFERENCE*

by

M. Smith †

Previously presented at a meeting of the North-Western Section in Manchester on January 5th, 1956. Read before the Institution in London on April 25th, 1956.

SUMMARY

A survey is given of the principal causes of interference to domestic radio and television; methods of detection and suppression of the various types of interference are also described, with particular reference to the work of the British Post Office investigating branch.

1. Introduction—The Magnitude of the Problem.

As will be seen from the Table overleaf the yearly figures for interference complaints for the Manchester area show a continual increase from 1947 to 1951, a fairly sharp drop in 1952, and then a continual steady rise to 1955. The decrease in complaints in 1952 is explained by the issue at that time of a new type of interference complaint form calling for a 14-day log of interference times when the source of interference was not known. There is no doubt that the issue of this type of complaint form which also contained very good advice on various types of aerial installations, resulted in the elimination of a number of complaints which could be described as unreasonable, and allowed more time for investigation of the really serious complaints.

Some years ago, broadcast interference complaints were classified into two main types according to their origin, namely "Oscillation", due to radiation from oscillatory circuits, and "Electrical", due to sparking, etc., from electrical equipment. This is a convenient classification and will be adopted in this paper.

2. Interference from Oscillatory Circuits

2.1. *Receiver Local Oscillators*

In the early days of broadcasting, the main cause of the oscillatory complaints was the reacting detector type of receiver, which, when held at the silent point of oscillation, could cause wipe out of neighbouring receivers. Complaints from these sources practically disappeared as the superheterodyne circuit came into general use.

With the addition of short-wave bands to the receiver, a modification of the existing intermediate frequency became necessary. The most usual choice was 465 kc/s, so that for a receiver tuned to Droitwich (200 kc/s), the local oscillator frequency would be (200 kc/s+465 kc/s) or 665 kc/s; the North Regional frequency at that time was 668 kc/s and due to the inadequate screening of the local oscillator and its associated wiring in some of the receivers, the resultant interference was a continuous 3,000 c/s note or whistle on North Regional.

Localization of this type of interference offered many problems. Direction finding by orientation of the receiver frame aerial was usually ineffective at a distance from the offending receiver, as loss of the North Regional signal caused loss of the audible beat frequency; occasionally after dark interference from foreign stations prevented the taking of usable bearings. Even when reasonable bearings could be made a cul-de-sac and terraced houses offered further problems.

Many visits could be made to the complainant without hearing the interference, and completion of a log by the complainant often proved of invaluable assistance in pinning down the times of interference. From the times of interference extracted from such a log, it would be possible to check the kind of programmes preferred by the owner of the offending receiver and visits made at this time would be more likely to be effective.

The method of eliminating this interference was to re-tune the intermediate frequencies and local oscillator approximately 10 kc/s off the North Regional transmission, this method being adopted as against the more costly screening of the offending receiver.

There were other variations of this type of

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Summary of Reports of Radio and Television Interference Received by the Post Office in the Manchester Area

	1947	1948	1949	1950	1951	1952	1953	1954	1955	Monthly Totals
January ...	85	116	205	302	475	298	305	390	332	2,508
February ...	70	107	208	423	515	153	333	410	446	2,595
March ...	129	127	238	299	511	345	305	407	467	2,828
April ...	36	105	124	330	537	250	299	483	419	2,583
May ...	58	83	130	358	496	310	463	326	360	2,584
June ...	38	74	168	269	399	264	316	335	236	2,099
July ...	41	91	144	212	306	194	374	346	288	1,996
August ...	43	91	126	204	247	178	277	231	174	1,571
September...	68	101	144	276	280	179	237	267	388	1,940
October ...	67	92	178	432	299	267	369	418	503	2,825
November...	78	147	247	507	430	238	366	359	561	2,930
December ...	108	138	243	324	270	315	489	570	676	3,133
Yearly Totals ...	851	1.272	2,155	3,936	4,765	2.991	4,153	4.542	4,850	

interference due to various combinations of intermediate frequencies but in the North-West Region the example quoted was very common and disappeared with the new North Regional frequency allocation.

2.2. *Television Line Time-bases*

A serious form of interference between receivers results from the radiation of the 10 kc/s harmonics from the line time-base of television receivers. Pulse voltages of several thousand volts occur in these circuits and they are of complex wave shapes and rich in harmonics, and considerable peaking takes place at frequencies in the broadcast bands.

The interference is both directly radiated and mains borne, and considerable re-radiation can take place, especially from overhead supply lines, and under these circumstances interference can cover quite a large area.

Many complaints from this source are undoubtedly due to one or more of the following factors:—

(1) Poor aerial/earth systems.
(2) Party wall siting of both receivers.
(3) Unscreened receiver coils.
(4) Omission of band-pass receiver input tuning.
(5) Inefficient screening of television receivers.
(6) Omission of mains filters in both television and broadcast receivers using a.c./d.c. techniques.

Many broadcast receivers are working with inefficient aerials and without earth wires, and the severity of interference at a receiving installation depends upon the following factors:—

(1) The magnitude of the radio frequency disturbance at its source.
(2) The electrical coupling between the source and the aerial system of the radio receiver.
(3) The field strength of the transmission being received.
(4) The effective height of the receiving aerial.

The last three factors are to some extent within the control of the listener; the fitting of a good outside aerial will reduce the coupling between the disturbance source and the aerial system by increasing the distance between them; it should also increase the signal of the wanted transmission.

Re-siting of the broadcast receiver may also be necessary and other measures include the fitting of a mains filter at either the receiver socket or the house mains entry point, or both positions in extreme cases, plus the provision of a good earth wire where this is normally required by the receiver.

The re-siting of the receiver will depend upon its design, since receivers employing internal frame aerials and unscreened coils are more likely to require re-siting than receivers which require an external aerial and also have fully screened coils. Use can be made of the directive facilities of a frame aerial type of receiver but obviously the further away it is removed from the source, the better the rejection of the unwanted signal.

Localization of time-base interference can be extremely difficult in certain cases. Once again it is a beat frequency type of interference which necessitates the locating receiver being tuned to the station complained about. The discrimination of the beat note during an orchestral programme is rather difficult and attempts to pick up the interfering signal off station can lead to misleading results from other television receivers which, although radiating, are sufficiently attenuated to be swamped by the local station transmission.

Having located the offending receiver, on/off tests at the complainant's premises are carried out to prove definitely that the correct source has been found.

The suppression at the television receiver can be accomplished by complete screening and the incorporation of a mains filter. Complete screening of certain television receivers proves difficult in practice on account of factors such as cabinet design, the requirements of adequate ventilation and the maintenance of an adequate safety factor.

Quite a large percentage of television receivers use a.c./d.c. techniques and therefore the screening has to be accomplished in such a manner that there is no access by the viewer to any portion of the screening.

During the initial investigation of time-base complaints, use is made of metallized paper wrapped around the outside of the television receiver and bonded to the chassis to give a rough guide as to the level of the directly radiated interference. It is also extremely useful for providing convincing demonstrations to unco-operative source owners.

The use of metallized paper for internal screening is not very satisfactory as a permanent fixture; it tends to be easily torn during normal maintenance checks and many repeat complaints of time-base radiation occur due to non-replacement of torn screening or bonding after receiver maintenance.

2.3. *Parasitic Oscillations*

Another form of interference between receivers is that caused by parasitic oscillations; these occur in the output stages of broadcast receivers, or amplifiers, but they may occur in any stage of a television receiver. They also occur in the mixer stage of broadcast receivers especially where such receivers have a short-wave band, and in this case the length of switch wiring and the associated capacitance may be enough to cause the local oscillation to radiate on television frequencies. Cases have occurred where this condition arose only when the receiver was switched to the GRAM position.

A similar case occurred during the period when the Manchester area was receiving the Sutton Coldfield television transmitter and interference was caused over a three mile area. Considerable difficulty was experienced in localizing this particular source due to the fact that the receiver was only used for news head-lines and exceptional programmes. When located, the receiver was returned to the manufacturers and suitably modified by the addition of anti-parasitic anode and grid stoppers.

Television receivers close to an interfering source can be driven to peak white by this form of interference, but usually it takes the form of patterning. In one particular case the patterning was very similar to that caused by diathermy apparatus and when the faulty receiver was localized it was found that the power supply smoothing was open circuited, causing both speech or music modulation and modulation at mains frequencies.

2.4. *Radio Frequency Heaters*

Radio frequency heaters cause considerable interference from either fundamental or harmonic frequencies. Due to the immense power that requires to be dissipated on harmonics and the frequency drift during their operation, the use of filters or quarter wave stubs has usually proved impracticable and the normal practice is to alter the frequency sufficiently to clear the television interference. This can be a problem in areas where complainants have a choice of television stations and it is then necessary to ensure that the selected frequency of the r.f. heater will give interference-free reception of both stations.

During a recent case of television interference from a r.f. heater on approximately 16·5 Mc/s it was found that variations of loading caused the frequency to vary almost one megacycle to 17·3 Mc/s. The heater was completely over-loading local television receivers and causing extremely severe patterning on more distant receivers. In this instance the third harmonic was responsible and different loading caused a 2·5 Mc/s increase in frequency. It was therefore seen that any frequency alteration to clear the interference would have to be such as to cause an increase in the frequency of the r.f. heater as otherwise it would require a much larger change of frequency to clear the interference.

This was rather fortunate because the frequency was increased without detriment to the r.f. heater by the removal of a fixed capacitor plate, whereas it would have been impractical to fit additional capacitance and the inductance design would not permit any modification.

In this particular case the r.f. heater third harmonic is now very close to Sutton Coldfield transmission, but as the nearest viewers on this frequency are 25 miles away, no harm is being done, and the factory operates fairly continuously in a built-up area without causing any television interference.

2.5. *V.H.F. Transmissions*

Many complaints of overhearing of business radio or police transmissions are received, and are in fact due to second channel or spurious response of the television receiver and hence the responsibility of the manufacturer or supplier to fit a suitable filter. In many cases a complete cure is obtained by the fitting of a quarter wave open stub to the receiver aerial input circuit. Sometimes the receivers are unduly susceptible to these spurious responses on account of mismatched aerials, and very often the fitting of a stub or filter offers an improvement in picture signal.

2.6. *Oscillating Lamps*

During the period when Sutton Coldfield was being received in the Manchester area a considerable number of complaints due to oscillating lamps were being received, but since increased field strength is now provided by the Holme Moss station, the number of complaints from this particular source has considerably decreased.

An interesting point about these oscillating lamps is that in every case they have been vacuum lamps and those marked "gas-filled" were found no longer to contain any gas, probably due to it having been absorbed by the metal and glasswork over a period of years.

3. "Electrical" Interference

3.1. *Commutator Motors*

Commutator interference is the most common cause of electrical type of television interference and commutator motors are contained in all classes of equipment such as sewing machines, hairdryers, adding machines, hairclippers, and others too numerous to list. Interference of this nature normally offers few problems in either localization or suppression.

Suppression of commutator type television interference is carried out by the use of inductors or capacitors or a combination of both; in some cases it is necessary to rearrange the field connections and in others for a smaller segment commutator to be fitted, but these are isolated cases, and in the majority of cases the interference is sufficiently attenuated by the insertion of two small dust-core inductors either in the motor brush leads or in the mains input connections to the motor. Sewing machine motors are probably the most numerous offenders and they may cause severe interference because the foot switch is so designed that it is difficult to fit suppressors at the point at which the interference is generated.

Complaints are sometimes received about motors which have already been suppressed. On test it has been found that either the owner has omitted to renew the carbon brushes or, owing to the unbalance of the motor or drive, or the habit of the user in holding the pulley drive wheel for slower motor speeds, the coil which carries the initial surge current has become open circuited: the operator then commences spinning the pulley-drive wheel to start the motor, and due to this open circuit condition the standard suppression previously fitted is rendered ineffective.

3.2. *Thermostats*

Thermostatic interference is sometimes difficult to localize on account of its spasmodic operation and sometimes offers problems in suppression due to its inaccessibility, and also the temperature of its situation. Thermostats are being used in numerous devices some of which are electric bedwarmers, percolators, flashing signs, smoothing irons, etc.

More modern thermostats have make-and-break contacts of the snap-action type and are less likely to cause television interference.

3.3. *Bells and Illuminated Bell Pushes*

Electric bells occasionally cause severe television interference and recently with the increased use of illuminated bell pushes, there have been a large number of complaints localized to electric bells which due to the current passed through the illuminated bell push are causing a continual arc without ringing the bell, and of course this interference continues for hours. If the bell is run from a transformer it is often possible to short out the make-and-break contact and ring the bell from the a.c. supply. This is much easier and more effective than a suppressor and was adopted in the private patients' home of a large hospital where some hundreds of rooms were fitted with a bell calling system in each room.

3.4. *Neon Signs*

Neon signs, provided they are efficiently installed, do not cause interference to television but if portions of the wiring or metal work become unbonded or faults develop in the tube connections, transformer insulation, etc., they cause severe interference over a wide area. The most common fault is unbonded wiring.

3.5. *Overhead Transmission Wiring*

Faults on overhead e.h.t. routes cause similar interference to neon signs but it is usually more difficult to localize and difficulty is often experienced in localizing the particular pylon on a route. The faults are usually found to be cracked or dirty insulators and interference along the pylon route can be severe and is usually accompanied by a frying noise on the sound.

4. Locating Sources of Interference

Localizing the interference source to either medium wave, long wave or television frequencies is done by the use of small battery-operated radio receivers.

Interference to medium wave and long wave reception is usually mains borne, the disturbances set up by the interfering plant being conveyed to the supply mains to the electric wiring of the complainant's premises and then radiated to the aerial lead-in, etc. To avoid interference of this nature, it is desirable to employ an outdoor aerial with all internal wiring as short as possible.

Indoor aerials and frame aerials are much inferior on account of their smaller pick-up of the wanted signal and their greater exposure to the interference radiated from adjacent mains wiring. Frame aerials are useful for rejecting directly radiated interference from a given point but suffer from the disadvantage that as broadcast interference is usually radiated from the house wiring which is contained in the walls, ceiling, etc., the frame aerial is thus contained in an interference field. Mains aerials are highly unsatisfactory since they provide a direct path into the receiver for any interference they may be carrying.

Mains propagated interference will generally be audible on the portable receiver when it is placed over the supply mains on the pavement outside the complainant's premises. The mains can then be followed and observations of the varying intensity of the interference indicates the source. Occasionally the interference level may increase or decrease on account of varying levels of the main cable; it may disappear altogether and on occasions it is necessary to return and retrace in another direction.

Difficulty is sometimes experienced by not being able to pick up the interference more than a few yards either side of a complainant's premises. Search is then made over the mains wiring or the path it could be expected to follow and continued around the various streets until the interference is heard on the locating receiver. Overhead wiring sometimes offers problems, and usually an aerial fitted in the roof of the radio investigation car offers a solution when difficulty is experienced in picking up the interference on the receiver frame aerial. From previous experience it is usually possible to recognize a particular form of interference, and in this case a local survey is made without having to make use of the portable receiver.

The Post Office's W.T.12 receiver for location of interference on frequencies from 30 Mc/s to 100 Mc/s is provided with vertical rod aerials and a loop aerial. Due to the multiple re-radiation which takes place in a built-up area, the taking of cross bearings is sometimes impossible and difficulty is sometimes experienced with peaks of interference on the rod aerial which may be remote from the source. Occasionally use is made of a horizontal dipole on the roof of the vehicle and in other cases a temporary beam aerial has been used. In many cases interference first seen on the vision can be recognized when heard on the sound, and a known plant item can be more easily localized.

5. Dealing with Complaints

After localization, permission is obtained from the plant owner to fit the necessary suppression. In general the most effective suppression is found by trial and error and usually suppression for similar machines is the same.

During the period when the Sutton Coldfield transmission was the only one available in the Manchester area, suppression was rarely difficult as due to the low field strength of the received signal, the great majority of complainants used highly efficient aerials. Cases have since been received where plant items suppressed during this period are blamed for interference to Holme Moss which has a much greater field strength; upon investigation these have been found to be entirely due to the complainant using a ground-level aerial sited on the party wall behind which the suppressed equipment is being used.

The effects of the continued growth of interference complaints have led to the public in general becoming more interference conscious and more favourable to granting facilities for testing their apparatus. In many instances they apply for information on suppression for their own appliances after having seen the effect of interference on their own receivers. In addition, manufacturers of electrical appliances are now not only fitting suppression during manufacture but advertising the fact that their equipment is so fitted and it would appear that most people nowadays require their new equipment to be already suppressed, not only on the grounds of expense but also because internally fitted suppression should be more efficient and less likely to suffer physical damage.

Although many manufacturers are now fitting suppressors during manufacture, complaints are occasionally received about suppressed apparatus. In many cases the fault lies in an inefficient aerial usually fitted at ground level, and under these circumstances complainants are sometimes reluctant to incur extra expense in either moving the existing aerial or fitting a more efficient type. It cannot be too strongly stressed that complainants have a responsibility to fit as good an aerial as circumstances permit. Ground level aerials are most unsatisfactory even if they give a fair signal when first installed; they are too prone to variation from day to day, and cases have occurred where a vehicle stopping outside a complainant's house to investigate a complaint has resulted in the picture vanishing due to blanketing of the ground level aerial.

The Wireless Telegraphy Act regulations requiring the suppression of interference cannot be enforced unless the Post Office is satisfied that the complainant has done all that can reasonably be expected of him to minimize the effect of the interference.

It is not economically possible to suppress interference down to zero and the present regulations allow a noise field of 50 microvolts at any distance of not less than 33 feet over the frequency range 40-70 Mc/s and a terminal voltage measured from each supply line to earth of 750 microvolts over the same frequencies.

There is no doubt that it would be considerably more efficient if all apparatus was suppressed during manufacture than for the equipment to be made, sold to a user, and then have to be localized by engineers before suppression can be effected. One can only hope that in the near future it will only be necessary to localize older type equipment or equipment that has developed faults in use.

LONDON DISCUSSION

In the Chair: Mr. D. W. Heightman (*Member*)

W. Nethercot: As Mr. Smith has spoken very comprehensively on radio interference from the investigation officer's point of view, I propose to confine my remarks to the research aspect.

I do not know if it is generally appreciated how much work has been carried out on radio interference right from the early 30's, initially on the causes of interference and, equally important, on the methods of measurement and the design of simple and reliable measuring apparatus. This, in conjunction with the determination of the signal-to-noise ratios necessary for the satisfactory reception of broadcast and television services, together with B.B.C. nation-wide surveys of the service fields, enabled permissible limits of interference to be specified in British Standards by the beginning of the war. In fact, by that time radio interference had largely become a practical and economic, rather than a technical, problem and since the war the trend has continued. In general we know how interference is caused and how it can be suppressed, but often it may be very difficult to identify and locate a specific source of interference and to fit the appropriate suppression equipment.

I think the research effort in the immediate future will largely be directed to the higher frequencies, in particular to those of Band III. We are not sure how serious the interference problem is in this region, neither are we completely satisfied with the position as regards measurement and suppression.

I do not think Mr. Smith has emphasized sufficiently the problem of motor car ignition interference. The figures of complaints he quotes are misleading in that they indicate ignition interference to be much less important than is actually the case. The reason, of course, is that most people do not complain because they realize that effective action is not possible with highly mobile sources of interference.

The introduction of a regulation requiring all motor vehicles sold after 1st July, 1953, to be adequately suppressed has already had considerable repercussions in the motor industry. If suppression is needed for Band III television, and as yet we do not know how much will be required, then the suppression measures are likely to be more elaborate than those for Band I. Although the cost of suppression for an individual vehicle is a very small proportion of its total cost, the overall cost to the industry may be anything between £200,000 and £1,000,000 per annum, depending on the degree of suppression achieved.

For most domestic equipment the cost of suppression is a much greater proportion of the cost of the equipment and this is one of the reasons why the regulation introduced for the control of interference from small electric motors is a user's and not a manufacturer's regulation. However, the introduction of the regulation has tended to stimulate the manufacturer into supplying his products already suppressed and from the interference aspect this is the ideal solution.

It is necessary to remember, however, that there has to be a compromise between the cost of suppression, the cost of Post Office investigation of complaints of interference, and amenities gained by effective suppression.

M. Smith (in reply): I think that is quite a good policy for the Post Office only to insist on new cars being fitted with suppressors, because it would be quite a problem to chase around after all the earlier cars, trying to check on whether suppressors were fitted or not. Eventually, of course, all cars on the roads will be those that are suppressed. It is an offence to remove a suppressor from a car that has been manufactured since 1952. I suppose that if the interference from motor cars does not grow less, then probably the Post Office may take further steps—I do not know—but it seems to me the insistence on suppression on cars manufactured since 1952 should be effective.

The Chairman: I believe that the experience has been that Band III is far less susceptible to ignition interference than Band I, and that suppressors that are effective for Band I are not so for Band III. I understand that the Post Office and other bodies have made some measurements on this and Mr. Nethercot made an important point when he said that we need more facts and figures. The whole subject is very empirical.

W. Nethercot (in reply): The Electrical Research Association has made roadside measurements on some 5,000 vehicles and the conclusion is that if suppression is needed for Band III, then more suppressors will be required than for Band I. The necessity or otherwise for suppression on Band III will depend amongst other things on the minimum field strength for satisfactory reception, which is likely to be greater than that for Band I and the type of aerial used.

F. R. W. Strafford: Having had experience in this subject for many years I have come to the conclusion that dealers and installers are still very sadly lacking in inclination to implement the requirements which have been extensively publicized in the technical and trade press.

I cannot help feeling that, after all the brain power and money which has been put into the suppression business, and into the investigation of complaints of interference (almost 50 per cent. of which can be cured by putting up efficient aerials, curing intermittent faults in the wiring of buildings and correcting faulty receivers) there is a question as to whether there is any fundamental need for this service in view of the public attitude today. I believe that interest in interference on medium and long waves is gradually subsiding. I believe people take it for granted that there should be all these noises.

On television, however, the public is very much more conscious of interference because there is something to look at as well as to listen to and I hink that television is the service on which we ought to concentrate perhaps exclusively. Here he main causes of interference are from motor vehicle ignition and small commutating motors. Thoughtful motorists can with small expenditure reduce to a very considerable extent the vehicle nterference while manufacturers of motors could greatly improve the position if they would increase the number of segments on their commutators and use correctly shaped brushes.

If dealers and installers were to take more patient interest in their installations and give people the correct type of aerial there would be better all-round reception. The standard of reception here is probably better than that in America because we are generally more particular about such things. Nevertheless I think we need to educate the dealer and the installer into giving this better personal attention.

The company with whom I am connected built a transmitting station to act as a pilot transmitter for the I.T.A. at Croydon because we did not have the answer to a lot of problems on the sort of aerials to erect and how bad interference or "ghosting" might be.

This transmitter radiated approximately 1 kW e.r.p. on its vision channel and a large nucleus of viewers had to use very much better aerials than they would have done had the I.T.A. commenced at that time on the full power of 60 kW. These viewers had to use 3, 6 and 9 element outdoor aerials. Due to their good directional characteristics and gain the reports showed that the general effects of interference were lower, nor were there as many "ghosts" as one would have expected.

But these reports can easily lull us into a sense of false security. As time goes on, and with the I.T.A. radiating 100 kW e.r.p. or more, installers will reduce the degree of aerial efficiency possibly to such an extent that the effects of interference may then be as bad as, or perhaps worse than, at present experienced on Band I.

This practice goes right back to the early days of broadcasting, for you will remember that it was the fashion to use tall masts with very large aerials, but as receivers became more sensitive the aerials became smaller and less efficient. One offsets the other to a degree sufficient to unbalance the position in favour of interference and I think that this abuse will always be with us.

M. Smith (in reply): I fully agree with Mr. Strafford, with the exception of his statement about broadcast interference and television interference. From our figures in Manchester they are about equal at the moment. Regarding the fitting of efficient aerials, I personally would like to see it definitely stated on a complaint form that unless a good aerial is fitted the complaint will not be accepted.

The Chairman: Mr. Smith might like to comment on the increasing use of ferrite rod aerials in receivers where there is provision for rotation.

M. Smith (in reply): Ferrite rod aerials, in certain circumstances, can be useful when interference is coming from a particular source. However, broadcast interference is 95 per cent. mains borne, and any aerial, whether it is ferrite rod or frame, in a living room is surrounded by a field of interference and it is difficult to get away from interference in some cases with an aerial of that type. On a certain set in my experience, direct switching to an outside aerial from the internal ferrite rod showed a very much greater received signal.

R. Brennand (*Associate Member*): I am concerned with the development of electronic equipment for medical applications, and we have had considerable difficulty in obtaining limits for permissible harmonic radiation from short wave diathermy apparatus. This is not a new problem, it has been going on for at least a decade, and from our side started with interference to radar during the last war.

The present difficulties are, of course, accentuated by the various television stations in Band I and also Band III. I would like Mr. Smith's comments on whether it is desirable to segregate the medical users on to 27·12 Mc/s, which is the Atlantic City Convention frequency, or whether we should use frequencies in the range of 34 to 37 Mc/s which seem to have been adopted for industrial heating and welding applications. I would point out that the second harmonic of 27·12 Mc/s falls in Band I and the seventh harmonic in Band III.

The other thing I should like to comment on is the use of field strength meters for determining the location of television aerials. On fitting up the aerial and checking the receiver after taking a number of readings with a field strength meter, it has been found that multi-path interference may be such that the picture is almost unrecognisable. This shows the danger of employing a field strength meter for receiver aerial siting, but I believe this is a common practice.

M. Smith (in reply): There is some new r.f. heating and medical apparatus made for 36 Mc/s, but the majority is old equipment which was originally on 50 Mc/s and has been modified to 36 Mc/s, this being the lowest frequency to which it is practicable to retune. If it had to be moved any lower it would cease to oscillate without complete re-modification.

Allocation of frequencies is a very complex problem, for instance 36 Mc/s diathermy apparatus may cause interference to 36 Mc/s i.f. television receivers. The local oscillator of such a television receiver for Holme Moss is operating on 51 Mc/s + 35 Mc/s = 86 Mc/s; the second harmonic of this interferes with business radio on 173 Mc/s. In turn business radio on various frequencies causes interference to television receivers due to spurious responses.

I personally think the present allocation of frequencies is on the whole satisfactory and unlikely to be much improved, and the small percentage of peculiar interference complaints arising in this manner will always be with us however we juggle with frequencies.

The Chairman: I would like to comment on the question of the 36 Mc/s i.f. rejection. One would consider 60 db as being a fairly good rejection figure, but if you have several kilowatts within not many yards, rejection is difficult to achieve.

F. R. W. Strafford: Mr. Brennand raised a very interesting point which concerns the making of a field strength contour map. It has been the principle in the past to make these measurements with an omni-directional dipole and plot the results on a pen recorder. The measurement thus made has been the sum of all the signals coming in from all different directions due to reflection, many of which are of no value to the viewer at all, and in fact if sufficiently displaced can appear as "ghosts."

When we were making measurements on the transmission from our pilot station in the Croydon area we immediately noted this point. Using an omni-directional receiving aerial we were able to get excellent field strengths in places where it was impossible to receive a satisfactory picture due to "ghosting." It was obvious that the correct way of making these measurements was to use a highly directional aerial and to keep it pointed to the transmitter. To get the absolute value of the field strength it is a simple matter to allow for the gain of the directional aerial.

F. Boysen: I would like to ask Mr. Smith if he can tell us anything about the "nuisance value" of certain types of interference, particularly discontinuous noise from contact devices such as bed blankets, where you may have the thermostat contact closing once every minute or less and in some cases only after several minutes. Has he any views on when it becomes a nuisance? Obviously if you have only one click or white dash on the screen every hour, it does not matter; but an increase in the frequency can become intolerable.

M. Smith (in reply): I do agree that thermostatic interference is very annoying. It is also a very great headache to investigation officers in the field because to trace interference that lasts for 3/5 seconds and comes on every 20 minutes is quite a problem. There should not be any interference from a snap-action switch, only a click and not a prolonged arc, which you get with faulty thermostats. Thermostatic devices are rather difficult to cure: most manufacturers of electric irons, for instance, now, I think, do arrange to replace the thermostat; whilst they eventually go wrong again, due to the great heat, it does seem to be at the moment the only reasonable cure. Some irons respond to the addition of a capacitor across the main input, but this is not a definite cure for all cases.

* * *

A vote of thanks to the Author was moved by Mr. J. D. Collingwood, a member of the Programme and Papers Committee.

NEW BRITISH STANDARDS

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

B.S.419 : 1956 **Varnished cotton cloth sheet and tape for electrical purposes.**

Refers to yellow and black varnished woven cotton cloth coated on both sides in the form of sheet and tape (or strip) in thicknesses up to 10 mils and width of approximately 36 in. for sheet and up to and including 4 in. for tape.

Separate limits are given for cloths of the two colours in the clauses in which the specified performances are different. The test for determination of electric-strength of tapes under mechanical tension has been modified and has now to be made at two measured extensions, with proof voltages specified for both. A test for extensibility of bias-cut tape has been added but the limits have to be agreed between the purchaser and the manufacturer. An additional limit has been introduced into the clause dealing with tensile strength to cover the joins in bias-cut tape.

In the tests for ageing, which are now extended to include ageing in oil, the criterion is no longer bursting strength but tearing strength as determined by an apparatus of the Marx-Elmendorf type. An additional clause and associated method of test has been introduced to control acidity in the cloth as received, and developed acidity after specified treatment.

B.S.2131 : 1956 **Fixed paper-dielectric capacitors for d.c. use in telecommunications and allied electronic equipment.** Price 3s. 6d.

Applies to fixed capacitors using impregnated paper dielectric and metal foil electrodes and suitable for d.c. operation with or without a small superimposed a.c. component. The standard may be applied to capacitors of equivalent performance having other dielectrics. The standard requires reference to B.S.2011, "Basic climatic and durability tests for components for radio and allied electronic equipment." At a later date, a second part specifying standard sizes, ratings, etc., of capacitors, will be added.

B.S.2214:1955 **The performance of power transformers (not excluding 2kVA rating) for radio and allied electronic equipment.** Price 3s.

Deals with general-purpose power transformers of up to 2kVA rating, for operation at frequencies up to 3 kc/s, and intended for use in radio and allied electronic equipment. The standard applies to open enclosed non-sealed and hermetically sealed transformers; vibrator and pulse types are excluded. Electrical and mechanical tests are specified. Low atmospheric-pressure tests are not specified, and transformers complying with the standard may not therefore be suitable for use in aircraft. In addition, the transformers will not necessarily meet all the requirements of the Services. The standard requires reference to B.S.2011, British Standard climatic and durability tests for components for radio and allied electronic equipment.

B.S.2311:1955 **Colour codes for connections in radio and allied electronic equipment (excluding telephone exchange and associated transmission equipment).** Price 2s. 6d.

Recommends two forms of colour coding for the identification of the wiring of radio and allied electronic equipment, excluding telephone exchange and associated transmission equipment.

Section 2 specifies a basic functional colour code for use in simple units, where it is only necessary to differentiate between the various parts of a circuit. Section 3 details the colour code for a more complete identification system in which each wire is coded, either to identify it as a particular wire or to identify the two points in the circuit to which the wire is connected.

B.S.2707:1956 **Electrical performance of semi-conductor rectifiers (metal rectifiers).** Price 2s. 6d.

Applies to rectifier elements and stacks for use when supplying d.c. power from a.c. sources at frequencies up to 20 kc/s.

The basis of rating is described and the cooling conditions envisaged are stated. Type and routine production tests are specified, and terminal and identification markings are given. Various methods of connection are listed, and these are illustrated by figures.

Rectifiers for measuring instruments and for telecommunication are not included, except those used for power supply to telecommunication apparatus.

New British Standards *(contd.)*

B.S.2746 : 1956 **P.V.C. insulation and sheath of electric cables.** Price 7s. 6d.

Specified standard colours, physical test methods and requirements for polyvinyl-chloride insulation and sheath taken from electric cables. The types covered are general purpose, hard grade and transparent flexible insulation; general purpose, arctic and non-contaminating sheath. Tests include colour stability, tensile strength, elongation at break, cold bend, ageing, hot deformation, heat, insulation resistance, fire resistance and migration of plasticizer.

B.S.2754 : 1956 **Memorandum on the design of electrical apparatus having double insulation.** Price 4s.

Explains the principles involved in the use of double insulation for electrical appliances as a protection against electric shock, and the various types of construction in which double insulation can be used. A section is included dealing with the testing of particular appliances.

B.S.2757 : 1956 **Classification of insulating materials for electrical machinery and apparatus on the basis of thermal stability in service.** Price 4s.

Defines seven classes of electrical insulating materials on the basis of thermal stability in service. The temperatures assigned to the classes by agreement within the International Electrotechnical Commission are stated and guidance is given in an appendix on the classification of a number of particular insulating materials.

NEW CODE OF PRACTICE

C.P.1005 Part 3 : 1956. **Use of electronic valves. Photocells, transmitting valves and cold-cathode gas-filled valves.** Price 3s.

Gives additional recommendations for photocells, transmiting valves and cold cathode gas-filled valves of glow discharge and arc-discharge types. Should be read in conjunction with the recommendations for all electronic valves in Section 2 of Part 1 of the Code.

NEW STANDARDS FROM OVERSEAS

The following new oversea standards are now available in the B.S.I. Library for loan, to members of the B.S.I.; copies are also available for sale on application to the Sales Branch at the address given on the previous page.

France—*Association Française de Normalisation:*

AFNOR C 42-100 Electrical measuring appliances and their accessories: rules.

AFNOR C 92-210 Television receivers connected to power mains.

AFNOR S 32-001 Gramophone records, 78 r.p.m., with lateral grooving: terminology and requirements.

AFNOR S 32-002 Long-playing gramophone records, 45 r.p.m.: terminology and requirements.

India—*Indian Standards Institution:*

IS 586 Leclanché type dry cells for telecommunication, signalling and general purposes.

IS 795 Canons for making abstracts.

Italy—*Associazione Elettrotechnica Italia:*

97 Standards for safety of radio receivers.

108 Climatic and mechanical tests of components of electronic apparatus.

109 Paper capacitors for electronics.

U.S.A.—

American Institute of Electrical Engineers:

AIEE 59 Proposed test code for metallic rectifiers.

American Society for Testing Materials:

ASTM Book of Standards, Pt. 6, 1955. Plastics, electrical insulation, rubber, electronics.

Institute of Radio Engineers:

55IRE 2.S1 Standards on antennas and waveguides: definitions for waveguide components.

55IRE 10.S1 Standards on industrial electronics: definitions of industrial electronic terms.

55IRE 17.S1 Standards on radio receivers: method of testing receivers employing ferrite core loop antennas.

55IRE 26.S2 Terminology for feedback control systems.

56IRE 7.S1 Electron devices: definitions of terms related to storage tubes.

National Bureau of Standards:

NBS C 571 Electron physics tables.

SOME COMMENTS ON WIDE BAND & FOLDED AERIALS *

by

Professor E. O. Willoughby, M.A., B.E.E., B.C.E., D.I.C. †

SUMMARY

The impedance-frequency characteristic of simple cylindrical aerials is discussed and it is shown that the bandwidth may be considerably improved by the use of appropriate correcting networks. The folded type of aerial automatically makes use of some of these principles. Folded aerials with equal and unequal legs are considered and experimental results illustrating the analysis are given.

1. Introduction

The work to be described commenced early in 1943 following a request from a British firm to investigate the bandwidths of folded aerials. The results of the earlier work were included in patents[1] and in an unpublished Central Radio Bureau war-time report (1945), a copy of which was supplied to the B.B.C.

The presentation used in that report had the merit of giving a simple physical picture of the behaviour of such aerials with but little mathematics. It has therefore been drawn on for the following paper, which gives some elementary principles suitable for band-pass aerials and illustrates their practical application by experimental results.

2. The Need for Wide Band Aerials[2,3]

For those not versed in aerial operation, Fig. 1 compares the base impedance $R+jX$ of a relatively thin aerial of length to diameter ratio of 240:1 with the base impedance of a thick aerial having a ratio of 10:1. This graph will serve to show how the "Q" of a cylindrical aerial, at either quarter- or half-wave resonance, falls with decrease of l/d ratio. Further, it shows how the lower the l/d ratio, the lower the fraction of 0·25λ and 0·5λ respectively at which the quarter-wave and half-wave resonances occur.

Even lower values of Q may be obtained using cylindrical aerials of lower l/d, or by using conical aerials of large vertex angle. However, the overall physical cross-section of such aerials becomes embarrassing in practice, as the operating wavelength becomes longer, hence the value of methods which can improve the match of a relatively thin aerial to a constant resistance transmission line over a range of frequencies.

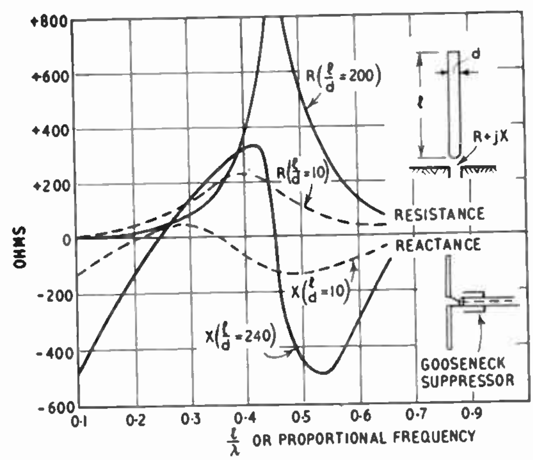

Fig. 1.—Variation with l/λ (or frequency) of the base impedance of two cylindrical aerials for which $l/d=240$ and $l/d=10$ respectively.

Concerning the matching of aerials to transmission lines, the half-wave dipole (approximately λ/2 in overall length), a balanced aerial, has a centre impedance of approximately 72 ohms and concentric tube transmission lines of this impedance are available. Note, however, that in such applications, it is necessary to use a properly placed quarter-wave choke in series with the outer sheath of the transmission line to suppress standing waves on the outer conductor. This is often called a "goose neck" suppressor. Fortunately, if the characteristic impedance of this choke is kept as high as is practical, usually

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about 40 ohms, it is effective in suppressing currents on the outer conductor over the frequency range (± 3 per cent. of the centre frequency) in which this type of aerial is useful.

The dipole aerial formed from two half-wave elements (approximately λ in overall length) has a centre impedance which is about 400 ohms for a l/d ratio of 30 and balanced transmission lines are readily constructed which can match this impedance.

In the next Section of the paper, ideal lumped-series and lumped-parallel circuits are used to show how, with appropriate correcting networks, unity power factor may be achieved at two positions above and below resonance respectively, in addition to that corresponding to natural resonance.

In the ideal case of series resonance, the resistances at the unity power factor positions above and below natural resonance are automatically stepped up above the resonant resistance to give an input impedance versus frequency characteristic similar in shape to that of overcoupled tuned circuits of equal Q. In the practical aerial case, however, the steeply rising resistance frequency characteristic enables the low frequency resistance to be stepped up to the value at natural resonance as above, while above the resonant frequency the sharply rising resistance characteristic inevitably results in a resistance much higher than the resonant resistance if appreciable bandwidth is attempted. This limitation results in such methods being rarely satisfactory, with standing wave ratios of 1·1 to 1·2:1 over bandwidths of more than ± 3 per cent. of the centre operating frequency, even with relatively thick aerials. The original Western Electric radio-altimeter aerial was an example of this type of aerial.

In the ideal case of parallel resonance, the half-wave resonant aerial is a much better approximation to the lumped-circuit resonance and further, the correcting currents enable the lower resistance on either side of resonance to be stepped up, at the unity power factor points, to the resistance value at resonance. The practical difficulty with this type of correcting circuit is that the slope of the reactance curve of the aerial or idealized lumped circuit at anti-resonance is of the opposite sign to that required, if compensation is to be achieved by an anti-resonant shunt circuit across the transmission-line feeder.

In applying this method to a practical aerial to obtain a wide bandwidth, it is desirable to have reactance, at frequencies corresponding to the peaks of the aerial reactance, of substantially twice the magnitude of the peaks and of opposite sign. However, the peak values of this reactance are so high that for series over-compensation, to reverse the sign of the

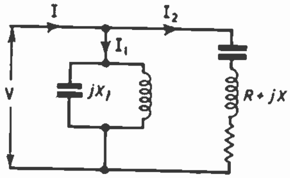

Fig. 2.—Basic lumped circuit used to illustrate the elementary theory.

reactance and swing it to a sufficiently high level, involves values of the reactance components which are hard to realize physically with practical components except in a relatively thick, low-Q aerial. In this case, however, there are theoretical possibilities of very wide bandwidth.

3. Elementary Theory

The basic lumped circuit is shown in Fig. 2. If X_1 is the overall reactance of the parallel circuit, passing current I_1, and $R+jX$ is the impedance of the series circuit passing current I_2, and these two circuits are arranged to be resonant at the same frequency, X and X_1 will be of opposite signs on either side of this resonant frequency. Referring to Fig. 3, two unity power factor points will occur at frequencies on either side of resonance.

$$Z=\frac{V}{I}=\frac{(R+jX)\,jX_1}{R+j\,(X+X_1)} \quad \text{.........(1)}$$

If this is to be a pure resistance R_T, we have

$$R_T=\frac{-XX_1}{R}=\frac{RX_1}{X+X_1} \quad \text{.........(2)}$$

which also gives a unity power factor condition

$$XX_1+X^2+R^2=0 \quad \text{.........(3)}$$

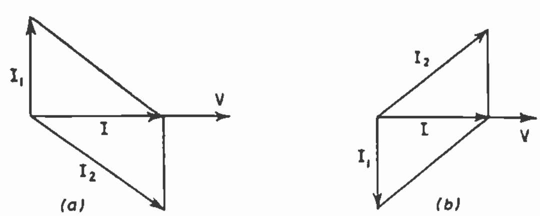

Fig. 3.—Vector diagrams showing the two unity power factor conditions.

Further, for the unity power factor condition, consideration of the vector diagram of Fig. 3 shows that

$$I = \frac{V}{\sqrt{R^2+X^2}} \cdot \frac{R}{\sqrt{R^2+X^2}}$$

Hence

$$R_T = \left(\frac{V}{I}\right)_{\text{unity P.F.}} = R + \frac{X^2}{R}$$

a result also derivable from eq. (2) and (3).

The two relations most useful in considering resonances of the type represented by Fig. 3 in aerial work are:

$$R_T = R\frac{X_1}{X_1+X} \qquad \text{.........(4)}$$

$$R_T = R + \frac{X^2}{R} \qquad \text{.........(5)}$$

In each case subject to the unity power factor condition

$$X_1 = -\left(X + \frac{R^2}{X}\right) \qquad \text{.........(6)}$$

Due, however, to the rapidly changing radiation resistance about $\lambda/4$ resonance, when attempting very wide band performance it is often desirable to work at frequencies above the unity power factor condition on the low frequency side of $\lambda/4$ resonance. Hence it is desirable to have the general form of the impedance for reference.

Using equation (1) we obtain

$$Z = \frac{X_1^2R + \mathrm{j}[X_1R^2 + (X+X_1)XX_1]}{R^2+(X+X_1)^2} \qquad \text{.........(7)}$$

and the phase angle is equal to

$$\arctan\left(\frac{X^2+XX_1+R^2}{X_1R}\right) \qquad \text{.........(8)}$$

Further, at considerable distances from resonance, where $X+X_1=0$

$$Z \simeq \frac{X_1^2}{R} + \mathrm{j}X_1 .$$

3.1. *Application of the Theory to Aerials with Stubs*

Near $\lambda/4$ resonance, an aerial is series resonant and a parallel-tuned stub or a short-circuited $\lambda/4$ stub, included in the barrel of the aerial, may be used to simulate the circuit of Fig. 2.

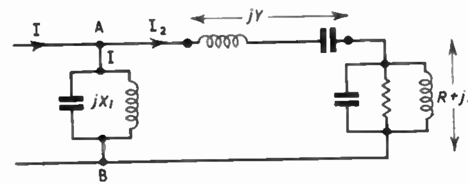

Fig. 4 (a) (Above).—Additional series-tuned circuit "Y" necessary near λ/2 resonance.

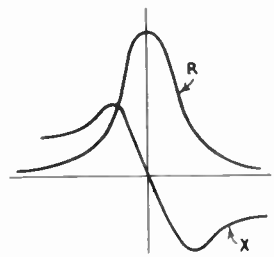

Fig. 4 (b) (Left).—Impedance components of the lumped parallel-resonant circuit representing an aerial near λ/2 resonance.

Near $\lambda/2$ resonance, the aerial is "parallel-tuned" and the application of the band-pass principle of equations (1) to (5) involves an extra series-tuned circuit "Y" of highly reactive elements as shown in Fig. 4a.

In the lumped circuit case the reactance curves would have peaks at $\pm\mathrm{j}R/2$ and a resistance of $R/2$ as shown in Fig. 4b.

If at these points it can be arranged that $\mathrm{j}Y = \mp\mathrm{j}R$ and if at the same time $\mathrm{j}X_1 = \pm\mathrm{j}R$ at the two points A and B, the aerial and connecting network will result in two unity power factor tuning points of $Z=R$. This latter result is of use in guiding the design of wide band circuits formed from $\lambda/2$ resonant aerials.

3.2. *Folded Aerials with Equal Legs*

The folded aerial is a type of circuit which automatically makes use of some of the above principles.[4] Consider the general monopole folded aerial with equal legs, in which one end is excited with a voltage V, and as a result the other end assumes a potential v to ground (Fig. 5).

Fig. 5.—General folded-type monopole aerial.

Since radiation impedances are linear, the principle of superposition applies and it is logical to apply two independent sets of voltages to the aerial and add the results. One set $(\frac{1}{2}V+v)$ applied to each leg in parallel, corresponds to the radiation of the composite aerial, and the other set, a push-pull pair of voltages $\frac{1}{2}(V-v)$ and $-\frac{1}{2}(V-v)$ gives rise to loop currents causing no appreciable radiation. The addition of these two sets of voltages and two sets of currents then gives a complete picture of the behaviour of the aerial, and the coupling between the two systems of voltages is substantially nil.

If R_A+jX_A is the base impedance of the aerial formed by connecting two legs in parallel at their base and jX_L is the base loop impedance, then the radiation component of current in each leg is

$$\frac{\frac{1}{2}(V+v)}{2(R_A+jX_A)}=\frac{V+v}{4(R_A+jX_A)} \quad \text{.........(9)}$$

The current in the second leg must equal the loop current, since the two are connected in series. Hence

$$\frac{V-v}{jX_L}=\frac{V+v}{4(R_A+jX_A)}$$
$$=\frac{2V}{4(R_A+jX_A)+jX_L}$$
$$=\frac{2v}{4(R_A+jX_A)-jX_L}, \quad \text{.........(10)}$$

the last two ratios being derived from the first two. Hence in input impedance is

$$(R_A+jX_A)+\tfrac{1}{4}jX_L,$$

which corresponds to twice the current given by the ratio (10). Note that in studying the above case, the following interesting results can be derived.

(*a*) If $X_L=\infty$, equation (10) can only be satisfied if $V+v=0$ with second leg open circuited, i.e., push-pull operation with no appreciable radiation.

(*b*) If the second leg of the aerial is grounded, $v=0$ and the feed impedance is composed of jX_L and $4(R_A+jX_A)$ in parallel and the overall impedance is

$$\frac{jX_L \,.\, 4(R_A+jX_A)}{jX_L+4(R_A+jX_A)}.$$

Hence we see that if $X_L=\infty$, the input impedance is $4(R_A+jX_A)$. This is the result usually given and is the relatively restricted case where $X_L=\infty$ and $X_A=0$ simultaneously. The input impedance is then a resistance $4R_A$.

3.4. *Folded Aerials with Unequal Legs*

Consider the uniform aerial shown in Fig. 6, where the capacitance to ground per unit length of leg 1 is C_1 and that per unit length of leg 2 is C_2 and we neglect for the time being any complications which may arise from irregularities near the feed point. Note that although the capacitance to ground per unit length of leg may vary according to the height of a section above the ground, their ratio is substantially constant, and it is their ratio with which we are mainly concerned.

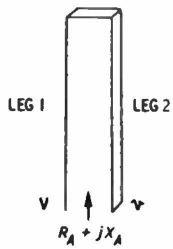

Fig. 6.—Folded monopole with unequal legs.

Let R_A+jX_A be the equivalent base impedance of the two legs of the aerial, fed in parallel, and jX_L the base loop impedance between the two legs. Let V be the voltage applied to the feed terminal of leg 1, and let v be the voltage set up on the end of leg 2 as a result. Further, applying the principle of superposition, let u, u be the voltages supplying the radiation currents. Then $V-u$, $v-u$ will be the voltages supplying the non-radiating reactive currents.

Thus the components of these non-radiating currents to ground must be equal in magnitude and opposite in sign. Hence

$$\frac{V-u}{\frac{C_1+C_2}{C_1}(R_A+jX_A)}+\frac{v-u}{\frac{C_1+C_2}{C_2}(R_A+jX_A)}=0.$$

Therefore

$$u=\frac{C_1V+C_2v}{C_1+C_2} \quad \text{.........(11)}$$

Now since the current feeding leg 2 flows through the loop reactance jX_L,

$$\frac{C_1V+C_2v}{C_1+C_2}\cdot\frac{1}{R_A+jX_A}\cdot\frac{C_2}{C_1+C_2}=\frac{V-v}{jX_L} \quad \text{......(12)}$$

Hence the total input current due to applied voltage V is

$$I_T=I_{\text{loop}}+I_{\text{rad}} \text{ leg } 1$$
$$=\frac{C_1V+C_2v}{C_1+C_2}\cdot\frac{1}{R_A+jX_A}$$

Now from equation (12)

$$v = V . \left[\frac{\dfrac{1}{jX_L} - \dfrac{C_1C_2}{(C_1+C_2)^2\,(R_A+jX_A)}}{\dfrac{1}{jX_L} + \dfrac{C_2^2}{(C_1+C_2)^2\,(R_A+jX_A)}} \right] \quad ..(13)$$

Substituting in equation (11) yields

$$u = V . \left[\frac{\dfrac{1}{jX_L}}{\dfrac{1}{jX_L} + \dfrac{C_2^2}{(C_1+C_2)^2\,(R_A+jX_A)}} \right] \quad ..(14)$$

But the total current input is

$$\frac{u}{R_A+jX_A} = \frac{V}{R_A + j\left\{X_A + \left(\dfrac{C_2}{C_1+C_2}\right)^2 X_L\right\}},$$

and therefore the input impedance is

$$Z_1 = R_A + j\left\{X_A + \left(\frac{C_2}{C_1+C_2}\right)^2 X_L\right\}.$$

Case 1.—Aerial open-circuited at the base and approximately $\lambda/2$ long. There is no impedance transformation, although partial reactance cancellation is present over a range about $X_L=0$, $X_A=0$, at which $Z_1=R_A$.

Case 2.—Aerial approximately $\lambda/4$ long, and second leg short-circuited to ground. Here $v=0$. The input impedance consists of the radiation component of the first leg in parallel with the loop reactance. That is,

$$Z_T = \frac{(R_A+jX_A)\left[\dfrac{(C_1+C_2)}{C_1}\right]^2 . jX_L}{jX_L + (R_A+jX_A)\left[\dfrac{C_2+C_1}{C_1}\right]^2}$$

$$= \frac{(R_A+jX_A)\,jX_L}{R_A + j\left[X_A + X_L\left(\dfrac{C_1}{C_1+C_2}\right)^2\right]} \quad ......(15)$$

If $X_L=\infty$, the input impedance becomes

$$\left[\frac{C_1+C_2}{C_1}\right]^2 (R_A+jX_A),$$

and if $X_A=0$, this is a resistance.

The general case of unity power factor is illustrated by the vector diagram of Fig. 7 and results in an impedance of

$$R_T = \left(R_A + \frac{X_A^2}{R_A}\right) . \left[\frac{C_1+C_2}{C_1}\right]^2 \quad ....(16)$$

From equation (15), this may be written

$$R_T = \frac{-X_AX_L}{R_A}$$

$$= R_A . \frac{X_L}{X_A + X_L\left[\dfrac{C_1}{C_1+C_2}\right]^2}$$

$$= R_A . \left[\frac{C_1+C_2}{C_1}\right]^2 . \frac{X_L}{X_L + \left[\dfrac{C_1+C_2}{C_1}\right]^2 X_A} \quad ...(17)$$

This shows the possibility of wide band operation, if X_L can be made large and X_A kept low in the operating range of frequencies, where $\left[\dfrac{C_1+C_2}{C_1}\right]^2$ is high, e.g., 9 or more.

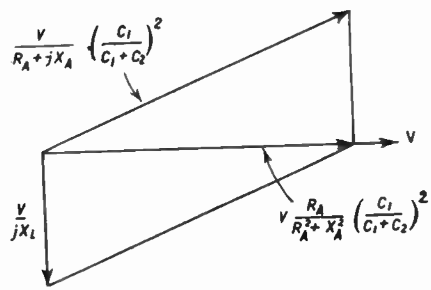

Fig. 7.—Vector diagram illustrating the general case of unity power factor for a folded aerial with unequal legs.

4. Experimental Results illustrating the Analysis

In ultra-short-wave experimental work, design and development, one can rarely use the guiding theory in full detail. The theory gives a set of bounding conditions which the experimenter aims to approach, but in practice many factors cannot be experimentally determined.

For instance, in folded aerials, we speak of $Z_A=R_A+jX_A$ as the impedance of an envelope aerial formed by a number of legs in parallel, but any attempt to connect the legs in parallel and measure the envelope impedance in the usual practical case would defeat itself, because of the relatively large effects of the paralleling connections and indeterminable base capacitance effects. Nevertheless, published information on aerials of similar l/d ratio as the envelope guides us in the design.

4.1. *Barrel Type Aerials*

4.1.1. Series compensated aerial

This arrangement is shown in Fig. 8. Note the reactance cancellation near the resonance between the reactance of the stub in the barrel of the aerial and the series reactance at the base of the system. The taper reduces base capacitance of the aerial to ground.

4.1.2. Parallel compensated aerial

The shunt-tuned impedance-correcting circuit (Fig. 9) steps up the resistance, well away from resonance, to give a much wider bandwidth (cf. Fig. 2) for a given standing wave ratio. This type of correction is satisfactory for moderate quality, relatively wide-band performance such as is suitable for communication circuits. The aerials of

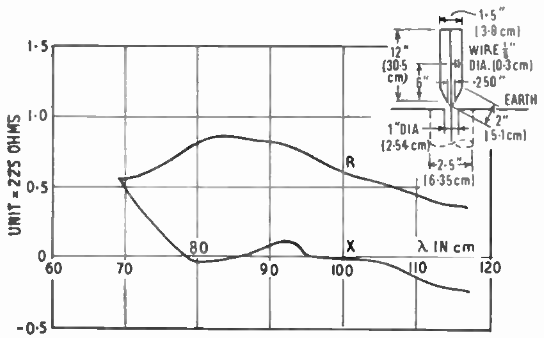

Fig. 8.—Series compensated short cone aerial.

Figs. 8 and 9 serve to illustrate a principle, and are not of much practical importance. The dotted figure is for a less favourable shunt tuning of the circuit at the base of the aerial.

4.2. *Cases of Symmetrical Folded Aerials*

In this arrangement (Fig. 10), the aerial system consists of the transformed envelope impedance $Z_A = 4(R_A + jX_A)$ in parallel with the loop impedance jX_1. The unity power factor conditions for this case, equations (4) and (5) can be re-written

$$R_T = 4R_A\left(\frac{X_1}{X_1 + 4X_A}\right) \quad \text{.........(4')}$$

$$R_T = 4\left(R_A + \frac{X_A^2}{R_A}\right) \quad \text{.........(5')}$$

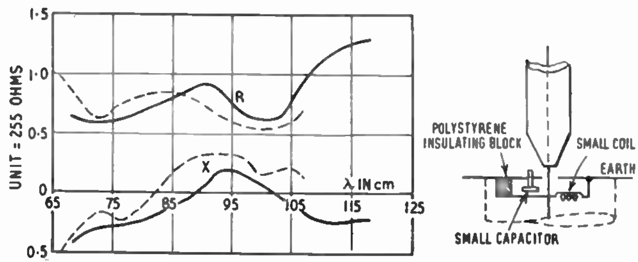

Fig. 9.—Short cone aerial with compensated parallel circuit (series compensation 4½ turns/in.). Maximum inductance, low Q parallel circuit. Low inductance, high Q parallel circuit.

Each case is subject to the unity power factor condition

$$X_1 = -4\left(X_A + \frac{R_A^2}{X_A}\right) \quad \text{.........(6')}$$

Figure 10 is drawn for three different values of the gap or leg spacing. The characteristic impedance Z_1 of the loop between the legs in each case is

Spacing	Z_1
½ inch (1·27 cm)	68 ohms
¾ ,, (1·91 cm)	92 ,,
1¼ ,, (3·18 cm)	133 ,,

Note that in all three cases, the aerial envelope has a relatively high thickness to length ratio. This causes the envelope series resonance to occur at a frequency appreciably lower than that corresponding to the overall

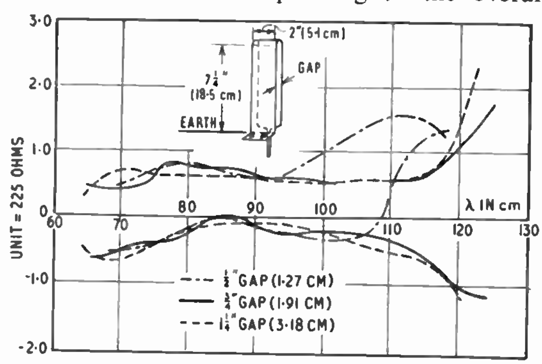

Fig. 10.—Parallel-strip symmetrical folded aerial.

aerial length, and results in the loop anti-resonant frequency being higher than the envelope series resonance.

In general, $R_A + jX_A$ changes but little for all three cases, the effective Q of the envelope being but a little lower for the wider spacing of the legs. However, jX_1 changes appreciably, being of the form $jZ_1 \tan 2\pi l/\lambda$.

For $\frac{1}{2}$ in. and $\frac{3}{4}$ in. spacing of the legs, the two higher frequency resonances come nearer together, due to the non-coincidence of the loop anti-resonance and envelope series resonance as for the symmetrical simple band-pass principle.

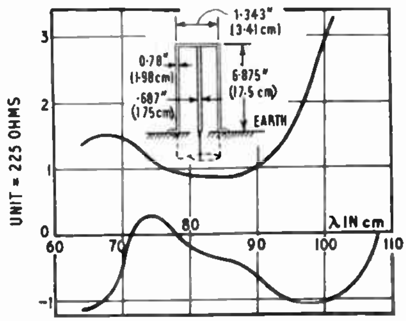

Fig. 11.—Unsymmetrical folded aerial.

For the $1\frac{1}{4}$ in. spacing, the loop impedance is too high at all points in the neighbourhood of envelope resonance for condition (6′) to be satisfied, and these two higher-frequency resonances of the simpler cases do not occur.

Concerning the low-frequency resonance, at the unity power factor condition the $\frac{1}{2}$ in. spacing produces a sufficiently low loop characteristic impedance for there to be a resonance at approximately 108 cm. In the case of wider spacings, however, the low-frequency resonance occurs at wavelengths greater than the 125 cm, which was the low-frequency limit of our experimental range.

The application of this principle allows a useful wideband unit to be developed. The B.B.C. television aerial at Sutton Coldfield made use of such units, properly combined in groups.[5]

4.3. *Cases of Unsymmetrical Folded Aerials*

These cases are illustrated by Figs. 11 and 12. The aerial consists of the transformed envelope impedance

$$Z_A = \left[\frac{C_1+C_2}{C_1}\right]^2 (R_A + jX_A)\,, \quad \ldots\ldots(4'')$$

in parallel with a loop impedance

$$jX_1 = jZ_{12} \tan 2\pi\, l/\lambda\,.$$

Here Z_{12} is the characteristic impedance of the transmission line which is formed by the extension of the central conductor of the feeder and the two outer legs as return.

The relevant equations for unity power factor give:

$$R_T = \left[\frac{C_1+C_2}{C_1}\right]^2 \cdot R_A \cdot \frac{X_1}{X_1 + \left[\dfrac{C_1+C_2}{C_1}\right]^2 X_A} \quad \ldots\ldots\ldots(5'')$$

$$R_T = \left[\frac{C_1+C_2}{C_1}\right]^2 \left(R_A + \frac{X_A^2}{R_A}\right) \quad \ldots\ldots\ldots(6'')$$

Subject to the unity power factor condition itself

$$X_1 = \left[\frac{C_1+C_2}{C_1}\right]^2 \left(X_A + \frac{R_A^2}{X_A}\right)\,.$$

By field plotting, we find (Fig. 12) that

$$\frac{C_1+C_2}{C_1} = \frac{3\cdot7}{1\cdot7}$$

and since Z_{12} is large (a fair approximation near the middle of the range),

$$R_T = \left(\frac{3\cdot7}{1\cdot7}\right)^2 \left[36 + \frac{X_A^2}{36}\right]\,,$$

which is satisfied if $X_A = 14$, a quite reasonable value.

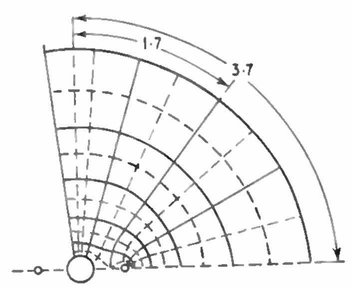

Fig. 12.—Quadrant of field plot for the determination of the ratio $(C_1+C_2)/C_1$.

$$\textit{Resonant resistance} = \left(\frac{3.7}{1.7}\right)^2 \times 36 = 171\,\Omega$$

The three resonances are clearly shown. There is little doubt that if the complexity of a shunt capacitance at the feed point were warranted, it could be used to bring the central zero-reactance nearer to the centre of the band-pass and improve the flatness of the impedance frequency characteristic.

Note that apart from the examples given here, considerable modifications are possible in the loop tuning—it may be short circuited at an appropriate height and filled with a dielectric to bring loop and envelope resonances to the same frequency. This is very convenient, but shunt capacitance at the feed point and an appropriate shunt circuit across the loop will give much the same result.

4.4. *Folded Aerial Impedance Transformation of Ratio Less than* 4:1

It should be noted that it is particularly difficult to obtain intermediate impedances. For instance, there are applications where an unbalanced vertical aerial over a ground plane could, with advantage, be transformed to 72 ohms.

If a 72 ohm transmission line existed where the centre conductor was of the same cross-section as the thicker leg of the impedance transforming folded aerial, it is likely that 2:1 transformation could be obtained. However, connecting a fine wire to the base of even two out of three symmetrical wires in a 9:4 impedance transformation causes a higher impedance or lower capacitance per unit length of leg in the neighbourhood of the feed point and the desired impedance transformation is not obtained.

It is important to note here that the voltage and current entering the aerial at the feed point determine the feed impedance. Connecting two legs together to a single feed connection causes a serious discontinuity in the capacitance per unit length of lead corresponding to the two legs in parallel and tends to bring the feed impedance nearer to that corresponding to a folded aerial of equal legs.

Feeding a single wire of a group of parallel wires, however, does not suffer so greatly from discontinuity at the feed point, and the higher order impedance transformations are readily obtained.

Added by Professor Willoughby, 25th June 1956

5. Conclusions

Folded aerials are strong mechanically, and the closed loop formed by the aerial across its transmission line makes driving easy to arrange. For wide band operation and high quality matching to the transmission line, the need of a low characteristic impedance in the transmission line formed by the loop of the aerial should not be overlooked (see Fig. 10).

It should be noted that details of input connections are particularly important in cases of impedance transforming folded aerials, as they can modify input impedance seriously; when feeding a single loop folded aerial, a two-wire transmission line plus two quarter wave transforming sections may be a more effective arrangement than a four-wire transmission line of the same impedance as the aerial itself.

If a single wide band aerial is to be fed from a concentric tube transmission line, an ideal arrangement is a half-wave dipole formed from two concentric tubes, the centre of which is continuous and supports the aerial, and the outer, divided into equal lengths at the middle, forms the dipole. Between the two ends of the dipole are included two concentric short-circuited stubs in series, and these can be designed to improve bandpass. This aerial is closely related to the folded aerial in that it has a reactive loop across the input terminals, but it does not experience any impedance transformation, as the second leg is screened and cannot radiate.

It is the author's conviction that many opportunities for the solid earthing of broadcasting aerials, and the inclusion of top loading as a loop in a two-wire folded aerial with one end earthed to give a more convenient feed impedance, are missed through designers not appreciating the principles put forward in this paper.

6. Bibliography and References

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4. W. van B. Roberts, "Input impedance of a folded dipole," *R.C.A. Rev.*, **8**, p. 289, June 1947.
5. P. A. T. Bevan and H. Page, "The Sutton Coldfield television broadcast station," *Proc. Instn Elect. Engrs*, **98**, Part III, p. 416, November 1951.

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

534.771

Study of audiometer standardization. R. LEHMANN. *Onde Electrique*, **36**, pp. 466-77, May 1956.

The author reviews a number of problems set by audiometer standardization, with particular reference to those relating to audiometer zeroing, that is, to the measurement of the average threshold of hearing. The various problems met in bone and air conduction are considered, and the many causes of error met by experimenters are pointed out. The author describes the difficulties met in the task of relating acoustical pressures measured on human ears to corresponding pressures measured on artificial ears. He relates the results achieved in that particular line in various countries, and brings out the discrepancies which still exist. Finally, a summary is given of the position regarding audiometer standardization in France at present.

534.843:621.374.32

New acoustic characteristic of rooms and the development of a multipurpose electronic counter. R. LAMORAL and R. TREMBASKY. *Onde Electrique*, **36**, pp. 441-9, May 1956.

The article presents a new conception and apparatus suitable for measuring it. It appears that the classical reverberation time is insufficient to define the acoustic characteristics of a room and the idea of diffusion as an index, which is a function of frequency, is advanced. The apparatus described is primarily intended to measure this index, but in the course of its development it appeared to be useful for making other measurements, time of reverberation, sonometry, sound insulation, damping irregularities, etc.

538.245

Introduction to the study of magneto-optical phenomena in ferrites at super high frequencies. J. BENOIT. *Onde Electrique*, **36**, pp. 480-507, June 1956.

The application at s.h.f. of the magneto-optical phenomena of ferrites is still little known. At this time, when the technique is emerging from the laboratory stage and is being developed industrially, it is useful to describe its broad principles. The present article is limited to the elementary theory and to a few measurements and typical applications.

621-526

On the possibilities of application of the methods of servo-technics in the field of industrial process control. L. K. TOSSAVAINEN, *Teknillinen Aikakauslehti*, **46**, pp. 306-12, June 1956.

The article describes how the methods of servo theory can be used in industrial process control. With the aid of the Laplace transformation, the equations describing the operation of a single loop control system are derived qualitatively and the effect of disturbances is accounted for. The dynamic characteristics of the process itself are determined by means of experimental frequency response analysis. The process transfer function is given graphically as well as in its analytical form. As a next step, the steady-state error and the relationship between transient and frequency response are considered. The optimum controller settings can be predicted with the aid of simple graphical methods.

621.315.212

A low loss waveguide cable without phase and attenuation distortion. H. G. UNGER. *Archiv der Elektriscen Übertragung*, **10**, pp. 253-60, June 1956.

In the case of the TE_{01} mode in a circular metallic waveguide with dielectric tubular insert the attenuation constant shows a minimum dependent on frequency; the envelope velocity can have two extreme values. With a correct design one extreme value of the envelope velocity and the minimum of the attenuation constant fall on the same frequency. At this frequency the TE_{01} mode is transmitted without distortion of phase or attenuation. For a wideband waveguide cable with these properties the diameter and wall thickness of the dielectric tubular insert must be small.

621.318.42

Winding calculations for Ferroxcube cores. J. ARRAZAU. *Onde Electrique*, **36**, pp. 252-67, March 1956.

After defining the effective permeability of a magnetic circuit having a non-uniform cross-section, the paper describes Ferroxcube pot type cores. The effect of temperature and of the various losses is then examined. Brief reference is made to stability with time, and to the non-linearity of the magnetization curve. Practical considerations concerning windings are completed by a worked out example.

621.372.5

A method of analysing the performance of tandem-connected four-terminal networks. P. W. SEYMOUR. *Proc. Inst Radio Engrs, Aust.*, **17**, pp. 249-55, July 1956.

After a brief review of the classical quadripole theory, the paper covers definitions of the reference parameters of a quadripole and operation between nominal impedances. Use is then made of these definitions to analyse a simple case involving tandem-connection of two quadripoles. A graphical technique for calculation purposes is introduced, and a simple example of the application of the results derived is given. Brief reference is made to the scope of the generalized treatment of this subject.

621.372.853.2

Relations between the structure of ferrite and the conditions for their resonance in waveguides: Unidirectional waveguides. J. SUCHET. *Onde Electrique*, **36**, pp. 508-19, June 1956.

The principle of ferromagnetic resonance of ferrites at super high frequencies and its application to the construction of gyrators and separators has been recently described. The resonant frequency is given as a function of the magnetic moment and effective field by the equation $2\pi f = \gamma H_{eff}$. After a brief recapitulation of fundamental ideas of the physical significance of magnetism in solids, the author indicates the relations which exist between the structure of ferrites and their magnetic properties. The nature of the factor g (effective value) and its derivation from spectroscopic factors of the ions of the system, the calculation of the magnetic moment, as well as the effective field, the nature of the internal compensating field as well as the influence of manufacturing conditions are all in turn examined. Finally, a calculation is made of the characteristics of unidirectional wave guides for transverse or axial fields, equipped with nickel zinc or nickel aluminate ferrites, and conclusions are drawn regarding the realization of these arrangements.

621.373.423

Investigation of an interdigital delay line. F. PASCHKE. *Archiv der Elektrischen Ubertragung*, **10**, pp. 195-206, May 1956.

The first two sections of the paper discuss general relationships of lines of periodical structure, and the dispersion and coupling impedances of an interdigital delay line with all-pass characteristics are investigated. The fundamental mode of this line has, over a wide range, a phase velocity whose direction is opposed to the flow of energy so that it appears suitable as a structural element of carcinotrons. The attainable tuning range is extremely wide. By a suitable choice of the dimensions the first backward travelling Hartree harmonic can be widely suppressed with respect to the fundamental mode. The hazard, encountered in particular with high power levels, of a parasitic mode of short wavelength caused by interaction between the beam and the first partial mode is thus eliminated. The last section of the paper investigates how the dispersion of the all-pass line can be modified by suitable arrangements. The discussion relates in particular to the possibilities of expanding the tuning range. By a suitable layout a line with band pass properties is attained; with such a line a frequency modulation characteristic with a tangent of inflection is attained on an O-carcinotron similar to that of a reflex klystron. The linearity of this characteristic, superior to that of the all-pass line within a certain range, is obtained by a sacrifice in modulation slope and tuning range. It is also shown that the design of a wide-band delay line for amplifier tubes of high power level is possible. For testing the dispersion by experiment, measurements were made on "cold" delay lines and carcinotrons. The results show a good agreement with theory in the case of the all-pass line as well as in that of the band-pass line.

621.385.1

Recent developments in the domain of "O-carcinotron" tubes.—P. PALLUEL. *Onde Electrique*, **36**, pp. 318-35, April 1956.

Using electronic coupling between en electron beam and a retarded inverse wave, the "O-carcinotron" is a wide-band oscillator tube, electronically tuned and with an oscillation frequency little affected by exterior charges. Theoretical predictions regarding ronditions for oscillation, operating performance and senstivity to various effects have been confirmed in practice. A range of six models cover 1,000 to 15,000 Mc/s by octave intervals, overlapping in the commonly used bands. The use of short, massive, interdigital lines gives high performance coupled with robustness and reproducibility.

621.396.61/2

Single side band communication equipments. *J. L.* DELVAUX. *Onde Electrique*, **36**, pp. 520-31, June 1956.

The principles of single side band communication systems are described and the reasons which have led to a simplification of conventional equipments. A description is given of equipments produced, and the results of transmission tests are detailed.

621.397.61(44)

Standardization of television equipment at Radiodiffusion-Télévision Française. L. GOUSSOT. *Onde Electrique*, **36**, pp. 479-86 and 541-50, May and June 1956.

Radiodiffusion Télévision Française have been working for some time on the re-design and standardization of their equipment. This article describes the main technical features of video frequency television studio equipment. Standardization has led on the mechanical side to units in individual, closed boxes, and to the establishment of external electrical characteristics. The characteristics of the television signal and pattern measuring methods are tabulated. Components are grouped according to functions and their precise characteristics are tabulated in an appendix.

621.396.65(497.1):621.396.677.45

Development work for production of modern radio relay equipment in Yugoslavia. Z. FAZARINC. *Elektrotehniski Vestnik*, **24**, pp. 89-111, April-May 1956.

A brief survey is given of the work achieved in the field of radio links in the Institute of Telecommunications, Ljubljana. This is followed by a description of the 12-channel pulse-position modulated wireless telephony equipment UKD-12, which operates on decimetre waves and was constructed by the Institute for the radio relay link between Ljubljana and Bled. The first part of the paper deals with the operating principles and circuitry of this equipment; oscillograms are given showing transformations of pulse forms in the modulator and demodulator, and the process of wireless transmission of position-modulated pulses on carrier frequencies around 400 Mc/s is described. Helical aerials are used. Technical data and diagrams of some characteristics of the UKD-12 system are also included.